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The relationship between index testing and California Bearing Ratio values for natural road construction materials in South Africa

By

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Declaration

I, Izak Johannes Breytenbach, hereby declare that the work presented in this dissertation is my own unless referenced otherwise. I also declare that this work has not been submitted at any other institute for any degree, examination or other purpose.

Signed ______________________

Date ______________________

Abstract

The research portrayed in this dissertation aims to derive empirical means of predicting CBR values from index testing parameters and parameters calculated from them (e.g. shrinkage product).

The project involved compiling a database of test results for a range of rock material types across moist and dry regions in southern Africa. The database was compiled in such a way that it represents natural gravels sampled (mostly) for construction or rehabilitation of road layer works. The database included a location description, material description, Weinert N-Value, Atterberg Limits, grading analysis and CBR values. In addition to this, the linear shrinkage product, shrinkage product, grading coefficient, grading modulus and dust ratio were calculated and also used in the analyses.

All the samples were divided into two groups based on climate, as described by Weinert (1980). The data was then further sub-divided into compaction classes (95%, 98% and 100% Mod AASHTO) and within these compaction classes, each sample was assigned to a rock material group based on the classification proposed by Weinert (1980), but with minor alterations (e.g. further subdivision of pedogenic deposits). A total of 60 groups were created.

Data processing was done using grading normalised to 100% passing the 37,5mm screen. In order to limit interdependency resulting from the cumulative grading, the sieve analysis results were converted to percentages retained on each sieve. This was necessary as statistical regressions often rejected datasets due to interdependency among input parameters (such as Atterberg Limits and cumulative grading).

Based on the nature of the data, both stepwise linear regressions and Weibull regressions were performed. Though the Weibull regression is more suitable to the data (in theory) the linear regression could not be excluded, due to variable data. In addition, the existing model proposed by Kleyn (1955) – which was derived empirically by Stephens (1988) – was also retained for the analysis. In an attempt to refine Kleyn's model, the two parameters used by the method (i.e. grading modulus and plasticity index) were used in normal linear regressions in an attempt to adapt the model to specific material (and compaction) groups in the two climatic regions.

More than 130 regressions were done for the final analysis (excluding experimental regressions, etc.), after restricting the predicted CBR ranges in an attempt to eliminate the prevailing data trend. The attempt proved futile, though, placing severe restrictions on the derived models. For each of the 60 groups all four methods were tested (i.e. stepwise linear regression, Weibull regression, Kleyn's model and a linear model adapted for each group based on Kleyn's model) and the most suitable model selected. A number of regressions were incomplete due to insufficient data, particularly in the groups associated with dry regions.

Results proved poor and are ascribed to data variability rather than test methods. The data variability, in turn, is the result of test methods with poor reproducibility and repeatability. In short, the test methods (the CBR in particular) resulted in inconsistent data and subsequently poor results, making accurate predictions nearly impossible.

Dedication

This dissertation is dedicated to my father, Frans, without whom I would not be where I am. It was indeed a blessing and honour to be raised as your son. You have taught me the values of love and life and have inspired in me a passion for what I love and respect for all things around me, created by God. Through many a sacrifice on your behalf you have provided me with abundant opportunities, none of which I can repay. I therefore dedicate this dissertation to you, with a son's love.

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Symbols and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BSI	British Standards
c	Cohesion
CBR	California Bearing Ratio
COLTO	Committee of Land Transport Officials
DCP	Dynamic Cone Penetrometer
DPSH	Dynamic Probe Super Heavy
DR	Dust Ratio
FA	Fineness Average
GC	Grading Coefficient
GI	Group Index
GM	Grading Modulus
I_f	Formation Index
LL	Liquid Limit
LS	Linear Shrinkage
LSP	Linear Shrinkage Product (Linear Shrinkage × P075)
MDD	Maximum Dry Density
Mod AASHTO	Modified AASHTO (compaction) - see AASHTO
MSCBR	(Equivalent to) Mod AASHTO density
MSPE	Mean square prediction error
NSCBR	(Equivalent to) 98% Mod AASHTO density
OMC	Optimum Moisture Content
PI	Plasticity Index (referred to as PIN in database)
PL	Plastic Limit
PSCBR	(Equivalent to) 95% Mod AASHTO density
r	Correlation Coefficient
s	Shear Strength
SANAS	South African National Accreditation Service
SEE	Standard Error of Estimate
SP	Shrinkage Product (Linear Shrinkage × P425)

TMH	Testing Methods for Highways
USCS	Unified Soil Classification System
Φ	Angle of shearing resistance
σ_n	Normal stress

1. Introduction

1.1 Motivation for Research

At present South Africa's infrastructure is expanding rapidly. A large number of new urban and lightly trafficked roads are planned or under construction. This – in addition to maintenance of existing roads – results in a large amount of material testing. The CBR, or California Bearing Ratio, is the most popular, common and comprehensive test currently used in road construction. The test has been utilised for decades and is familiar to the parties involved with the interpretation of results, consequent road design and construction.

The expanding infrastructure, however, places significant strain on facilities that are responsible for material testing – particularly with the California Bearing Ratio test. The test requires large amounts of material and is time-consuming to perform. Additional drawbacks of the CBR tests include haulage, testing costs and ultimately disposal of the tested material. Laboratories are often booked over capacity causing a delay in testing and result delivery which, in turn, leads to delayed project schedules.

Many individuals feel that the CBR needs to be replaced, at least partially, due to the above-mentioned problems and the fact that the test results lack satisfactory reproducibility. A number of solutions or alternative tests have been suggested in the past and will be discussed in this dissertation. One such alternative has been the prediction of CBR values from other parameters such as the grading modulus and Atterberg Limits. Predictions such as these are considered in this research project.

1.2 Aim of Research

The research presented in this dissertation concerns itself with the prediction of CBR values in an attempt to reduce the amount of CBR testing done in industry. A number of existing models are considered and their predictive capabilities are compared using a large database developed for this project. Once evaluated, the models are either refined or new models derived. Such derivation was, however, done after the materials were grouped according to climate and specified material groups. No record has been found of similar attempts, with the exception of models developed specifically for single material types (e.g. calcretes) and hence the research was expected to deliver unique results.

2. Literature Review

The CBR is essentially a measure of the shear strength of a material at a known density (and moisture content). The shear strength of soils can generally be considered in terms of Coulomb's Law, as discussed by Croney (1977). Failure of a soil occurs when individual grains move relative to one another (Rosenak, 1963), as described in fundamental soil mechanics. Equation 2.1 illustrates the relationship between the shear strength (or resistance to shear) of a soil and its cohesion and angle of shearing resistance (friction angle).

$$s = c + \sigma_n \tan\varphi \qquad \text{Eq 2.1}$$

where

s = shear strength
c = cohesion
σ_n = normal stress
φ = angle of shearing resistance

It is clear that the shear strength of non-cohesive soils is determined solely by friction and interlocking of particles, whilst in cohesive materials the shear strength depends on both cohesion (the water bonds between clay particles) and the internal friction.

In road construction materials, entirely cohesive or non-cohesive natural materials are not generally used. Whilst materials such as decomposed granitic sand or noritic clay may represent occurrences of mostly non-cohesive or cohesive materials respectively, natural materials are usually found to be a mixture of cohesive and non-cohesive constituents. The strength of a soil material therefore comprises two components. The frictional component, which depends on the friction and interlock between the soils grains, is a function primarily affected by the particle size distribution (grading) of the material. This component is also affected by an applied stress normal to the shear plane. The effect of compaction on particle interlock must be anticipated, particularly when discussing compaction-related tests. Craig (1997: 28) states "Compaction is the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air: there is no significant change in the volume of water in the soil". (This statement must be considered in the context of the CBR, where the sample is not only compacted, but soaked for four days).

The second strength component is the cohesion of the material. The effect of cohesion is influenced by the grain size (distribution), the affinity of the particles to moisture (plasticity) and the moisture content.

Considering the above it is apparent why compaction of any tested material results in increased soils strength. The particle interlock and particle packing is modified during compaction resulting in forced interlocking and denser packing. However, with three compactive efforts being used throughout (i.e. 95%, 98% and 100% Mod AASHTO), the prediction of CBR values would therefore require analysis of parameters representing interlock, friction and cohesion. The grading is essential in representing the constituents to interlock and cohesion. In the absence of hydrometer results in the data available for the research, the constituent finer than 0,075 mm (P075) will be considered as representative of cohesive materials. Atterberg Limits, reflecting the relationship between a material's moisture content and plasticity, are also associated with the cohesion of such a material. The grading and Atterberg Limits are therefore deemed the critical parameters in the prediction of CBR. Simultaneously, additional parameters developed from the primary grading and plasticity properties such as the grading modulus, grading coefficient, dust ratio, linear shrinkage product and shrinkage product are also analysed.

2.1 History of the California Bearing Ratio

By definition, the CBR can be described as follows: "The California Bearing Ratio of a material is the load in Newtons, expressed as a percentage of California standard values, required to allow a circular piston of 1935mm^2 to penetrate the surface of a compacted material at a rate of 1,27mm per minute to a depth of 2,54mm, 5,08mm and 7,62mm. The California standard values for these depths are 13 344N, 20 016N and 25 354N respectively" (TMH1, 1986: 35).

In order to appreciate the development of the CBR, a short description of its history, as described by Otte (1977) is included.

The use of grading and Atterberg Limits alone were not sufficient in qualifying materials for road construction use due to the fact that such materials behave differently under different moisture and density conditions. Using Proctor's original compaction technique, Porter developed the CBR-penetration and swell test around 1930 (Otte, 1977). The penetration test was developed in order to establish the material's shear strength, whilst the swell test would indicate the material's (potentially worst state) post-compaction behaviour – i.e. when wetted (and ultimately saturated).

Initially the test used static compaction of 13,78 MPa to simulate densities achieved by years of service operation. The compaction saw a 150mm diameter sample compacted at roughly 1,25mm per minute. This was followed by the 13,78MPa load which was applied and held for one minute, and then removed. The method, however, proved impractical because static compaction devices were not readily available. For this reason the falling hammer setup was introduced, as it was more practical and obtainable.

The compactive effort initially used with the falling hammer (per 25mm layer) involved twenty drops, using a 4,53kg hammer falling a distance of 457mm. The falling hammer method proved more practical and consequently the static compaction method was discontinued. After the static compaction method was discontinued, the falling hammer method was further adapted and modified in an effort to fine-tune its performance. The four day soaking period was also introduced, after which the amount of swelling could be determined and the penetration test could be conducted.

The test setup and equipment used for the original test is not dissimilar in nature from what is used currently. The apparatus consisted of a 1935mm^2 penetration piston, penetrating at 1,27mm per minute. The effort required to penetrate intervals of 2,54mm was recorded and compared with the forces required to penetrate a standard broken rock sample (a widely used limestone from California). As is practice today, the recorded force was expressed as a percentage of the required force for testing the standard sample. The standards for 2,54mm, 5,08mm and 7,62mm penetration were established at 6 895kPa, 10 342kPa and 13 100kPa, respectively.

2.2 Current CBR test methods

Internationally CBR tests are conducted under the same name, however, not all tests utilise the same procedures or test apparatus. Though the tests essentially remain the same, results are interpreted and compared despite differences in test methods. In addition, different compactive efforts are also used e.g. Proctor or Mod AASHTO. The purpose of this section is not to give a detailed description of each test method, but merely to point out some of the differences mentioned. Details of the different test methods are available from sources included in the reference list.

2.2.1 South African Standards

Through the years minor adjustments have been made to the CBR test method, but the essence of the test has remained the same. The test still measures the load required to allow a standard piston to penetrate the surface of the compacted material, as well as the amount of swell observed (TMH1, 1986). The standard penetrations measured are 2,54mm, 5,08mm and 7,62mm. The respective standard loads used in the comparison are 13 344kN, 20 016kN and 25 354kN (TMH1, 1986).

In the South African context, a standard mould – as described by TMH1 (1986) specifications – is used for the test. This mould has a different volume compared with other test methods, resulting in a higher compaction density. The material to be tested is air dried and sieved through a 19,0mm sieve. Any material remaining on the 19,0mm sieve is then lightly crushed until it passes through the sieve and added to the sample. Once the sample has been split into smaller samples and wetted to optimum moisture content, the sample is covered with a damp sack – which is to prevent evaporation – and left to stand for thirty minutes. This ensures even moisture distribution throughout the sample (TMH1, 1986).

Once the first phase of the material preparation is complete, sample material is placed into the moulds and prepared to specification. The loaded moulds are again tamped to specification, which ensures even compaction at optimum moisture content (TMH1, 1986). The obvious distinction between the dry CBR and soaked CBR test is the following step: with a dry CBR the penetration test is conducted after sample compaction. With the soaked CBR test, however, the compacted sample is soaked for four days in a soaking bath. Sample saturation is attempted in order to induce the possible worst case moisture conditions in the entire sample; however, full and uniform saturation is not always achieved. Once soaking is complete, the sample is penetrated. By definition, the CBR is always soaked, unless otherwise stated.

2.2.2 British Standards

Although the basic test is similar to the South African version, small differences are encountered in the test method and procedure. By British standards, material passing a 20mm sieve is used (BSI, 1990), as opposed to a 19,0mm sieve by South African methods (TMH1, 1986). In addition, particles retained on the 20mm sieve are removed from the test (BSI, 1990), whereby South African standards the material is lightly crushed and added to the sample (TMH1, 1986). Should more than 25% of the material be retained on the 20mm sieve, the test is considered not applicable (BSI, 1990).

British standards also make provision and provide guidelines for static compaction (BSI, 1990), something which is not practised in South African testing. But perhaps the biggest difference between South African and British standards is in compactive effort. By British standards, compaction continues until increments of one fifth of the mould height are reached (BSI, 1990), whereas South African standards have specified numbers of blows for layer compaction cycles. In addition, in the British test samples are compacted at specified moisture contents or increments of moisture contents (BSI, 1990).

2.2.3 AASHTO Standards

As with South African standards, AASHTO standards specify the use of material passing the 19,0mm sieve; however the method can be modified should there be larger particles). This modification involves replacing the material retained on the 19,0mm sieve with an equal amount (by mass) of material passing the 19,0mm sieve and retained on the 4,75mm sieve. The compaction of the sample is then done either at optimum moisture content, or at a range of moisture contents, which is to be specified by the requesting agency (AASHTO, 2005). It is also standard practice – unless otherwise requested – to conduct the four day soaked CBR test (AASHTO, 2005).

With regard to physical differences in test apparatus, the AASHTO specified mould has the same diameter as the South African and British moulds, but has a height of 177,80mm (±7,0mm) and a spacer disk with a different height than the South African version. Associated with this is a compactive effort different from both the South African and British methods (AASHTO, 2005).

2.3 Index Tests

Locally, index tests are referred to as Atterberg Limits and include the liquid and plastic limits of a material (Croney, 1977). From these two parameters the plasticity index is calculated, as discussed in section 2.3.3. Of significance again, is the difference in the manner and protocol of determination between South African standards and British standards.

2.3.1 Liquid Limit

According to the BSI (1990: 4), the liquid limit is "…the empirically established moisture content at which a soil passes from the liquid state to the plastic state". By British standards, two tests can be used to determine the liquid limit, namely the cone penetrometer test and the Casagrande test. Samples for both tests are prepared in a similar fashion. The penetrometer test is described to be the better test, due to the fact that it is a static test, the result of which depends on the soil's shear strength (BSI, 1990). The Casagrande test, in contrast, is prone to variations in results introduced by discrepancies by individual operators i.e. interpretation of the test varies between operators (BSI, 1990). The cone penetrometer test also yields more reproducible results and is apparently easier to conduct than the Casagrande test (BSI, 1990; Sampson, 1983).

The Casagrande test is used as the standard South African test for determining the liquid limit (TMH1, 1986). The method correlates well with the Casagrande method specified in British standards with some variations arising from a different hardness of the rubber base (usually about 4%). Detailed descriptions are available in the source documents, BSI (1990) and TMH1 (1986).

2.3.2 Plastic Limit

The plastic limit is defined as "…the moisture content, expressed as a percentage of the mass of the oven-dried soil, at the boundary between the plastic and semi-solid states" (TMH1, 1986: 17). Another description is the "moisture content at which a soil becomes too dry to be plastic" (BSI, 1990: 13).

The method used in South African laboratories to determine the plastic limit involves taking a portion of the sample and rolling it into a thread of uniform diameter (TMH1, 1986). Depending on the nature of the material (cohesive or non-cohesive), the method of rolling the thread in the hands varies slightly. In essence, the thread is formed until it starts to disintegrate. Disintegration takes place due to a lack of cohesion which results from insufficient moisture. At this point the moisture content can be determined by weighing the dried sample and the plastic limit can be determined (TMH1, 1986). From this brief description it is obvious that results are dependent on the operator, as two individuals may set different limits to what they consider to be disintegration of the sample material. The British method closely resembles the South African method.

2.3.3 Plasticity Index

The plasticity index is calculated according to TMH1 (1986) as follows:

Plasticity index = liquid limit – plastic limit Eq 2.2

This applies to both British and South African standards, though symbols used are not identical.

2.4 CBR: Influencing Properties

A range of factors influences the CBR of a particular material. Carter and Bentley (1991) mentioned the soil type, density, moisture content and method of sample preparation as playing an important role. Apart from the material properties themselves, moisture conditions are also pivotal. The moisture conditions at which the material is to be used vary according to climatic region, and as such the CBR test is used to simulate the worst likely conditions in service (Emery, 1987).

Properties playing an important role in the CBR values of calcretes, as identified by Lawrance and Toole (1984), include the grading, the strength of the hard particles and the plasticity of the fines. They specified the important parameters to be the grading modulus, the percentage passing the 0,425mm sieve, the aggregate pliers value and the linear shrinkage (Lawrance and Toole, 1984). They also state that the dry density serves as a good indication of the material quality, the general indication being that a higher dry density relates to a better quality material. Croney (1977) confirms this statement by stating that a higher dry density results in a higher CBR value at a constant moisture content during compaction.

2.5 The CBR and Moisture

2.5.1 Moisture and Compaction

A major criticism of the CBR is its poor reproducibility that results from the test procedure. The moisture content of a sample may show significant variance when remoulding, and hampers reproducibility (Kleyn, 1955).

A second important issue concerning compaction and moisture content involves the nature of the CBR sample. According to Black (1961) three types of samples can be used for CBR testing: 1) a recompacted soil sample in a standard laboratory mould, 2) an undisturbed sample, cut and trimmed to closely fit the standard mould and 3) an in-situ sample which is tested at the surface. Considering the first two sample types (recompacted and undisturbed moulds) of identical origin, Black (1961) explains that there will still be a significant difference in the CBR results even if the dry density and moisture contents are identical. The reason for this is that the recompacted sample would have completely different pore water pressures to the undisturbed sample (Black, 1961). That being stated, it is more likely that in practice, material will be removed and used somewhere else during construction. Bearing this in mind, the recompacted sample yields a more applicable result with regard to construction.

2.5.2 Moisture and Material Selection

Much has been discussed about the relationship between moisture and the CBR. Until around 1938, the CBR value was determined both before and after soaking. At this point however, Porter recommended that only the results of the soaked CBR be used (Otte, 1997). Porter's explanation is that soaking the material induces swell and moisture absorption, and ultimately reveals a loss in material strength (Otte, 1977). Hence, it can be said that the soaked CBR represents the worst case scenario, as the soaked strength is lower than the strength at field equilibrium moisture content (Emery, 1985).

Many authors feel that the soaked CBR test is an over-conservative approach and that results in material selection and construction being more expensive than need be. The fact is that the soaked CBR simulates conditions that often do not or will never exist in certain areas (or very seldom occur). Haupt (1981) argues that if it was possible to predict the moisture conditions that would prevail under a covered area, thinner pavements and more readily available, sub-standard materials can be used. He also concludes that should the in-situ moisture conditions be predicted, the expected heave and settlement could be more accurately predicted and designed for, ultimately reducing the cost of construction.

Another point discussed is the use of the dry or unsoaked CBR. The point made here is that lower quality material could be used that would fulfil requirements for a dry CBR, but not a soaked CBR. Emery (1985) shows that lower quality material can be used if the predicted in-situ moisture content is low enough. He also cautions that while this is possible and is likely to save costs on materials, the cost must be weighed against premature failure due to inferior materials being used.

2.6 Alternatives to the CBR

Many individuals have tried to propose alternatives to the CBR, whilst others have tried using other existing tests to obtain similar results.

Croney (1977) mentions an alternative to the CBR, particularly for concrete roads, to be a large-scale plate bearing test, carried out in-situ. He also points out that the cone penetration test is a suitable method for assessing large areas of soil in a short time. However, whilst the plate load test may yield usable results, it is doubtful that the cone penetration test would deliver results specific enough for material to be utilised in construction design.

Other authors attempt to develop a smaller test similar to the CBR. The so-called Iowa Bearing Value (or mini-CBR) is proposed by Nogami and Villibor (1979) and – as the name states – is in essence merely a smaller version of the CBR.

A number of regions (e.g. Western Australia, Texas, Zimbabwe, etc.) make use of the Texas Triaxial (or Western Australian Confined Compression Test). The method is essentially a static triaxial test to identify a soil class. Testing involves determining the static failure load at five different confining pressures (Lay, 1981). This information is then used in conjunction with Mohr circles to classify the material. Lay (1981) notes that results are usually dependant on moisture content.

2.7 Soil Classification Systems

Numerous classification systems are in existence in the road construction industry at present. Some systems are original, while some are modifications or fusion of other systems. Such systems attempt to relate specific factors (e.g. soil description) to properties, such as engineering parameters (Croney, 1977). Below is a short description of four classification systems, three of which are commonly used, and a fourth which will be utilised in this dissertation.

2.7.1 Casagrande Soil Classification System

The Casagrande system divides soil material into classes based on grain size distribution (e.g. gravel and gravelly soils). Each class is complemented with a description that aids in field identification. The classes are then subdivided into sub-groups (e.g. well-graded, gravel-sands with small clay content) and awarded a group symbol. From here each sub-group is supplied with generally applicable test methods and observations associated with it. This is followed by a generalised description of expected characteristics associated with each sub-group, including value as a road foundation material, potential frost action, shrinkage or swelling properties, drainage characteristics and maximum dry density at optimum compaction. The scheme provides a very useful indication for making preliminary decisions concerning material use (Croney, 1977).

2.7.2 Unified Soil Classification System

The Unified Soil Classification System (USCS) was developed from the Casagrande system and shows many similarities, although it is more thorough and considered as more complete (Carter and Bentley, 1991). In this system, coarse and fine-grained soils are classified based on their particle size distributions and plasticity. The system distinguishes between silts and clays by a graphical relationship between the plasticity index and liquid limit, as determined by Casagrande, using empirical data (Carter and Bentley, 1991).

The USCS has also been adapted by the American Society for Testing and Materials (ASTM). Apart from presentation, the ASTM and USCS are basically one and the same; however, the ASTM requires classification tests whereas the USCS allows classification by visual inspection (Carter and Bentley, 1991). Carter and Bentley (1991) also state that the British classification system is based on the Casagrande System but with additional classes. In order to use the system for the British Standards, soils and gravels are defined slightly differently, due to the different grain sizes used for classification in the British system.

2.7.3 AASHTO System

The American Association of State Highway and Transportation Officials (AASHTO, 2005) uses a different approach to the Casagrande system (and therefore different to British and USCS). Eight classes are distinguished in this system, of which the eighth (Group A8) class comprises highly organic materials that are not classified by grading or plasticity, but rather by visual inspection. A general distinction in this system is granular material (Groups A-1, A-2 and A-3) and the silt-clay materials (Groups A-4, A-5, A-6 and A-7). Carter and Bentley (1991) explain that this system does not provide as clear a border of the classes as the Casagrande system, because some materials that may be classified as “granular” material may yet contain large quantities of clay or silt. They also emphasise that the aim of the AASHTO System is not to classify soil, but rather to classify the material’s suitability for use as pavement subgrade. In general the scheme shows that the lower the group index is, the more suitable the material is for pavement subgrade.

2.7.4 Weinert's Classification System

The system proposed by Weinert (1980) does not focus specifically on soil materials, but rather parent rock materials. The scheme divides rock material into two main classes, namely decomposing rock and disintegrating rock. Both of these classes are subdivided as illustrated below in Table 2. 1. Weinert (1980) considers differences in material type and behaviour related to its origin, as well as the climate under which it weathers.

The approach Weinert (1980) uses to classify construction material is based on the mineral composition and subsequent behaviour thereof under different conditions of breakdown. His argument is logical and sensible. To illustrate his approach, the short summary below is included.

Weinert (1980) identifies the basic crystalline rocks as the single most problematic rock type, especially in regions where the Weinert N-value is less than five. In such regions, the annual moisture in the soil profile is such that decomposition dominates over disintegration. What makes this significant in the case of basic crystalline rock, is that due to its mineral composition, a basic crystalline rock will weather to smectite clay comprising mainly of montmorillonite, or where the N-value is less than two and strong leaching is present, kaolinite (Weinert, 1980). The former clay mineral type is not desired in road construction materials as it is associated with conditions of low shear strength and potential volumetric change (i.e. heaving and shrinking).

Concerning acid crystalline rocks, Weinert (1980) emphasises the abundance of quartz in the mineral composition. Decomposition of other acid crystalline rock minerals proceeds directly to the kaolinite stage, whilst the quartz – which often constitutes up to 30% in volume - does not decompose. This results in a free-draining,

Table 2. 1 A Summary of Weinert's rock classification scheme (adapted from Weinert, 1980)

Class	**Group**	**Rock types**
Decomposing	Basic Crystalline	Diorite, gabbro, norite, peridotite, serpentinite, anorthosite, diabase, dolerite, andesite, basalt, phonolite Metamorphic: Amphibolite and greenschist
	Acid Crystalline	Granite, pegmatite, syenite, felsite, rhyolite Metamorphic: Gneiss
Disintegrating	High Silica	Igneous: Vein quartz, quartz porphyry Sedimentary: Chert Metamorphic: Hornfels, quartzite
	Arenaceous	Sedimentary: Arkose, conglomerate, gritstone, sandstone Metamorphic: Mica schist
	Argillaceous	Sedimentary: Shale, mudstone, siltstone Metamorphic: Phyllite, sericite schist, slate
	Carbonate	Sedimentary: Dolomite, limestone Metamorphic: Marble
Special	Diamictites	Tillite, breccia
	Metalliferous	Ironstone, magnetite, magnesite, haematite
Soils	Pedogenic	Calcrete, ferricrete, silcrete, phoscrete, gypcrete
	Soil	Transported soils

sandy, kaolinitic material with a low plasticity. The result of the non-decomposed quartz gives the material a behaviour more closely resembling silt than clay (Weinert, 1980).

2.8 Existing Work on the Relationship between CBR and Index Tests

Seeing as the CBR test is time-consuming, a good indication of CBR values from index tests would be beneficial. To this end attempts have been made to relate index test parameters to CBR values, most of them with little or moderate success. Many of these attempts were made in other countries where material and climatic regions vary significantly from South Africa (e.g. Morin and Todor, 1976). Netterberg (1994) compiled a review of the research that had been done up to 1994. Many of the original sources used in his review were unobtainable at the time of this research, and as such the sources are cited from Netterberg's (1994) report. Stephens (1990) also discusses some of the proposed models and their limitations.

Netterberg (1994) highlights perhaps the biggest problem very early on in his report, namely test methods. He states that research done on the topic does often not specify the test methods or compactive effort that was used. It is for this reason that a section was included earlier in which test methods and their differences were illustrated. Many authors also neglect to specify the descriptive statistics related to their results (e.g. a correlation coefficient).

Although previous research does exist which correlates other parameters (e.g. maximum dry density, bearing capacity, etc.) with the CBR, only parameters obtainable from typical index tests (i.e. Atterberg Limits and grading) are considered in this dissertation (excluding the hydrometer test).

2.8.1 Netterberg; Netterberg and Paige-Green

Netterberg (1994) emphasises the use of bar linear shrinkage (as described in TMH1, 1979) as opposed to plasticity index, as described by himself in earlier research (Netterberg, 1969). According to him the bar linear shrinkage gives a better indication of material properties. Applying his insight to the analysis of calcretes, Netterberg (1978a) proposes a formula that predicted a minimum soaked Mod AASHTO CBR with a 95% probability. Netterberg and Paige-Green (1988) provide an additional two equations that are used for the mean CBR and the lower ten percentile CBR. For the purpose of this dissertation, only the mean CBR is of importance (Netterberg and Paige-Green, 1988):

$$\text{Mean CBR} = -(0{,}25)\text{LSP} + 124 \qquad \text{Eq 2.3}$$

where

LSP is the bar linear shrinkage × P075

This equation yielded a -0,73 correlation coefficient (r^2 = 53%) with a standard error of estimate (SEE) of 25.

2.8.2 Lawrance and Toole

Work by Lawrance and Toole (1984) focus specifically on calcretes in Botswana. Figure 2.1 shows the results obtained by these two authors. The subsequent general empirical formula derived from this graph is as follows:

$$CBR = 619{,}27(LS \times \%P425)^{-0{,}3875} \qquad \text{Eq 2.4}$$

The equation was derived (Paige-Green, P., 2007, personal communication, CSIR, Pretoria) after removing outliers from the data provided within the graph (r^2 = 0,66).

Lawrance and Toole (1984) note that should a material have a lower plastic fraction, the permissible plastic material allowed may be relaxed (i.e. be higher). Stephens (1990), however, is of the opinion that the relationship proposed by Lawrance and Toole (1984) overestimates the CBR value, but he does not substantiate this due to a lack of suitable data.

2.8.3 Kleyn

The system introduced by Kleyn (1955) is probably the first worthwhile attempt at relating index parameters to CBR values, though the method was developed in an attempt to verify or confirm the CBR, rather than predict it. Kleyn (1955) derived this method to address inconsistencies in the CBR test. He uses the grading modulus and plasticity index in an attempt to derive a CBR value and achieved some success.

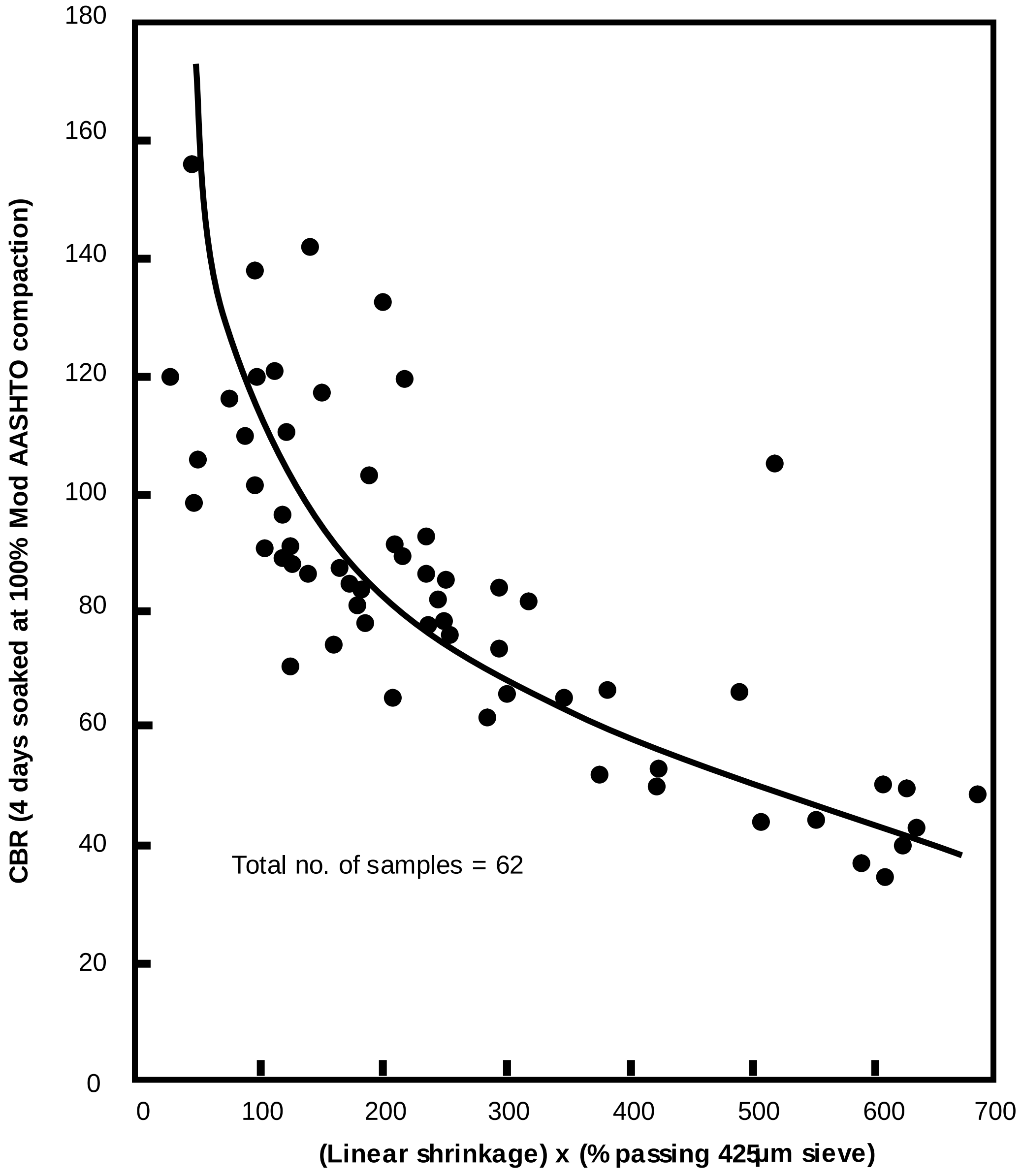

Figure 2.1 The relationship between CBR and the product of linear shrinkage and percentage passing 425µm sieve (from Lawrance and Toole, 1984)

However, overall results appear to vary significantly. The relationship is illustrated in Figure 2.2. Some authors later attempted to refine the system proposed by Kleyn (or elaborate on it) but soon encountered difficulty because Kleyn used the Proctor density in his work as opposed to the more generally used Mod AASHTO density. Stephens (1990) compares Kleyn's method with data from the (then) Natal Roads Department (NRD). His findings show that despite refining the method to specific compaction densities, a wide spread of results is obtained (Stephens, 1990). A later

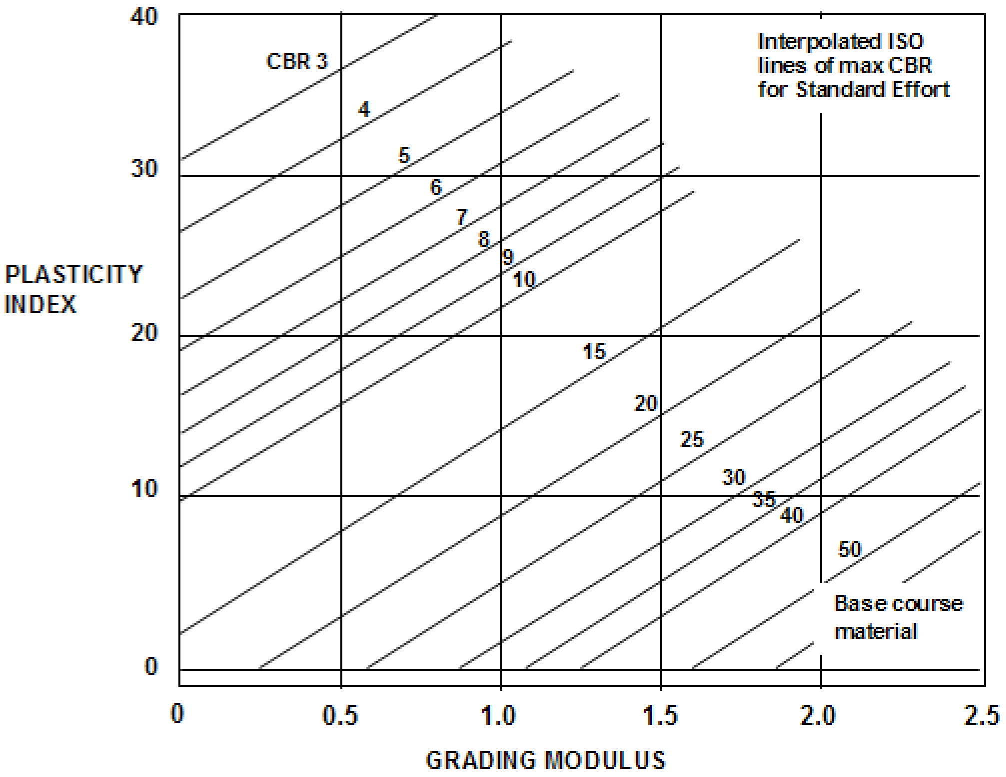

Figure 2.2 Determining CBR from Plasticity Index and Grading Modulus for SA Soils (Kleyn, 1955)

derivation by L.F. de Wet suggests that the CBR could be calculated by:

$$\log_{10}CBR = 0{,}29GM - 0{,}024 - PI + 1{,}23 \qquad \text{Eq 2.5}$$

where the CBR is at standard Proctor density (VKE Swaziland, 1986).

Equation 2.5 contains two constants and as such is believed to include a typing error. It is likely that the equation has only one constant and that the functions "-0,024 – PI" should in fact read "-0,024 × PI". It had been noted that fine materials with a grading modulus of less than 1,00 may show low CBR values (VKE Swaziland, 1986). Associated with this information, conversion factors are used to obtain approximate Mod AASHTO dry densities from maximum Proctor densities (Taute, 1986 in Netterberg, 1994: 4-13). This is of significance to the present research, because using this method (Mod AASHTO compaction) on recent results would necessitate a conversion factor and/or modification to some of the formulae or induce restrictions on the predictions.

2.8.4 Stephens

Stephens (1988) uses the chart derived by Kleyn (1955) in his research and derives the following equation:

$$\log_e CBR = (12GM - PI)/(18{,}5) + \log_e 16{,}7 \qquad \text{Eq 2.6}$$

Stephens (1988, 1990) concludes that the method developed by Kleyn (1955) yields fairly poor results when applied to soils from KwaZulu-Natal. Bearing this in mind, Stephens (1992) continues his research, focussing on clayey soils. The results of his research, however, are of limited use due to the fact that he has problems relating the results obtained from ideally mixed soils (from his research) to real soils. He concludes that the so-called "dilution effect" impedes the correlation.

Stephens (1988, 1990) executed extensive research comparing other authors' work with his own. It is interesting to note that he finds poor correlations in most instances where he applies other authors' models to soils from KwaZulu-Natal.

2.8.5 Gawith and Perrin

Stephens (1988) discusses the equations proposed by Gawith and Perrin (1962, cited in Stephens, 1988) for Victorian soils in Australia, stating that the equations are developed by a multiple regression analysis. Three equations are provided:

$$\log_{10} CBR = 1{,}668 - 0{,}00506A + 0{,}00186B - 0{,}0168LS - 0{,}000385BLS \qquad \text{Eq 2.7}$$

$$\log_{10}CBR = 1,886 - 0,0143PI - 0,0045A + 0,00515(B/A) - 0,00456(B^2/A^2) - 0,0037C \qquad \text{Eq 2.8}$$

$$CBR = 4,5 + [(20\text{-}GI)/18]^2 \qquad \text{Eq 2.9}$$

where

A = P425 (% passing 425μm sieve)
B = P075 (% passing 75 μm sieve)
C = P2360 (% passing 2,360mm sieve)
GI = Group index
LS = Linear shrinkage

According to Stephens (1988), the use of Equation 2.9 was excluded by Victorian road authorities, whilst the use of Equation 2.7 and Equation 2.8 was restricted to subgrade materials. Apparently these equations were later further limited to only be used for fine-grained, cohesive soils with a maximum CBR value of 20%. The equations were also ruled out for use in pavement materials (Stephens, 1988). The equations are criticised for high overestimations by Livneh and Greenstein (1978, cited in Netterberg, 1994).

Locally, Stephens applied the equations to soils in KwaZulu-Natal (Stephens, 1988). In his research he uses 95% Mod AASHTO compaction values. None of the three equations produced results that are considered reliable.

2.8.6 Wermers

Netterberg (1994) describes work done by Wermers (1963, cited in Netterberg, 1994) which he in turn cites from Livneh and Greenstein (1978 cited in Netterberg, 1994). However, he does not include this source in his reference list and as such the source remains unclear. Netterberg does, however, provide the equations and recommends that these equations be tested for South African soils.

Wermers (1963, cited in Netterberg 1994) proposes equations for relating index tests to CBR values for A, B and C horizons of loess and silty clays in the Central United States. The following equations are proposed:

$$CBR = 14{,}10 - 0{,}05PL - 0{,}14LL + 0{,}16G - 0{,}05Q \qquad \text{Eq 2.10}$$

$$CBR = 135{,}8 - 1{,}28G - 1{,}36Q - 1{,}45F + 0{,}07PI - 0{,}2PL - 0{,}09GI \qquad \text{Eq 2.11}$$

$$CBR = 19{,}85 + 0{,}48PL - 0{,}73PI - 0{,}20G - 0{,}11Q - 0{,}61GI - 0{,}18FA \qquad \text{Eq 2.12}$$

$$CBR = 35{,}12 + 0{,}07Q - 0{,}44FA \qquad \text{Eq 2.13}$$

where

G = R420 (% retained on 420 µm sieve)
Q = P420 – P050 (% passing 420 µm; % passing 50 µm)
F = P050 (% passing 50 µm sieve)
GI = Group index
FA = (P2000 + P420 + P074 + P020 + P005 + P001)/6
LL = Liquid limit
PL = Plastic limit
PI = Plasticity index

Livneh and Greenstein (1978, cited in Netterberg 1994) also use these formulae to evaluate Israeli loess and silty clays. It was found that the CBR is overestimated when using Equation 2.10, Equation 2.11 and Equation 2.12. A similar equation was derived that seemed suitable to the Israeli soils, specifically A-4 and A-6 soil groups (Livneh and Greenstein, 1978, cited in Netterberg 1994):

$$CBR = 13{,}0 - 0{,}05PL - 0{,}15LL - 0{,}05Q \qquad \text{Eq 2.14}$$

According to Netterberg (1994), the CBR is likely the equivalent of 92% Mod AASHTO, compacted at 1% lower than optimum moisture content. He also states that the soils were of AASHTO classification classes A-4 and A-6, whilst also being considered to belong to Unified groups CL or CL-ML. Other properties of the soils are:

PI = 2% - 23%
P2000 = 80% - 100%
P425 = 70% - 99%
P075 = 45% - 98%

2.8.7 South African Railways

Netterberg (1994) again describes a personally communicated relationship, used by the then South African Railways (H.P. Rauch, 1970). The "new" parameter used is termed the formation index (I_f), and is calculated as follows:

I_f = Liquid limit + Plastic limit + P074 Eq 2.15

It is noted that if results can not be obtained due to the nature of the material (presumable being non-plastic), the sum of the liquid and plastic limits can be accepted as 45. From here the soaked (Mod AASHTO) CBR – average of top and bottom penetration – is estimated by:

$\log CBR = -(0,0068)I_f + 2,10$ Eq 2.16

Results from this method showed correlation coefficients (r) ranging between 0,6 and 0,7 (r^2 values of 0,36 – 0,49), depending on whether the data are screened (Netterberg, 1994).

2.8.8 Stephenson et al

Work by Stephenson *et al.* (1967, cited in Netterberg, 1994) relates grain size distribution, plastic limit and liquid limit to the CBR. Their research was done on Alabama soils which contain kaolinitic clay. Considering this, they brought plasticity properties into account. Of significance here is that the so-called Alabama static compaction method is used; however Netterberg (1994) concludes that the method yields close to the same compactive effort used locally and as such, indicates that the method essentially determines soaked Mod AASHTO CBR values. The equations proposed by Stephenson *et al.* (1967, cited in Netterberg, 1994) are as follows:

$$\log CBR = 2{,}446826 - (0{,}003272)X_1 + (0{,}00000)X_1^2 - (0{,}007582)X_2 + (0{,}000003)X_2^2 - (0{,}000184)X_3 \qquad \text{Eq 2.17}$$

$$\log CBR = 2{,}334984 - (0{,}002425)X_1 - (0{,}00692)X_2 \qquad \text{Eq 2.18}$$

where

CBR = CBR after Alabama *static* 14MPa compaction
X_1 = P4750 + P2000 + P420 + P250 + P074
X_2 = %clay (P005) of P2000 (as from elutriation test)
X_3 = (PL)/(LL-15)

The results of Equation 2.18 indicate a good correlation between measured and calculated CBR values (correlation coefficient of 0,88; r^2 = 0,77). Netterberg emphasises the fact that the addition of a plasticity parameter (Equation 2.17) does not result in any noticeable improvement. Stephenson *et al.* also compiled an estimation chart for CBR values, as indicated in Figure 2.3.

2.8.9 De Graft-Johnson et al.

Netterberg (1994) cites research conducted by De Graft-Johnson *et al.* (1969a, in Ruenkrairergsa, 1987). The research is concerned with CBR values of lateritic soils in Ghana. The authors develop the so-called suitability index, from which a CBR can be calculated. The spread of their results is illustrated in Figure 2.4. These results are determined by the following:

$$CBR = 35(SI) - 8 \qquad \text{Eq 2.19}$$

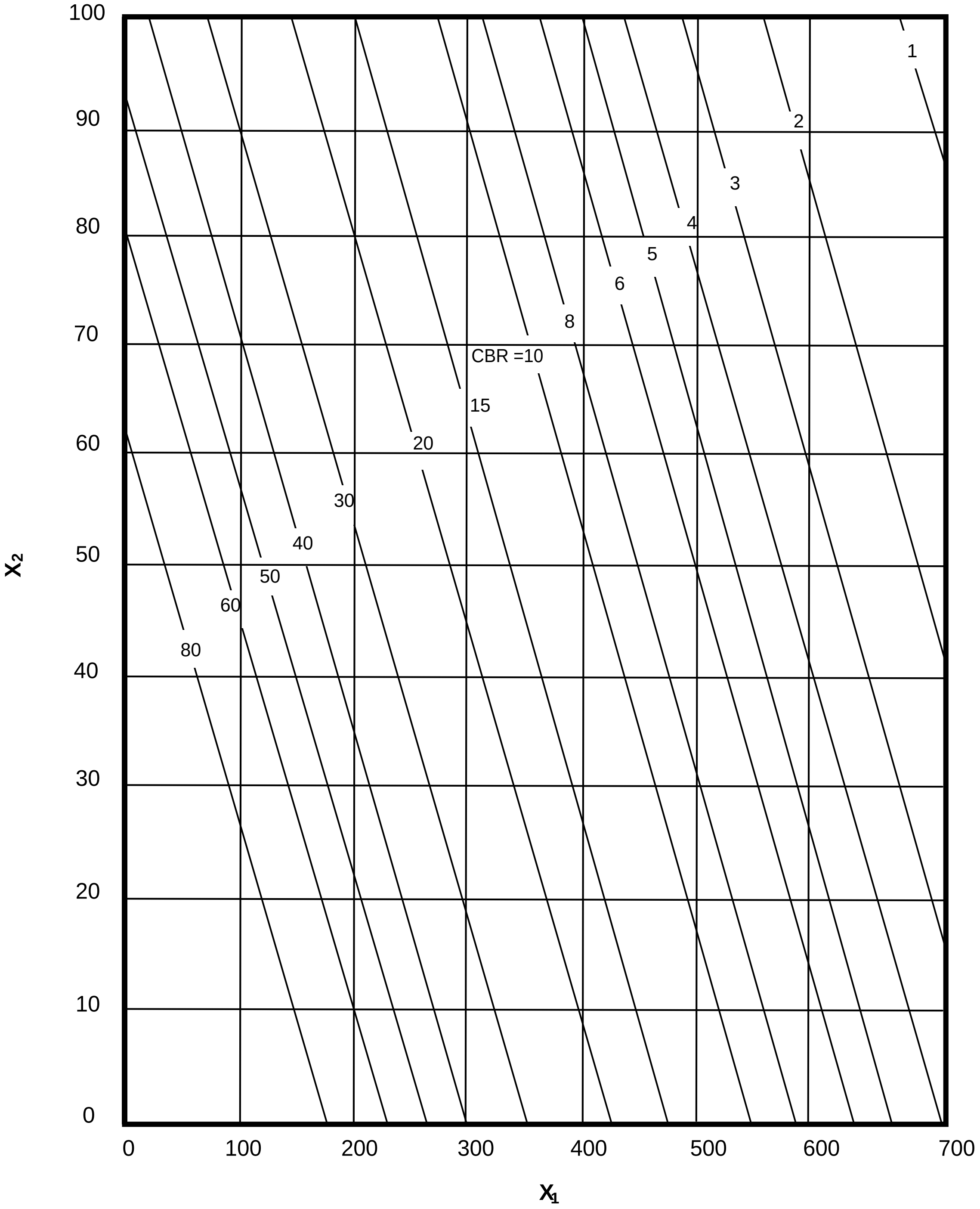

Figure 2.3 CBR estimation by Stephenson *et al*. (1967)

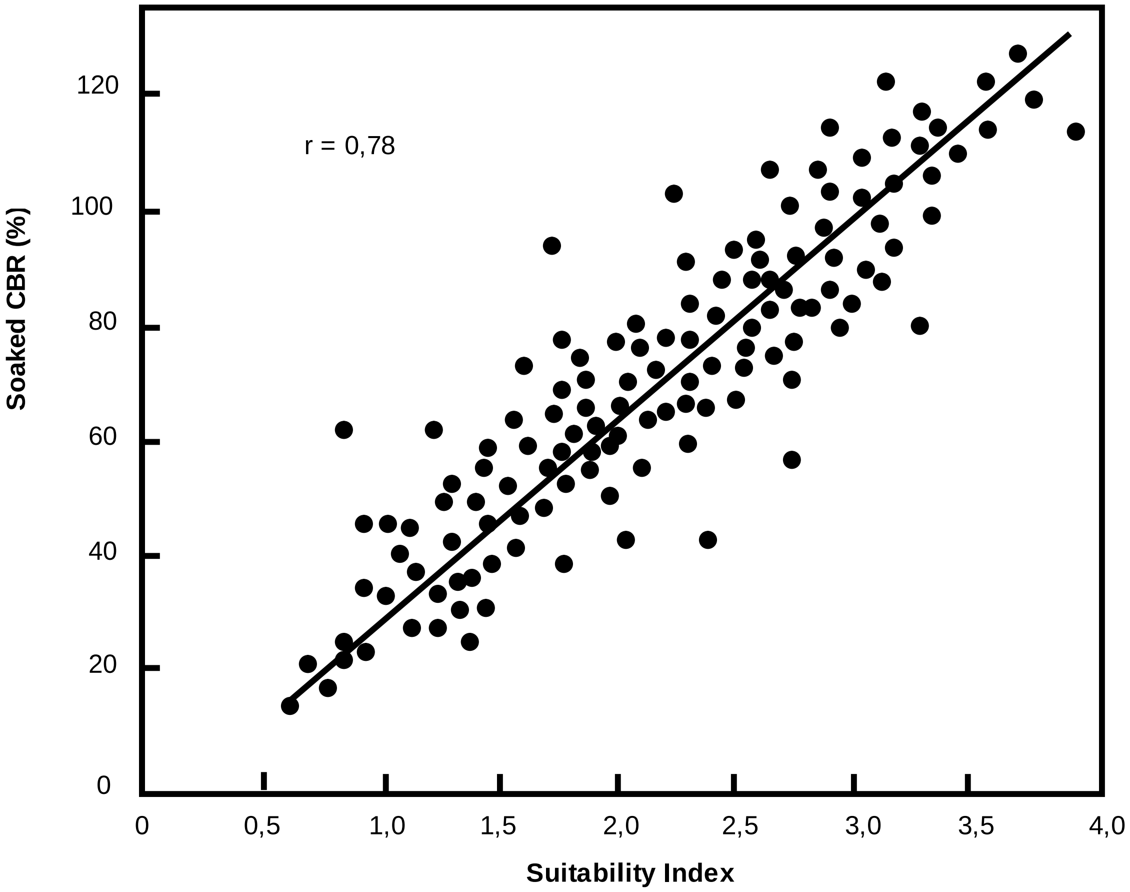

Figure 2.4 CBR and the "suitability index" for Ghanaian Lateritic Soils (de Graft-Johnson *et al.*, 1969a)

where

SI = (R2000)/(LL logPI)

R = % retained on 2000 µm sieve.

The methods of compaction or specifications are not indicated for this research. Similar work by De Graft-Johnson *et al.* (1969b) – done on lateritic gravels, also from Ghana – specifies the use of British standard sieves and compaction to the maximum dry density as per Ghanian standards. The four day soaked CBR test closely resembles the South African test method, but the full test details are not known (e.g. mould sizes, operational procedures etc.). It is likely that the method resembles the old British Standard method for heavy compaction (Paige-Green, P., 2007, personal communication, CSIR, Pretoria).

2.8.10 Sood et al.

Sood *et al.* (1978) and Dhir *et al.* (1987) conducted research on so-called "moorums" in India. Netterberg (1994) states in this discussion that "moorums" probably refer to laterite gravels. The results of the research done by Sood *et al*. (1978) are presented as three equations, in which two included maximum dry density (Proctor compaction) as a parameter (these may be regarded as 95% Mod AASHTO). These equations were not considered in this dissertation, as the maximum dry density is not considered. The first equation, however, is related to indicator tests and sieve analysis only, and reads as follows:

$$CBR = 50{,}05 - 0{,}35(R2360) - 1{,}11(P075) + 0{,}25(PI) \qquad \text{Eq 2.20}$$

where

R2360 = % retained on the 2,360mm sieve
P075 = % passing the 0,075mm sieve

This method has a correlation coefficient of 0,81 ($r^2 = 0{,}66$) and a standard error of estimation of 4,03 according to Netterberg (1994). Seeing that other parameters considered by these authors are based on Proctor compaction densities, it is assumed that the CBR determinations are also done at Proctor compaction densities.

The equations apparently show good correlation during further testing and are generally acceptable for materials with CBR values between seven and twenty eight.

2.8.11 Haupt

Netterberg (1994) gives a comprehensive discussion of research done by Haupt (1980) that will not be included in this section. These results will be included later on in this dissertation. Haupt's (1980) results were based on four days soaked Proctor compaction CBR tests. He proposes six equations for estimating CBR values. A list of these equations, including their respective correlation coefficients, standard error of estimation and accuracy (at 85% confidence level) as discussed by Netterberg (1994) follows:

$$CBR = 2,1(e^{GM}) - 23\log[LS(P425)^{0,7}] + 54 \qquad \text{Eq 2.21}$$

$(r = 0,83;\ SEE = 7,6;\ \text{accuracy} = 41\%;\ r^2 = 0,69)$

$$CBR = 96,3 - 17,8\log[LS(P425)^{0,7}] - 28,7\log(P075) \qquad \text{Eq 2.22}$$

$(R = 0,83;\ SEE = 8,5;\ \text{accuracy} = 42\%;\ r^2 = 0,69)$

$$CBR = 97,7 - 17,1\log[PI(P425)^{0,5}] - 30,7\log(P075) \qquad \text{Eq 2.23}$$

$(R = 0,81;\ SEE = 8,0;\ \text{accuracy} = 44\%;\ r^2 = 0,66)$

$$CBR = 119,6 - 33\log[LL^{0,7}(P425)^{0,3}] - 33.2\log(P075) \qquad \text{Eq 2.24}$$

$(R = 0,79;\ SEE = 8,4;\ \text{accuracy} = 45\%;\ r^2 = 0,62)$

$$CBR = 80,5 - 32,3\log[LS(P425)^{0,7}] \qquad \text{Eq 2.25}$$

$(R = 0,77;\ SEE = 8,7;\ \text{accuracy} = 48\%;\ r^2 = 0,59)$

$$CBR = 90 - 47,4\log(P075) \qquad \text{Eq 2.26}$$

$(R = 0,77;\ SEE = 8,7;\ \text{accuracy} = 48\%;\ r^2 = 0,59)$

Haupt (1980) states that materials with CBR values above 50% are underestimated by these equations. He also stipulates that the research be used only as a preliminary analysis of subgrade and subbase materials.

2.8.12 Davel

The research of Davel (1989) was done on ferricretes. Using in excess of 900 results, he attempted to compare CBR, $\log_e$CBR, grading modulus, plasticity index, linear shrinkage, maximum dry density and optimum moisture content with each other in an attempt to find any relationships. The results are rather dismal, with the highest correlation coefficient being 0,48 ($r^2 = 0,23$). Nevertheless, the equations proposed by

Davel (1989) are also considered in this dissertation, as it is the only source that considers the grading modulus as the only parameter in prediction of a single (although potentially highly variable) material. His equations predict a four day soaked CBR value at different Mod AASHTO maximum dry densities:

$\ln CBR_{98} = 0{,}99\ln GM + 3{,}75$ Eq 2.27
$(r = 0{,}48; r^2 = 0{,}23)$

$\ln CBR_{95} = 0{,}97\ln GM + 3{,}38$ Eq 2.28
$(r = 0{,}46; r^2 = 0{,}21\%)$

$\ln CBR_{93} = 1{,}02\ln GM + 3{,}03$ Eq 2.29
$(r = 0{,}48; r^2 = 0{,}23)$

$\ln CBR_{90} = 1{,}08\ln GM + 2{,}55$ Eq 2.30
$(r = 0{,}46; r^2 = 0{,}21)$

Figure 2.5 roughly indicates the relationship proposed by Davel between CBR values, Mod AASHTO maximum dry density and grading moduli.

2.9 Conversion Factors for the CBR

2.9.1 Mod AASHTO vs Proctor

In an attempt to correlate CBR tests done at different densities, Haupt (1980) derived an equation that converted maximum soaked Proctor CBR values to maximum soaked Mod AASHTO CBR values:

$CBR_P = 0{,}37CBR_M$ Eq 2.31

where

CBR_p = maximum Proctor soaked CBR (2,54mm)

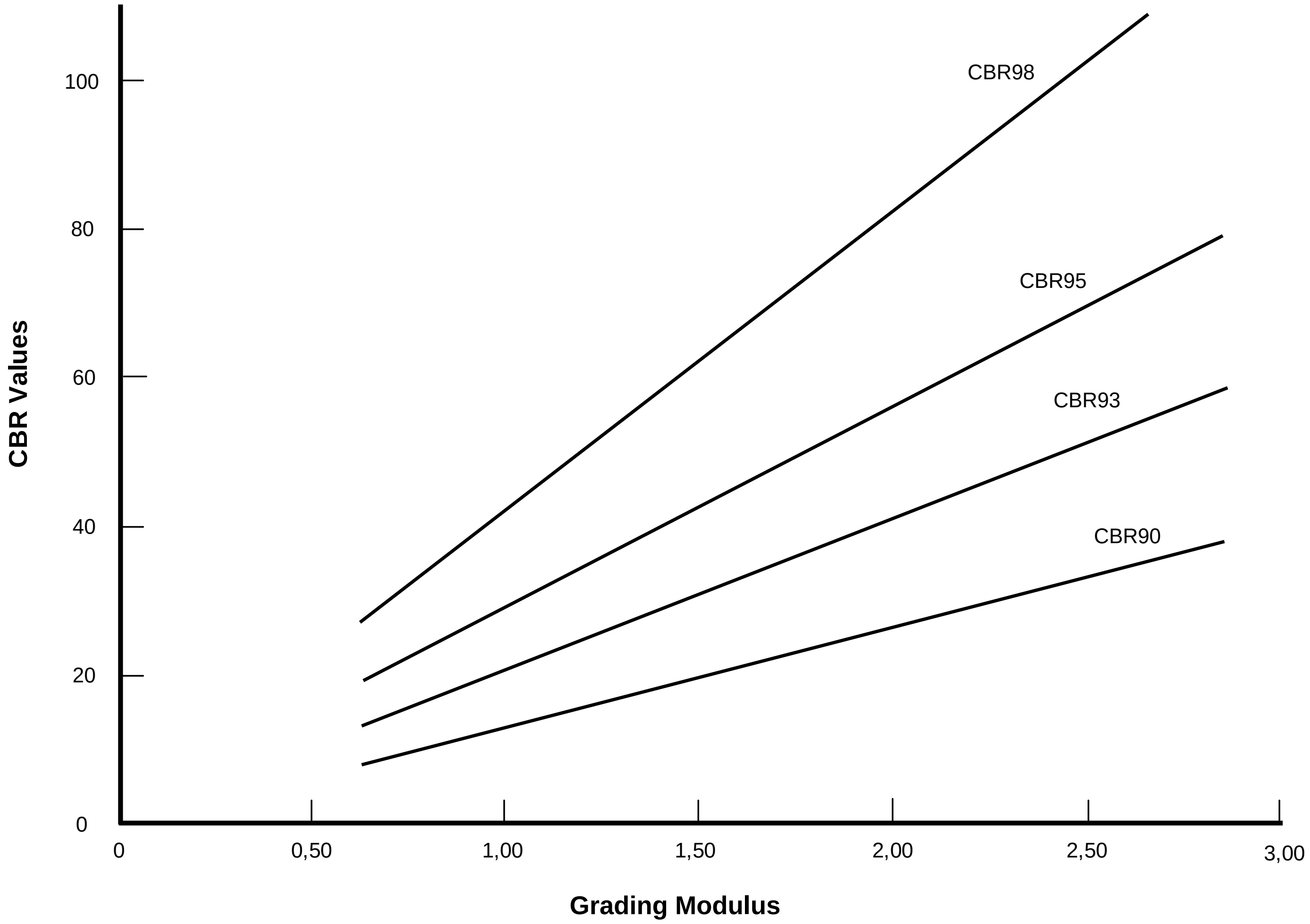

Figure 2.5 CBR from Grading Modulus for South African Ferricretes (From Davel, 1989)

CBR_M = maximum Mod AASHTO soaked CBR (2,54mm)

Though all the methods discussed in this chapter will be considered in data analyses for all compactions (not just the recommended compactive efforts), the possible relationship between the two tests mentioned must be borne in mind.

2.9.2 Soaked vs Unsoaked

Haupt (1980) also attempted to correlate soaked CBR values and unsoaked CBR values using relative Proctor density results. Although it is not of particular interest to this dissertation, it is worth taking note of. The following equation resulted from his analysis:

$$CBR_{UP} = 1,15\ CBR_{SP} + 1,2 \qquad \text{Eq 2.32}$$

where CBR_{UP} = unsoaked CBR at Proctor compaction (at OMC)
CBR_{SP} = four days soaked CBR at Proctor compaction.

2.10 Plasticity Index

As part of index testing, most laboratory result sheets include the potential expansiveness diagram (van der Merwe, 1964, 1976). The chart was first introduced by van der Merwe (1964) and later modified (van der Merwe, 1976). This method is commonly used as an indication of potential heave, particularly for purposes of residential development, which requires a cost-effective method.

This method considers both the weighted plasticity index and the clay fraction of a sample (both of which are included in a foundation indicator test) to derive its potential expansiveness (Figure 2.6). The different classes of expansion are based on plasticity indices. The low class ranged from 0% to 12%; the medium class from 12% to 22%; the high class from 22% to 32% and very high heave included all plasticity indices greater than 32%.

Data used in this dissertation are of materials that have been weathered to various degrees. The extent of weathering has a significant impact on the strength and/or suitability of material for use in road construction. It was decided to use the plasticity index to group materials into different weathering classes.

Although the plasticity index grouping used by van der Merwe (1964, 1976) does not correlate with the COLTO groupings, it is widely used in industry and was used in the interpretation of results.

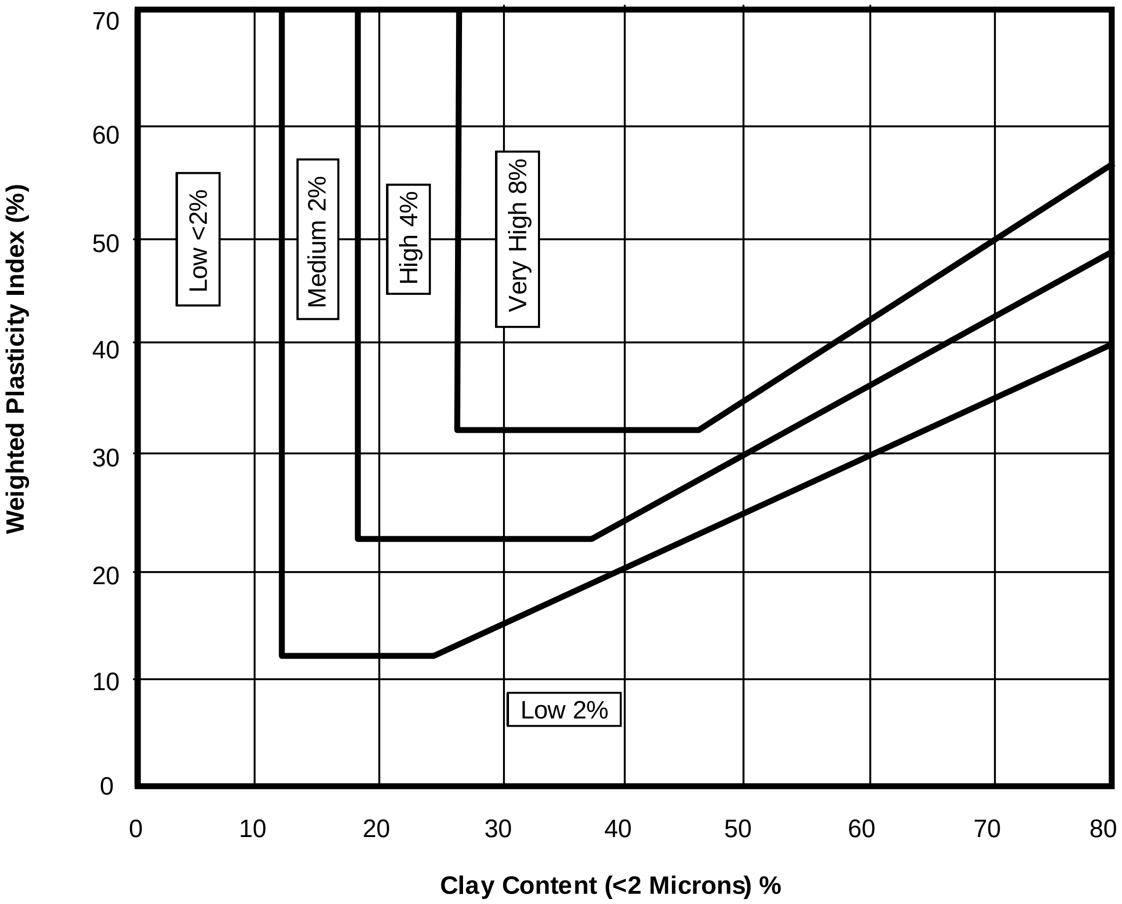

Figure 2.6 Classification diagram proposed by van der Merwe (1964, 1976)

It must be considered that some materials are subject to variability with regard to plasticity, though. Netterberg (1978) discusses the influence of drying temperatures on the liquid limit and plasticity indices of calcrete materials. Gidigasu (1976) points out similar effects of lateritic soils, though the influence comes from sample preparation. Gidigasu (1976) indicates that lateritic materials tend to show increasing plasticity indices upon mixing and remoulding prior to testing, citing a number of researchers.

3. Methodology

3.1 Data Gathering

For the purposes of the research project it is clear that a comprehensive database including a wide variety of materials and material properties would be required. The database should preferably be representative of all materials used in road construction in southern Africa and should also contain the results of samples obtained from both moist and dry regions of southern Africa. The mode of weathering in wet and dry areas would dictate definite differences in the mineralogy of the residual gravels.

The following parameters were entered into the database for each test result used:

- material type
- Weinert N-value or location from which to derive the Weinert N-value
- Atterberg Limits (including bar linear shrinkage)
- grading analysis (percentages passing 37,5mm, 26,5mm, 19,0mm, 13,2mm, 4,75mm, 2,0mm, 0,425mm and 0,75mm screens)
- CBR values at 100%, 98% and/or 95% Mod AASHTO density

From the available data, the following additional parameters were calculated, some of which will be discussed later on:

- linear shrinkage product
- shrinkage product
- grading modulus
- grading coefficient
- dust ratio

In considering the work of Paige-Green and Ventura (1999), the (bar) linear shrinkage parameter is included in the models, as is the grading coefficient (Paige-Green, 1999) in order to verify the parameters’ possible application. The linear shrinkage was also used to calculate the linear shrinkage product and shrinkage product, as referred to by Paige-Green (1989).

Both the optimum moisture content and maximum dry density were included, where available. These parameters are not considered as part of the research, as the main purpose is to predict CBR values from foundation indicator results and not optimum moisture content or maximum dry density. Nevertheless the two parameters are included, should they be required for any future research using the developed database.

The database used in this research was compiled from the following sources:

- a collective database of work done by Dr P Paige-Green of the CSIR
- The Transvaal Roads Department: Report on Investigation of existing road pavements on the Transvaal: Report L1/75 and field data volumes 1-12, compiled by Burrows (1975)
- data from the defunct National Databank for Roads (CSIR)
- laboratory results obtained from the author's personal work.
- data courteously provided by the Namibian roads department.

Data obtained from the Transvaal Roads Department required some processing prior to use. No CBR values were specified at the required densities, only CBR values tested at apparently randomly compacted densities. As a result, 98% and 95% Mod AASHTO density had to be manually calculated for each sample (100% was provided, though not always tested) and compared with the random tests conducted to find results at the suitable densities. Data from the Namibian roads department were used to represent data for the dry areas in South Africa.

DCP-derived CBR values are commonly found for load as well as interpretational results; i.e. deriving CBR values from DCP data (NCHRP, 2004). Such data were not considered for two reasons, the first being that only methodically tested and proven CBR values were used, and the second reason is the limited use of DCP-derived CBR values and the relatively poor calibrations associated with these determinations. The use of such derivations should therefore preferably be used only as a guide to complement material testing.

3.2 Data Grouping

Each test results obtained was assigned to either the moist or dry climatic region based on Weinert's N-value (Weinert, 1980). N-values of less than five were considered as data from moist regions, whilst data from areas with N-values of five and higher were considered to be of semi-arid or dry regions. Samples were then further separated, based on the compaction densities (i.e. 95% Mod AASHTO, 98% Mod AASHTO and 100% Mod AASHTO). Within the different density groups the materials were further subdivided into groups based on the rock groups identified by Weinert (1980) with the aim of finding a relationship between the material type and material behaviour. Weinert's (1980) rock group classification is illustrated in Table 3.1. All groups are not represented in this project, due to unavailability or too little test results of certain rock groups (e.g. metalliferous, carbonate, diamictite, metalliferous, alluvial and ferricrete groups). A summary of the data grouping and number of samples included in each group is presented in Table 3.2 .

Small adjustments were made to the material groups, where the soils were further subdivided into colluvium and alluvium. Aeolian materials were included in the colluvium group due to insufficient data to permit analysis of the former on its own, though this is strictly not adequate, due to the differences in origin and properties of colluvium and aeolian material. It is anticipated that the difference in depositional characteristics and particle sorting may be different for colluvium and alluvium. A direct comparison will not be possible, though, as alluvium is not included in the data set for moist regions, and the alluvial samples for dry regions are all from the same location.

Another adjustment was made to the pedogenic deposits. Only (partially) sufficient samples of ferricrete and calcrete were obtained for analysis and their separation into two groups is ascribed to the fact that ferricrete occurs mostly in moist regions and

Table 3.1 A Summary of Weinert's rock classification scheme (adapted from Weinert, 1980)

Class	**Group**	**Rock types**
Decomposing	Basic Crystalline	Diorite, gabbro, norite, peridotite, serpentinite, anorthosite, diabase, dolerite, andesite, basalt, phonolite Metamorphic: Amphibolite and greenschist
	Acid Crystalline	Granite, pegmatite, syenite, felsite, rhyolite Metamorphic: Gneiss
Disintegrating	High Silica	Igneous: Vein quartz, quartz porphyry Sedimentary: Chert Metamorphic: Hornfels, quartzite
	Arenaceous	Sedimentary: Arkose, conglomerate, gritstone, sandstone Metamorphic: Mica schist
	Argillaceous	Sedimentary: Shale, mudstone, siltstone Metamorphic: Phyllite, sericite schist, slate
	Carbonate	Sedimentary: Dolomite, limestone Metamorphic: Marble
Special	Diamictites	Tillite, breccia
	Metalliferous	Ironstone, magnetite, magnesite, haematite
Soils	Pedogenic	Calcrete, ferricrete, silcrete, phoscrete, gypcrete
	Soil	Transported soils

Table 3.2 Data Grouping and Number of Samples

All Materials							
Moist Areas (N<5)				Dry Areas (N>5)			
	95% Mod AASHTO	98% Mod AASHTO	100% Mod AASHTO		95% Mod AASHTO	98% Mod AASHTO	100% Mod AASHTO
Group Total*	574	1016	1179	Group Total*	619	624	581
Basic Crystalline	107	154	178	Basic Crystalline	50	50	50
Acid Crystalline	53	100	109	Acid Crystalline	66	66	66
High Silica	93	162	198	High Silica	77	80	80
Arenaceous	26	53	59	Arenaceous	54	54	36
Argillaceous	73	96	106	Argillaceous	154	155	131
Calcrete (Pedogenic)	19	27	34	Calcrete (Pedogenic)	72	72	72
Ferricrete (Pedogenic)	108	258	300	Ferricrete (Pedogenic)	10	10	10
Alluvium	0	0	0	Alluvium	38	38	38
Colluvium/aeolian	95	154	175	Colluvium/aeolian	81	82	81

* Includes carbonate, diamictite, metalliferous and other groups excluded due to insufficient numbers of samples

calcrete in dry regions. As such, the processes and environments in which these materials form are likely to induce different material characteristics and properties.

An additional group was created for each moisture region (and compaction effort) which contained only non-plastic materials. For this group the rock material type was disregarded. Analysis of this group included only grading and associated parameters, but no plasticity-related parameters. Non-plastic materials were identified as materials having a plasticity index of 0%.

The bulk data were entered into a spreadsheet and first divided into the two climatic groups prior to being further divided into the three compaction classes (i.e. 95%, 98% and 100% Mod AASHTO density). A group number was then allocated to each dataset based on the material group. The data was further separated into spreadsheets according to the rock material groups for statistical analysis.

Descriptive statistical analyses were considered for each material group in the two climatic regions (at the three specified compactive densities). A brief summary of the mean values calculated for each of the different ptoperties in each material group for 95%, 98% and 100% Mod AASHTO compaction in moist areas is presented in Table 3.3, Table 3.4 and Table 3.5. A full discussion of the descriptive statistics for each compaction effort, moisture regime and material group is included in Addendum A.

Summaries of the mean results for all of the material groups, at the three compaction efforts in dry areas, are provided in
Table 3.6, Table 3.7 and Table 3.8.

Many test results contained CBR values for penetrations done at 95%, 98% and 100% Mod AASHTO densities. This was considered an ideal data target, but was not always available.

Table 3.3 Mean Parameter Summary (95% Mod AASHTO, moist)

	All Groups	Basic Crystalline	Acid Crystalline	High Silica	Arenaceous	Argillaceous	Calcrete	Ferricrete	Colluvium	Non-Plastic
LL	26,5	33,0	27,9	20,8	13,2	25,5	29,6	24,7	29,6	-
PI	11,1	13,8	11,3	7,9	4,3	9,5	15,6	10,9	13,8	-
PL	15,3	19,2	16,6	12,9	8,8	16,0	14,1	13,8	15,8	-
LS	5,3	6,7	5,3	3,7	2,1	4,7	6,4	5,0	6,3	-
LSP	205,5	221,9	153,9	130,6	49,1	172,9	353,8	188,8	346,6	-
SP	307,3	317,8	252,3	211,2	98,0	229,1	465,9	306,5	497,7	-
GM	1,43	1,72	1,59	1,49	1,59	1,62	1,30	1,35	0,87	1,46
GC	16,2	20,8	22,1	16,3	19,1	20,2	16,2	19,7	6,9	19,7
CBR	19,6	22,2	18,2	26,3	24,9	17,1	23,4	17,0	13,3	33,8
n	574	107	53	93	26	73	19	108	95	62

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Table 3.4 Summary of Mean Values (98% Mod AASHTO, moist)

	All Groups	Basic Crystalline	Acid Crystalline	High Silica	Arenaceous	Argillaceous	Calcrete	Ferricrete	Colluvium	Non-Plastic
LL	25,8	32,8	27,0	20,7	13,2	27,4	31,2	23,2	29,6	-
PI	10,9	13,5	10,9	8,0	4,2	10,8	15,6	10,0	14,1	-
PL	14,9	19,3	16,1	12,7	9,0	16,6	15,6	13,3	15,5	-
LS	5,1	6,6	5,0	3,8	2,1	5,6	6,6	4,6	6,4	-
LSP	288,6	231,0	169,7	139,9	53,4	211,7	327,9	177,8	365,5	-
SP	315,7	334,2	271,7	225,8	108,8	289,5	464,5	292,3	520,7	-
GM	1,34	1,63	1,46	1,37	1,53	1,56	1,27	1,28	0,82	1,38
GC	16,0	19,3	19,6	14,2	17,1	20,0	16,3	18,0	5,6	13,2
CBR	21,2	24,6	20,9	27,7	31,2	22,6	24,1	16,1	15,2	36,2
n	1016	154	100	162	53	96	27	258	154	120

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Table 3.5 Summary of Group Mean Values (100% Mod AASHTO, moist)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Ferri-crete	Collu-vium	Non-Plastic
LL	25,9	33,0	27,0	20,9	13,6	27,6	30,0	23,4	29,9	-
PI	11,1	13,9	10,9	8,2	4,3	11,0	14,7	10,2	14,4	-
PL	14,8	19,1	16,1	12,7	9,2	16,6	15,2	13,2	15,6	-
LS	5,2	6,7	5,1	3,9	2,2	5,6	6,3	4,7	6,6	-
LSP	213,6	246,9	167,1	145,1	54,5	209,4	296,0	186,8	377,3	-
SP	322,9	355,5	268,7	233,0	111,1	285,4	438,1	302,5	537,5	-
GM	1,33	1,60	1,48	1,37	1,54	1,55	1,26	1,27	0,80	1,37
GC	15,9	18,9	19,8	14,2	17,2	19,8	15,6	17,9	5,3	12,8
CBR	32,1	34,0	32,2	41,0	47,4	35,0	36,4	25,9	22,7	53,9
n	1179	178	109	198	59	106	34	300	175	135

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

4. Data Analysis

The statistical analysis of the data sets for the different groups, as described in the previous chapter, was done using Microsoft® Excel, SAS® 9.1 and SPSS® 15.0 for Windows®.

A principal component analysis was first done using Microsoft® Excel for each material group by compaction groups and climatic groups and a summary of the descriptive statistics was obtained (Addendum A). In addition, descriptive statistics were also derived for the entire dataset (by compaction and climate group) to determine any specific variations or correlation properties of individual material groups compared with the collective data set. The parameters considered for the descriptive statistics and principal component analysis included the liquid limit,

Table 3.6 Mean Parameter Summary (95% Mod AASHTO, dry)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	21,5	15,9	23,3	18,5	24,0	25,3	24,0	25,4	15,5	-
PI	7,1	5,0	7,4	5,6	7,9	9,2	7,6	8,4	5,3	-
PL	14,4	10,9	15,9	12,9	16,1	16,2	16,4	17,1	10,2	-
LS	3,5	2,5	3,4	2,8	3,9	4,7	3,5	3,8	2,7	-
LSP	59,4	45,9	38,9	31,6	69,7	80,0	46,4	86,9	73,7	-
SP	119,9	99,2	93,4	74,7	108,7	134,3	122,3	180,1	161,5	-
GM	1,95	1,83	2,12	2,34	2,16	2,10	1,96	1,56	1,28	1,77
GC	18,4	23,0	29,4	13,0	12,6	20,1	19,9	17,3	10,1	13,6
CBR	37,4	34,5	43,2	47,2	28,1	25,4	51,9	55,0	29,5	41,6
n	619	50	66	77	54	154	72	38	81	103

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Table 3.7 Summary of Mean Values (98% Mod AASHTO, dry)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	21,6	15,9	23,3	18,8	24,0	25,3	24,0	25,4	15,5	-
PI	7,1	5,0	7,4	5,5	7,9	9,2	7,6	8,4	5,2	-
PL	14,5	10,9	15,9	13,3	16,1	16,2	16,4	17,1	10,3	-
LS	3,5	2,5	3,45	2,8	3,9	4,7	3,5	3,8	2,7	-
LSP	59,1	45,9	38,9	33,3	69,7	78,8	46,4	86,9	72,8	-
SP	119,3	99,2	93,4	76,8	108,7	132,2	122,3	180,1	159,6	-
GM	1,95	1,83	2,12	2,30	2,16	2,11	1,96	1,56	1,28	1,74
GC	18,4	23,0	29,4	13,3	12,6	20,2	19,9	17,3	9,9	13,8
CBR	63,3	56,2	68,3	100,7	43,8	39,3	82,2	92,7	48,6	73,2
n	624	50	66	80	54	155	72	38	82	113

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Table 3.8 Summary of Group Mean Values (100% Mod AASHTO, dry)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	21,6	15,9	23,3	18,8	25,9	26,0	24,0	25,4	15,4	-
PI	7,0	5	7,4	5,5	7,9	9,1	7,6	8,4	5,2	-
PL	14,6	10,9	15,9	13,3	18,0	16,9	16,4	17,1	10,2	-
LS	3,4	2,5	3,4	2,8	3,7	4,6	3,5	3,8	2,7	-
LSP	57,3	45,9	38,9	33,3	63,4	77,6	46,4	86,9	73,0	-
SP	116,6	99,2	93,4	76,8	84,5	128,1	122,3	180,1	160,0	-
GM	1,94	1,83	2,12	2,30	2,27	2,11	1,96	1,56	1,27	1,74
GC	18,6	23,0	29,4	13,3	11,4	20,8	19,9	17,3	9,9	13,8
CBR	90,0	79,5	93,2	150,4	51,1	47,9	113,4	128,2	70,1	102,9
n	581	50	66	80	36	131	72	38	81	113

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

plasticity index, plastic limit, (bulk) linear shrinkage, linear shrinkage product, shrinkage product, grading (as specified in section 3.1), grading modulus, grading coefficient, dust ratio and the CBR values recorded at 100% (MSCBR), 98% (NSCBR) and/or 95% (PSCBR) Mod AASHTO densities, respectively.

The principal component analysis was used as a preliminary indication of the parameters that show some correlation within the data set (i.e. interdependent parameters) and particularly related to the CBR values recorded. Considering the aim and hypothesis of the project, different material groups were expected to have correlations between different parameters as the materials were expected to exhibit distinctive properties. Some properties were expected to overlap, though (e.g. linear shrinkage and linear shrinkage product). A discussion on individual principal component analyses is to follow.

During data capturing outlier datasets were identified and removed. Such outliers were identified by suspicious values (e.g. a plasticity index of 128). Other indications of poor (and subsequently removed) data were non-consistent grading analyses (e.g. 100% passing the 37,5mm screen, 80% passing the 26,5mm screen and 90% passing the 19,0mm screen).

4.1 Principal Component Analysis: Moist Areas: 95% Mod AASHTO

A summary of the principal component analysis results for material groups compacted to 95% Mod AASHTO in moist areas is given in Table 4.1 and is discussed further in the following section. Correlation coefficients encountered can not be simply described in narrative terms due to the fact that correlations in different groups – and between different properties – were not constant, but instead varied from group to group and their statistical significance is a function of the number of datasets being analysed. As a result, when a parameter’s correlation is described as “fair”, “good” or “poor” in later discussions, the description is given for the group being discussed and not in definitive statistical terms (i.e. the groups all had different sample sizes).

4.1.1 All Groups

The principal component analysis identified a number of negative correlations with CBR values – i.e. if a certain parameter’s correlation value decreases, the CBR value increases or vice versa. The Atterberg Limits indicated a small, negative correlation, the highest being the plasticity index with a correlation of -0,40. The linear shrinkage product showed a fair correlation of -0,42. The shrinkage product showed a slightly improved correlation of -0,48.

Table 4.1 Parameter Correlation with CBR (95% Mod AASHTO, moist)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Ferri-crete	Collu-vium	Non-Plastic
LL	-0,36	-0,35	-0,40	-0,34	-0,46	-0,47	-0,73	-0,27	-0,37	-
PI	-0,41	-0,47	-0,42	-0,44	-0,39	-0,43	-0,68	-0,27	-0,46	-
PL	-0,22	-0,04	-0,26	-0,16	-0,48	-0,38	-0,72	-0,23	-0,16	-
LS	-0,39	-0,45	-0,43	-0,38	-0,36	-0,45	-0,70	-0,26	-0,49	-
LSP	-0,42	-0,57	-0,62	-0,46	-0,45	-0,25	-0,58	-0,31	-0,46	-
SP	-0,48	-0,62	-0,63	-0,54	-0,51	-0,38	-0,64	-0,36	-0,50	-
P37,5	-0,29	-0,27	-0,34	-0,40	-0,02	-0,14	-0,41	-0,19	0,01	-0,19
P26,5	-0,36	-0,35	-0,33	-0,53	-0,27	-0,18	-0,39	-0,33	0,01	-0,32
P19,0	-0,41	-0,48	-0,29	-0,61	-0,30	-0,17	-0,41	-0,38	-0,01	-0,41
P13,2	-0,44	-0,54	-0,33	-0,67	-0,31	-0,19	-0,42	-0,46	-0,03	-0,47
P4,75	-0,50	-0,62	-0,53	-0,71	-0,28	-0,23	-0,45	-0,48	-0,11	-0,52
P2,0	-0,52	-0,68	-0,64	-0,72	-0,23	-0,24	-0,44	-0,44	-0,27	-0,52
P425	-0,54	-0,71	-0,64	-0,72	-0,21	-0,22	-0,58	-0,54	-0,40	-0,51
P075	-0,53	-0,70	-0,65	-0,58	-0,43	-0,29	-0,67	-0,51	-0,46	-0,25
GM	0,57	0,73	0,68	0,72	0,27	0,26	0,63	0,53	0,45	0,51
GC	0,37	0,53	0,57	0,61	-0,04	0,16	0,42	0,29	0,39	-0,11

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

The most striking aspect revealed by the analysis, was the increase in negative correlation coefficient as the particle size decreased. The negative correlation increased from -0,42 (P19,0) to -0,53 (P075). This indicates that the coarser particles are indeed the dominant contributors to the CBR strength. The grading modulus showed a positive correlation of 0,56 confirming that coarser materials give better CBR values. This needs to be seen objectively from the analysis results and should not be considered as an isolated fact, as many other factors may also have an influence.

4.1.2 Basic Crystalline Materials

Considering the influences of Atterberg Limits and related parameters, it is not surprising to notice that the plasticity index, linear shrinkage, linear shrinkage products and shrinkage product resulted in correlation coefficients of -0,44, -0,40, -0,57 and -0,62 respectively. As the values of these parameters decrease, the CBR values increase.

As with the entire dataset, an increasing negative correlation coefficient was noted with decreasing particle sizes (i.e. the smaller the particle size being considered, the larger the negative correlation coefficient obtained). Simply stated, the finer the material, the lower the expected CBR value is (within limits). The best correlation coefficient achieved by grading, was P425, which achieved a coefficient of -0,71, which can be considered a good correlation. The result of good correlations between the CBR and the various grading parameters, is a good correlation of the grading modulus with the CBR values. The grading modulus had a correlation coefficient of 0,73, whilst the grading coefficient achieved a much lower value of 0,47.

4.1.3 Acid Crystalline Materials

As before, the principal component analysis showed that an increase in the Atterberg Limits was associated with a decrease in CBR, resulting in the negative correlation coefficient. The liquid limit and plasticity index had respective correlation coefficients of -0,40 and -0,42 with the CBR, whilst the linear shrinkage had a correlation coefficient of -0,43. Of interest is that both the linear shrinkage product and the shrinkage product had fairly good correlation coefficients, higher than those of the Atterberg Limits. The two parameters had respective correlation coefficients of -0,62 and -0,63.

The trend of an increasingly negative correlation coefficient with decreasing particle size distribution continues in this group. The P4,75 component had a correlation coefficient of -0,53 that improved to -0,65 for the P075 constituent. Consequently the grading modulus had a correlation coefficient of 0,68 – which can be considered as fair to good – whilst the grading coefficient only had a correlation coefficient of 0,52.

4.1.4 High Silica Materials

It appears that the Atterberg Limits of this group are not strongly related to the CBR− these materials are characterised by their low clay contents and high quartz (silica) contents, manifested by its low average plasticity indices. The principal component analysis confirms this. Correlation coefficients for the Atterberg Limits varied from -0,16 to -0,44. As expected, the grading, however, proved more significant. The correlation coefficient increased constantly from P26,5 (-0,53) to P425 (-0,72), with the P075 having a correlation coefficient of -0,58. The grading modulus had a correlation coefficient of 0,72 and the grading coefficient, 0,56. One could deduce from this that the strength of the high silica material group is more dependent on the grading than other groups and less dependent on the Atterberg Limits.

4.1.5 Arenaceous Materials

After considering the higher than expected coefficients of variation (refer to Addendum A), the poor correlation coefficients derived for this group was anticipated. What is of particular interest is the fact that the grading modulus, which had the lowest coefficient of variation of all the parameters in this material group, had a poor correlation of 0,27 with the CBR. In fact, the grading in all showed very poor correlation with the CBR, the best correlation being with P075, which had a fair correlation coefficient of only -0,43.

As noted with other groups before, a general decrease in Atterberg Limits was associated with an improved CBR. This held true in the arenaceous group, with the liquid and plastic limits having correlation coefficients of -0,46 and -0,48, respectively. It was the shrinkage product, though, that produced the best correlation coefficient in this group (-0,51). It is interesting to note that neither of the components generating this parameter (P425 or linear shrinkage) individually showed a good correlation with the CBR.

4.1.6 Argillaceous Materials

The argillaceous group showed poor correlations between individual parameters and the CBR at 95% Mod AASHTO compaction. The only two parameters showing any significant correlation were the liquid limit and plasticity index. These two parameters had correlation coefficients of -0,47 and -0,43 with the CBR, respectively. As before, it is understandable that a reduced plasticity index (or liquid limit for that matter) may be associated with an increased CBR value; however, the predominant lack of any other correlations with the CBR values is striking.

4.1.7 Calcrete Materials

The principal component analysis revealed that the coarser particle constituents had a smaller correlation than the fine particle constituents and Atterberg Limits. The coarser particle constituents had correlations of between 0,39 and 0,45 and ranged from the component passing the 2,0mm sieve to the component passing the 37,5mm sieve. The two finer components (P425 and P075) had correlations of -0,58 and -0,67 respectively. This could be the result of the softer nature of many of the coarser particles in calcretes, giving a false indication of the final grading under compaction and loading. This is supported by the findings of Lawrance and Toole (1984) that identified the need for an aggregate hardness parameter (Aggregate Pliers Value) in their analysis of calcretes. (Such a hardness parameter could possibly be sensibly applied to all material tests).

The Atterberg Limits showed good correlations. The liquid limit, plasticity index and plastic limit had respective correlations of -0,73, -0,68 and -0,72 with the CBR. At the same time good correlations were also achieved between the CBR and the linear shrinkage, linear shrinkage product and the shrinkage product, with correlations of -0,70, -0,58 and -0,64, respectively. Despite the seemingly improved correlations of the calcrete compared with other material groups, it must be considered that the calcrete group consisted of only nineteen samples.

4.1.8 Ferricrete Materials

The majority of parameters tested against the CBR values of the ferricretes showed poor or very poor correlation. Only three exceptions were observed. The P425 and P075 constituents showed respective correlations of -0,54 and -0,51. This suggests, as observed in other groups thus far, that an increase in finer particle constituents causes a decrease in CBR values.

The third parameter, which showed a fair correlation with the CBR, was the grading modulus. A correlation coefficient of 0,53 was revealed. It is interesting to note that the grading coefficient has a poor correlation coefficient of 0,29. This suggests, once more, that the grading modulus will prove more significant in the attempt to correlate parameters with CBR values.

4.1.9 Colluvium

The principal component analysis of colluvial materials delivered mixed results. Firstly, a number of parameters showed very poor correlation with the CBR, for example the P37,5 component had a correlation coefficient of only 0,01. The P075 constituent, on the other hand, had a fair correlation coefficient of -0,46. In conjunction with this, the plasticity index, linear shrinkage, linear shrinkage product and shrinkage product had respective correlation coefficients of -0,46; -0,49; -0,46 and 0,50. All four of these parameters, as well as the P075 constituent, can be related to the clay-sized content of a material and a consequent reduction in shear strength and as all five of the parameters mentioned have negative correlation coefficients, one can deduce that in general, an increase in the fines content results in a decrease in CBR values. This deduction also applies, at least partially or indirectly, to a classification system such as the COLTO system, where material class definition is based partially on the plasticity index.

The only other property that showed a fair correlation with the CBR was the grading modulus, with a correlation coefficient of 0,45. The positive coefficient indicates that an increase in the grading modulus (i.e. coarser materials) correlates with an increase in CBR values. It is worth mentioning that, as with ferricrete, the grading modulus had a noticeably better correlation coefficient with the CBR than the grading coefficient (0,39). This can perhaps be ascribed to the fact that the grading modulus considers a finer grain size distribution (down to the P075 component), whereas the grading coefficient considers the P2,0 as the smallest constituent. This is particularly significant as the finer particle constituents proved to have a better (negative) correlation with the CBR, than the intermediate and coarser particle sizes.

4.1.10 Non-Plastic Materials

Non-plastic materials revealed an increasing, negative correlation with the CBR as particle sizes decreased. It is interesting to note that this trend excludes the P075 constituent, as the constituent achieved a correlation coefficient of only -0,25. As is to be expected, none of the Atterberg Limits or shrinkage parameters showed any correlation with the CBR in this group and whilst the grading modulus achieved a correlation coefficient of 0,51 the grading coefficient only achieved a correlation coefficient of -0,11.

4.2 Principal Component Analysis: Moist Areas: 98% Mod AASHTO

A summary of the principal component analysis for materials compacted at 98% Mod AASHTO density and in moist areas is illustrated in Table 4.2.

4.2.1 All Groups

The principal component analysis of the entire group of materials compacted to 98% Mod AASHTO density revealed similar trends to those for the materials compacted to 95% Mod AASHTO density. The correlation coefficients increased negatively from the P37,5 (with a correlation coefficient of -0,24) to the P075 constituent (with a correlation coefficient of -0,48). In addition, the shrinkage product had a correlation coefficient of -0,42; whilst the grading modulus had a correlation coefficient of 0,51; the best of all the correlations in the group. It would appear, therefore, that the grading

Table 4.2 Parameter Correlation with CBR (98% Mod AASHTO, moist)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Ferri-crete	Collu-vium	Non-Plastic
LL	-0,32	-0,21	-0,44	-0,27	-0,42	-0,60	-0,68	-0,30	-0,31	-
PI	-0,37	-0,32	-0,46	-0,35	-0,34	-0,55	-0,60	-0,30	-0,41	-
PL	-0,19	0,04	-0,30	-0,12	-0,43	-0,46	-0,69	-0,25	-0,12	-
LS	-0,34	-0,29	-0,46	-0,28	-0,34	-0,41	-0,64	-0,29	-0,42	-
LSP	-0,37	-0,41	-0,48	-0,36	-0,41	-0,50	-0,48	-0,34	-0,41	-
SP	-0,42	-0,45	-0,52	-0,42	-0,43	-0,51	-0,57	-0,37	-0,45	-
P37,5	-0,24	-0,17	-0,20	-0,43	0,03	-0,09	-0,33	-0,11	0,02	-0,20
P26,5	-0,33	-0,29	-0,25	-0,51	-0,15	-0,13	-0,30	-0,22	0,01	-0,34
P19,0	-0,39	-0,43	-0,27	-0,58	-0,21	-0,17	-0,30	-0,26	-0,01	-0,45
P13,2	-0,41	-0,47	-0,39	-0,61	-0,22	-0,22	-0,11	-0,34	-0,05	-0,51
P4,75	-0,46	-0,53	-0,46	-0,62	-0,25	-0,28	-0,31	-0,39	-0,18	-0,59
P2,0	-0,47	-0,55	-0,50	-0,63	-0,23	-0,33	-0,32	-0,34	-0,39	-0,58
P425	-0,48	-0,54	-0,49	-0,62	-0,18	-0,33	-0,48	-0,44	-0,47	-0,49
P075	-0,48	-0,53	-0,51	-0,48	-0,33	-0,51	-0,61	-0,45	-0,43	-0,22
GM	0,51	0,56	0,53	0,63	0,25	0,40	0,53	0,44	0,51	0,52
GC	0,37	0,39	0,43	0,56	0,12	0,34	0,31	0,26	0,53	0,46

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

modulus is the single parameter that shows the best correlation with CBR values for the entire group compacted to 98% Mod AASHTO.

4.2.2 Basic Crystalline Materials

The Atterberg Limits showed poor correlations with CBR values within the basic crystalline group, whilst the linear shrinkage product and shrinkage product had respective correlation coefficients of -0,41 and -0,45. The best correlation between grading and CBR values was from the component passing the 2,0mm sieve; with a correlation coefficient of -0,55 which can be considered as fair. The grading modulus had the best correlation with the CBR in this group, with a correlation coefficient of 0,56.

4.2.3 Acid Crystalline Materials

The best correlation with the CBR in this group was from the grading modulus. A correlation coefficient of 0,53 was calculated, whilst a correlation coefficient of -0,52 was calculated between the CBR and the shrinkage product. Both the linear shrinkage product and linear shrinkage showed a significant, fair correlation with respective correlation coefficients of -0,48 and -0,46. The plasticity index had a correlation coefficient of -0,46 suggesting that it may also be significant in the eventual empirical predictions. Finally, as with most other groups analysed thus far, an increasing negative correlation was noted with reducing particle sizes.

4.2.4 High Silica Materials

It is mentioned in the statistical analysis (Addendum A) that the Atterberg Limits were expected to show little correlation with CBR values in the high silica group due to the fact that normalisation of the data resulted in very little improvement of the data quality. The principal component analysis confirmed this hypothesis. The liquid limit, plasticity index and plastic limit produced correlation coefficients of -0,27; -0,35 and -0,12 respectively. Grading, on the other hand, proved to have a fair to good correlation with CBR values. A correlation coefficient as high as -0,63 was found between the CBR and the percentage passing the 2,0mm sieve. The lowest bound of correlation coefficients for the grading was -0,43 for the P37,5 constituent. Even this can be considered a fair correlation. The correlation between the grading and CBR is further confirmed by the grading modulus and grading coefficient, which had correlation coefficients of 0,63 and 0,56, respectively.

4.2.5 Arenaceous Materials

In sharp contradiction to expectation, the grading modulus of the arenaceous materials only produced a correlation coefficient of 0,25 with the CBR. Four parameters showed notable correlation coefficient with the CBR values: the liquid limit (-0,42), the plastic limit (-0,43), the linear shrinkage product (-0,41) and the shrinkage product (-0,43). The use of these parameters in empirical predictions will most definitely be hampered by the material group's overall tendency toward non-plastic materials.

4.2.6 Argillaceous Materials

A number of parameters showed fair to good correlations with the CBR values in the argillaceous group. The liquid limit, plasticity index and plastic limit had correlation coefficients of -0,60, -0,55 and -0,46 with the CBR values, respectively. The linear shrinkage product and shrinkage product had correlation coefficients of -0,50 and -0,51 with the CBR respectively. Lastly, the P075 constituent had a correlation coefficient of -0,51. Considering all of the parameters showing a reasonable correlation with the CBR, it is apparent that the correlations are linked more to properties related to the fine-grained nature of the particles typical of mudrocks.

4.2.7 Calcrete Materials

Despite the high variability of the calcrete samples analysed and the high coefficients of variation obtained during the statistical analysis, surprisingly good correlations were found within the calcrete group. The liquid limit, plasticity index and plastic limit had correlation coefficients of -0,68, -0,60 and -0,69 with the CBR values, respectively. In addition to these, the linear shrinkage, linear shrinkage product and shrinkage product also showed fair to good correlations, especially the linear shrinkage, with a correlation coefficient of -0,64. Regarding the grading, only the P425 and P075 showed some correlation with the CBR values. This is not all together unexpected, as these parameters are used to determine the shrinkage product and linear shrinkage product respectively, and both of these products had good correlations with the CBR.

Lastly, the grading modulus had a fair correlation of 0,53 as opposed to the grading coefficient's correlation coefficient of only 0,31. This, again, suggests that the grading modulus is more representative of the calcrete group than the grading coefficient, though the sample population is not sufficiently large to substantiate this. Despite the promising correlations revealed above, the limited number of samples must once again be emphasised.

4.2.8 Ferricrete Materials

The principal component analysis of the ferricrete group revealed very little correlation between CBR values and other parameters. Only three parameters showed some correlation, namely the P425 constituent, the P075 constituent and the grading modulus. These three parameters had correlation coefficients of -0,44, -0,45 and 0,44 respectively. It is clear that the grading modulus again shows a better correlation with the CBR values than the grading coefficient. It would appear that in instances where the grading modulus and grading coefficient contradict each other, the grading modulus tends to correlate markedly better than the grading coefficient.

4.2.9 Colluvium

A number of parameters stand out from the principal component analysis with the CBR as the dependent parameter. The two best correlations were achieved by the grading modulus and grading coefficient, which had correlation coefficients of 0,51 and 0,53 respectively. The linear shrinkage, linear shrinkage product and shrinkage product also showed fair correlation, with correlation coefficients of -0,42, -0,41 and -0,45. It is also not unexpected to note that both the P425 and P075 parameters also showed fair correlations with the CBR. Finally, the plasticity index had a correlation coefficient of -0,41 indicating that it, too, has a reasonable correlation with the CBR values.

4.2.10 Non-Plastic Materials

The non-plastic materials showed an increasing, negative correlation with the CBR as particle size decreased. It is peculiar to notice that – as with the 95% Mod AASHTO group - this trend excludes the P075 parameter, as this achieved a correlation coefficient of only -0,22. None of the Atterberg Limits or shrinkage parameters showed good correlation with the CBR in this group and whilst the grading modulus produced a correlation coefficient of 0,52 the grading coefficient achieved a correlation coefficient of 0,46.

4.3 Principal Component Analysis: Moist Areas: 100% Mod AASHTO

Summaries of the principal component analysis for 100% Mod AASHTO compaction in moist areas are given in Table 4.3.

4.3.1 All Groups

The observed tendency of the correlation coefficients to increase negatively with decreasing particle size continued in the entire group compacted to 100% Mod AASHTO density. From the P4,75 to the P075 constituent, the correlation coefficient improved from -0,47 to -0,50 (i.e. a fair to good correlation). In accordance with this, the grading modulus achieved a correlation coefficient of 0,53 with the CBR. The shrinkage product was found to have a correlation coefficient of -0,46, suggesting that it may be a key parameter in the derivation of an empirical prediction model.

Table 4.3 Parameter Correlation with CBR (100% Mod AASHTO, moist)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Ferri-crete	Collu-vium	Non-Plastic
LL	-0,35	-0,24	-0,53	-0,26	-0,42	-0,47	-0,66	-0,33	-0,35	-
PI	-0,39	-0,34	-0,56	-0,34	-0,40	-0,44	-0,61	-0,32	-0,43	-
PL	-0,22	0,01	-0,36	-0,11	-0,39	-0,36	-0,65	-0,28	-0,17	-
LS	-0,37	-0,32	-0,57	-0,27	-0,38	-0,37	-0,63	-0,31	-0,44	-
LSP	-0,40	-0,44	-0,52	-0,36	-0,46	-0,45	-0,47	-0,38	-0,41	-
SP	-0,46	-0,48	-0,58	-0,43	-0,46	-0,45	-0,57	-0,43	-0,46	-
P37,5	-0,25	-0,21	-0,24	-0,38	0,13	-0,05	-0,38	-0,24	0,04	-0,19
P26,5	-0,33	-0,36	-0,29	-0,46	-0,04	-0,08	-0,35	-0,31	0,04	-0,27
P19,0	-0,38	-0,47	-0,32	-0,53	-0,12	-0,11	-0,33	-0,36	0,02	-0,36
P13,2	-0,40	-0,50	-0,37	-0,57	-0,15	-0,14	-0,15	-0,44	-0,02	-0,43
P4,75	-0,47	-0,55	-0,46	-0,61	-0,23	-0,18	-0,33	-0,54	-0,16	-0,57
P2,0	-0,49	-0,57	-0,49	-0,63	-0,24	-0,24	-0,32	-0,50	-0,38	-0,60
P425	-0,50	-0,56	-0,49	-0,63	-0,18	-0,24	-0,48	-0,57	-0,43	-0,55
P075	-0,50	-0,56	-0,53	-0,50	-0,31	-0,43	-0,61	-0,55	-0,42	-0,28
GM	0,53	0,59	0,54	0,64	0,26	0,31	0,53	0,58	0,49	0,56
GC	0,41	0,38	0,43	0,60	0,24	0,30	0,31	0,39	0,52	0,55

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

4.3.2 Basic Crystalline Materials

Apart from the linear shrinkage product and shrinkage product's correlation coefficients of -0,44 and -0,48, grading proved particularly significant in the correlation with CBR values. Whereas the grading thus far generally only became significant from the 2,0mm constituent, the principal component analysis revealed that in the basic crystalline group, a fair correlation is achieved from the P19 component and smaller. The P19,0 constituent had a fair correlation coefficient of -0,47 with the correlation coefficients improving with decreasing particle size. The

P075 constituent had a correlation coefficient of -0,56; however the component passing the 2,0mm sieve had the best correlation in the group (-0,57). As with the entire group, the grading modulus showed a correlation coefficient of 0,59 with the CBR although the grading coefficient failed to achieve even a fair correlation with the same parameter, with a value of only 0,38.

4.3.3 Acid Crystalline Materials

Apart from fair correlations between the CBR and the P2,0, P425 and P075 constituents, the grading modulus also produced a notable correlation coefficient of 0,54. Correlation coefficients of -0,53 and -0,56 were recorded between the CBR values and the liquid limits and plasticity index, respectively. Fair to good correlations came from the linear shrinkage, linear shrinkage product and shrinkage product with values of -0,57, -0,52 and -0,58 respectively. The last mentioned correlation borders between fair and good, but was unexpected as one tends to associate plastic clay minerals with basic crystalline materials, rather than with acid crystalline materials. On this basis, the deleterious effects of clays may be more pronounced in the acid crystalline group, which may result in a higher negative correlation with the CBR values.

4.3.4 High Silica Materials

The high silica group showed a range of parameters with fair to good correlation with the CBR values. Particle size distribution between the P19,0 and P075 constituents produced correlation coefficients between -0,50 and -0,63. Also, both the grading modulus and the grading coefficient showed fairly good correlation with the CBR, with the two parameters having correlation coefficients of 0,64 and 0,60, respectively. It would appear that once again, the grading modulus correlates with the CBR better than the grading coefficient.

4.3.5 Arenaceous Materials

Contrary to the trend observed thus far where a decreasing particle size plays an increasingly important part in the correlation with the CBR values, the arenaceous material group showed particularly poor correlations for the grading parameters. Instead, the Atterberg Limits and shrinkage parameters correlated best with the CBR values, although the correlations were only considered to be fair. Correlation coefficients of the Atterberg Limits ranged from -0,39 to -0,42 whilst the shrinkage parameters – including the linear shrinkage, the linear shrinkage product and the shrinkage product – had correlation coefficients between -0,38 and -0,46.

4.3.6 Argillaceous Materials

Only five parameters showed fair correlation with the CBR. The first two parameters were the liquid limit and plasticity index, which had correlation coefficients of -0,47 and -0,44 respectively. The linear shrinkage product and shrinkage product both had correlation coefficients of -0,45. The final parameter noted was the P075 constituent, with a correlation coefficient of -0,43. Notwithstanding the previously mentioned trend of good correlations with grading parameters, the grading modulus and grading coefficient had correlation coefficients of 0,31 and 0,30 which indicate that CBR values of argillaceous materials are less dependent on the grading, but rather more dependent (or limited) by the Atterberg Limits.

4.3.7 Calcrete Materials

As observed in the 98% Mod AASHTO group, CBR values of the calcrete show fair to good correlation with a number of parameters. The Atterberg Limits had the highest correlation coefficients, with the liquid limit, plasticity index and plastic limit achieving correlation coefficients of -0,66, -0,61 and -0,65, respectively. Simultaneously the linear shrinkage, linear shrinkage product and shrinkage product had correlation coefficients of -0,63, -0,47 and -0,57 respectively. Considering the products of the latter two parameters, it is not surprising then that the P425 and P075 constituents had respective correlation coefficients of -0,48 and -0,61. Finally, whilst the grading modulus achieved a correlation coefficient of 0,53 with CBR values, the grading coefficient once again failed to produce a reasonable correlation.

4.3.8 Ferricrete Materials

Ferricrete had a number of parameters which showed fair correlations with CBR values at best. Surprisingly, none of the Atterberg Limits were amongst these parameters. The shrinkage product had a correlation coefficient of -0,43, whilst sieve sizes between P13,2 and P075 varied in correlation coefficient between -0,44 and -0,57. Considering the contradictory results from the grading modulus and grading coefficient, it is interesting to note that, as with the other instances of conflicting grading parameters, the grading modulus had a much improved correlation coefficient compared with the grading coefficient. The former parameter had a correlation coefficient of 0,58 whilst the latter had a correlation coefficient of only 0,39.

4.3.9 Colluvium

Only three parameters proved to be significant with regard to correlation with CBR values. The shrinkage product produced a correlation coefficient of -0,46 with the CBR. Along with this, the grading modulus and grading coefficient had respective correlation coefficients of 0,49 and 0,52, which suggests that the latter may prove more useful in CBR prediction.

4.3.10 Non-Plastic Materials

The non-plastic materials revealed an increasing, negative correlation with the CBR as particle sizes decreased, particularly from the P475 constituent. The grading coefficient varied between -0,55 and -0,60 for distribution sizes between P4,75 and

P425. As with lower compaction efforts, the P075 constituent showed a much poorer correlation with the CBR, with a correlation coefficient of only -0,28. As is to be expected, none of the Atterberg Limits or shrinkage parameters showed even a poor correlation with the CBR in this group and whilst the grading modulus achieved a correlation coefficient of 0,56 the grading coefficient achieved a correlation coefficient of 0,55.

4.4 Principal Component Analysis: Dry Areas: 95% Mod AASHTO

As done in sections 4.1 through 4.3, dry materials were also analysed by means of a principal component analysis. Though nearly identical datasets were used for the three compactive groups (95%, 98% and 100% Mod AASHTO), a principal component analysis was done for each group to determine whether parameters correlated with the same – or even different – parameters as those of other compactions.

As little usable data was obtained from South African sources, nearly all the data analysed for dry regions were obtained from the Namibian Roads Department. Consequently the sample population is considerably smaller than that of moist areas. A summary of the principal component analysis for material groups compacted to 95% Mod AASHTO in dry areas is given in Table 4.4 and is discussed further in the following section.

4.4.1 All Groups

It was initially anticipated that materials in a dry climate would show a stronger correlation between grain size distribution and the CBR than materials from moist regions. Reasoning behind this was that in dry areas Atterberg Limits should be less pronounced due to reduced chemical weathering; hence the formation of chemical weathering (decomposition) products were expected to be less significant. However, the principal component analysis revealed that grading showed little correlation with the CBR for the combined material groups, with the exception of the P075 constituent

Table 4.4 Parameter Correlation with CBR (95% Mod AASHTO, dry)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	-0,20	-0,30	-0,08	0,01	-0,48	-0,13	-0,44	-0,32	-0,29	-
PI	-0,26	-0,52	-0,02	-0,04	-0,44	-0,19	-0,43	-0,40	-0,29	-
PL	-0,13	-0,15	-0,10	0,03	-0,41	-0,05	-0,40	-0,23	-0,27	-
LS	-0,30	-0,55	-0,10	-0,04	-0,46	-0,15	-0,44	-0,40	-0,34	-
LSP	-0,42	-0,69	-0,06	-0,24	-0,60	-0,46	-0,41	-0,49	-0,48	-
SP	-0,35	-0,72	-0,04	-0,21	-0,49	-0,37	-0,47	-0,51	-0,46	-
P37,5	-0,01	-0,02	0,07	-0,00	-0,11	-0,11	-0,01	-0,37	0,07	-0,11
P26,5	-0,05	-0,10	0,06	-0,06	-0,15	-0,16	-0,07	-0,37	0,05	-0,16
P19,0	-0,06	-0,13	0,04	-0,08	-0,16	-0,18	-0,12	-0,38	0,07	-0,19
P13,2	-0,09	-0,22	0,10	-0,14	-0,11	-0,19	-0,17	-0,52	0,06	-0,23
P4,75	-0,12	-0,33	0,23	-0,22	-0,04	-0,23	-0,21	-0,64	-0,03	-0,25
P2,0	-0,13	-0,37	0,33	-0,23	-0,01	-0,23	-0,17	-0,71	-0,08	-0,23
P425	-0,18	-0,56	0,20	-0,27	-0,09	-0,28	-0,13	-0,52	-0,14	-0,18
P075	-0,38	-0,56	0,06	-0,30	-0,57	-0,41	-0,22	-0,60	-0,45	-0,16
GM	0,21	0,54	-0,28	0,26	0,19	0,30	0,18	0,67	0,23	0,22
GC	0,08	0,28	-0,24	-0,02	-0,27	-0,06	0,05	0,51	0,06	0,11

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

which had a correlation of -0,38 with the CBR. Apart from the P075 constituent, the highest correlation with the CBR was with the P425 constituent, which was only -0,18.

The linear shrinkage product and shrinkage product showed some correlation with the CBR. The two parameters had correlation coefficients of -0,42 and -0,35 respectively. This, again, is unexpected as both parameters contain linear shrinkage as a product in its formulation. Linear shrinkage itself showed a better correlation with the CBR (0,30) than grading. As explained above, linear shrinkage is often associated with chemical weathering. Theoretically one would expect mechanical weathering – such as currently prevalent in dry areas – to result in non-plastic materials, whilst chemical weathering is expected to result in materials with a plastic (or at least partially plastic) nature. This, however, does not seem to be the case and a number of factors may be responsible for this result, e.g. varying climatic conditions through the geological past.

4.4.2 Basic Crystalline Materials

The basic crystalline group contained a number of parameters that showed fair and even good correlation with the CBR. The parameters, however, were once more associated rather with plasticity and associated properties, than grading.

In terms of grading, the P425 and P075 constituents both had correlations of -0,56 with CBR values, whilst the grading modulus had a correlation coefficient of 0,54. Fair correlations were noted between the CBR values and the plasticity index and linear shrinkage, with correlation coefficients of -0,52 and -0,55, respectively. The best correlations, however, were those of the linear shrinkage product (-0,69) and shrinkage product (-0,72). Both of these can be considered as good correlations. Again, it is unexpected that grading (excluding finer particle sizes) shows such poor correlation with the CBR.

4.4.3 Acid Crystalline Materials

In sharp contrast to the basic crystalline group, acid crystalline materials had limited correlating parameters. Also, the parameters identified had very limited correlations with CBR values. Only two parameters were noted to show any (poor) correlations with the CBR. The particle constituent passing the 2,0mm sieve had a correlation of 0,33 and the grading modulus had a correlation coefficient of -0,28. It is interesting to note that the component passing the 2,0mm sieve also had the best correlation of grading in the 95% Mod AASHTO density group in moist areas. This suggests that the component may be vital in lending strength to the material. As an example, consider granite which often weathers to coarse sand that will be reflected in the grading.

4.4.4 High Silica Materials

The high silica group also produced poor correlations with the CBR values. The three parameters with the best correlation were the P425, P075 and grading modulus, with correlation coefficients of -0,27, -0,30 and 0,26, respectively. It appears that correlations are rather based more on deleterious characteristics (i.e. a negative correlation) than favourable characteristics (i.e. a positive correlation). Despite this observation, the best correlation of -0,30 is still considered to be poor.

4.4.5 Arenaceous Materials

The lack of expected correlation between grading and CBR values continues in the arenaceous group. Instead, the opposite is observed again, with parameters associated with plasticity showing better correlation with the CBR than the grading parameters. A number of parameters were noted to have fair or good correlation coefficients.

A fair to good negative correlation of -0,57 is indicated between the CBR and the P075 constituent. It is also not without reason then that the liquid limit had a correlation of -0,48. Critically, though, the linear shrinkage, linear shrinkage product and shrinkage product had correlation coefficients of -0,46, -0,60 and -0,49, respectively. This confirms, once again, that the expected prevalent non-plastic character of materials in the dry region does not hold true.

4.4.6 Argillaceous Materials

As with arenaceous materials, the P075 constituent showed a fair correlation of -0,41 with the CBR, whilst the linear shrinkage product and shrinkage product had correlations coefficients of -0,46 and -0,37, respectively. The large difference, though, is the apparent lack of correlation between the CBR and the liquid limit observed in the arenaceous group. Also, a correlation coefficient of 0,30 is indicated for the grading modulus, despite the fact that individual grading parameters showed poor correlation with the CBR values.

4.4.7 Calcrete Materials

The principal component analysis revealed that the Atterberg Limits showed considerably better correlations than the grading parameters. The liquid limit, plasticity index and plastic limit had respective correlation coefficients of -0,44, -0,43 and -0,40 with the CBR values. Whilst the linear shrinkage product also showed a fair correlation (-0,41), the linear shrinkage and shrinkage product had correlation coefficients of -0,44 and -0,47, respectively. This trend was also observed in moist areas, where Atterberg Limits and other parameters related to plasticity (e.g. linear shrinkage) showed a better correlation than grading parameters. Here it is pivotal to keep in mind that calcrete is a pedogenic material and as such is largely dependent on its host material; hence Atterberg Limits will also be dependent to a large extent on the original host material.

4.4.8 Alluvial Materials

One clear exception to the trend observed thus far, is alluvial materials. The alluvial group is the only group in the dry climatic areas which shows good correlations between grading parameters and CBR values. Particle components passing the 13,2mm sieve and smaller showed correlation coefficients between -0,52 and -0,71, which can be considered as good correlations. In addition, the grading modulus and grading coefficient had correlation coefficients of 0,67 and 0,51, respectively. The former correlation is considered to be good and the latter, fair.

Shrinkage parameters also showed some correlation, with the linear shrinkage, linear shrinkage product and shrinkage product achieving correlations of -0,40, -0,49 and -0,51 with the CBR values. It must be emphasised, though, that all of the samples included came from the same source area and as such, the material may not necessarily be representative of a wide range of alluvial materials. For instance, the samples originating from this area may be well-sorted coarse sands and will therefore not represent clayey alluvium.

4.4.9 Colluvium

The principal component analysis of colluvial materials indicates once more that shrinkage parameters have the best correlation with CBR values. Correlation coefficients of -0,34, -0,48 and -0,46 are indicated for linear shrinkage, the linear shrinkage product and the shrinkage product, respectively. This is complemented by a correlation coefficient of -0,45 for the P075 constituent, indicating that deleterious, finer materials are more influential in the principal component analysis. Atterberg Limits also showed better correlation with the CBR than the remaining grading parameters, but are still considered to be poor.

4.4.10 Non-Plastic Materials

Non-plastic material parameters have very poor correlations with CBR values. The single best correlation coefficient was -0,25 and was recorded for the P4,75 constituent. Remaining parameters had very poor correlation coefficients.

4.5 Principal Component Analysis: Dry Areas: 98% Mod AASHTO

Summaries of the principal component analyses for 98% Mod AASHTO compaction in dry regions are illustrated in Table 4.5.

Table 4.5 Parameter Correlation with CBR (98% Mod AASHTO, dry)

	All Groups	Basic Crystal-line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	-0,22	-0,21	-0,17	-0,13	-0,43	-0,21	-0,40	-0,26	-0,30	-
PI	-0,28	-0,46	-0,12	-0,17	-0,36	-0,28	-0,37	-0,34	-0,24	-
PL	-0,15	-0,06	-0,19	-0,09	-0,39	-0,10	-0,38	-0,18	-0,31	-
LS	-0,31	-0,50	-0,18	-0,19	-0,35	-0,22	-0,38	-0,35	-0,30	-
LSP	-0,41	-0,62	-0,10	-0,46	-0,50	-0,41	-0,35	-0,45	-0,51	-
SP	-0,35	-0,66	-0,10	-0,42	-0,35	-0,32	-0,44	-0,48	-0,50	-
P37,5	-0,05	0,01	0,12	-0,21	0,01	-0,07	0,03	-0,30	0,07	-,023
P26,5	-0,12	-0,17	0,12	-0,32	-0,03	-0,11	-0,04	-0,30	0,03	-0,33
P19,0	-0,14	-0,19	0,11	-0,35	-0,04	-0,13	-0,11	-0,31	0,02	-0,36
P13,2	-0,18	-0,30	0,16	-0,38	-0,02	-0,14	-0,20	-0,47	0,00	-0,41
P4,75	-0,20	-0,43	0,26	-0,40	0,02	-0,16	-0,29	-0,61	-0,14	-0,44
P2,0	-0,19	-0,46	0,36	-0,38	0,03	-0,16	-0,26	-0,72	-0,19	-0,41
P425	-0,20	-0,55	0,22	-0,39	-0,02	-0,18	-0,22	-0,54	-0,26	-0,31
P075	-0,37	-0,52	0,08	-0,47	-0,45	-0,32	-0,16	-0,60	-0,54	-0,17
GM	0,25	0,57	-0,31	0,41	0,11	0,21	0,24	0,68	0,36	0,38
GC	0,05	0,33	-0,23	-0,26	-0,10	-0,04	0,14	0,61	0,15	0,14

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

4.5.1 All Groups

The principal component analysis of the entire group of materials from dry regions compacted to 98% Mod AASHTO density revealed a general lack of correlation between grading parameters and CBR values, similar to that observed in the 95% Mod AASHTO compaction group. Only four parameters showed any correlation with CBR values. In improving order these four parameters were the linear shrinkage (-0,31), the shrinkage product (-0,35), the P075 constituent (-0,37) and the linear shrinkage product (-0,41). As was discussed in section 4.4.1, this is somewhat unexpected as one might anticipate grading parameters to show a better correlation than Atterberg Limits or shrinkage parameters due to a *theoretically* reduced influence ascribed to less chemical decomposition in the dry regions.

4.5.2 Basic Crystalline Materials

Basic crystalline materials showed a number of largely improved correlations with CBR values compared with the entire group. This indicates a refined correlation which is ascribed to the material group. Whilst the liquid limit and plastic limit showed very little correlation with the CBR, the plasticity index had a correlation of -0,46. In addition to this, the linear shrinkage, linear shrinkage product and shrinkage product had correlation coefficients of -0,50, -0,62 and -0,66, respectively. These are considered fair to good correlations.

A number of grading parameters also showed notable correlation with the CBR, but as before it is important to notice that these parameters had a negative correlation. This signifies that rather than predicting strength, the parameters indicate weakness (i.e. an increase in the parameter is correlated with a decrease in the CBR). In compliance with the statement that larger particles lend strength to the CBR, whilst finer particles tend to be unfavourable (not to be confused with the vital finer matrix needed in the CBR sample), it is interesting to note that finer particle sizes (P425, P075) have significantly elevated negative correlation coefficients than coarser (e.g. P13,2) constituents. The constituents passing the 4,75mm and 2,0mm sieve have correlation coefficients of -0,43 and -0,46, respectively, whilst the P425 and P075 constituents had correlation coefficients of -0,55 and -0,52. The grading modulus also showed a fairly good correlation with the CBR (0,57).

4.5.3 Acid Crystalline Materials

In contrast to the basic crystalline group, the acid crystalline materials revealed a different set of correlations. Four parameters were noted to show (limited) correlation with the CBR. The constituent passing the 2,0mm sieve had a positive correlation of 0,36. This contradicts the findings made and discussed for basic crystalline materials. The P425 constituent also had a positive correlation, though at 0,22 it is of little significance. The positive correlation coefficient of the constituent passing the 2,0mm sieve can possibly be ascribed to the fact that granitic materials are often encountered as sands. This could signify that an increase in the sand component (i.e., passing the 2,0mm sieve) results in a stronger matrix which, in turn, results in higher CBR values This, however, should only hold true for sand particles having a diameter near 2,0mm as other smaller parameters (e.g. P425 and P075) showed little correlation with CBR values.

The correlation coefficients of the grading modulus and grading coefficient for the acid crystalline group also contradict those found for other material groups analysed thus far. Where other groups had positive correlation coefficients with the CBR, the acid crystalline has negative correlation coefficients for both the grading modulus (-0,31) and grading coefficient (-0,23). This tendency also applied to the 95% Mod AASHTO (dry) group, but was less pronounced.

It can be concluded then, that acid crystalline materials in a dry climate may derive much of their strength from particles of roughly 2,0mm diameter. The negative correlation coefficient of the grading modulus and grading modulus complies with this hypothesis. Clearly this hypothesis only holds true for optimum grading; i.e. a lower grading modulus of 0,18 may not necessarily signify better CBR values simply due to a low grading modulus, as such a low grading modulus is probably achieved by the inclusion of a large clay or silt constituent. Simply stated, the reduced grading modulus should correlate better with CBR scores, provided the sample comprises sandy materials and no fines.

4.5.4 High Silica Materials

Analysis of the high silica group revealed that the linear shrinkage product and shrinkage product had correlation coefficients of -0,46 and -0,42, respectively. Whilst the linear shrinkage itself had a correlation coefficient of only -0,19 the grading components of the linear shrinkage product and shrinkage product (P075 and P425, respectively) had correlation coefficients of -0,47 and -0,39 with the CBR values. In addition to these parameters, the component passing the 4,75mm sieve had a correlation coefficient of -0,40; whilst the grading modulus had a fair correlation (0,41) with the CBR values. As encountered with high silica materials in a moist region, Atterberg Limits showed very little correlation with the CBR values.

4.5.5 Arenaceous Materials

The four parameters showing the best correlation with CBR values in the arenaceous group were the liquid limit, plasticity index, linear shrinkage product and P075 constituent.

The liquid limit had a correlation coefficient of -0,43 with the CBR values, whilst the plastic limit had a correlation coefficient of -0,39. Both of these correlations can be classes as fair, when considering the remainder of the parameters. The plasticity index and linear shrinkage had slightly lower correlations (-0,36 and -0,35, respectively) with the CBR than the liquid limit and plastic limit.

Considering the (limited) correlation of the liquid limit with the CBR, as well as the P075 constituent's correlation coefficient of -0,45, it is not unexpected to note the linear shrinkage product's correlation coefficient of -0,50. The latter correlation coefficient is the best in this material group and is considered to be fair to good in relative terms.

4.5.6 Argillaceous Materials

Only three parameters were found to have some correlation with CBR values in the argillaceous group. The linear shrinkage product (-0,41) and shrinkage product (-0,32) showed fair and poor correlations, respectively. As has been observed numerous times, the P075 constituent also showed a better correlation with the CBR than the other parameters. This constituent had a poor correlation of -0,32, but compared with other parameters, the correlation is notable.

One would expect parameters such as the linear shrinkage product and shrinkage product to correlate well with the CBR values in the argillaceous group. However, one could also expect the Atterberg Limits to show some correlation which, in this case, did not materialise.

4.5.7 Calcrete Materials

Despite the high variability of the calcrete samples analysed and the high coefficients of variation shown by the statistical analysis, surprisingly good correlations were found within the calcrete group, particularly amongst the Atterberg Limits and shrinkage parameters.

The liquid limit (-0,40), plasticity index (-0,37) and plastic limit (-0,38) showed notable correlation with CBR values. Calcrete materials, as mentioned, are often dependent on their host materials' properties, which determine their own.

In addition to the Atterberg Limits, the linear shrinkage, linear shrinkage product and shrinkage product had correlation coefficients of -0,38, -0,35 and -0,44, respectively. These correlation coefficients are also not particularly good, but are notable when considering the remaining correlations.

4.5.8 Alluvial Materials

The principal component analysis of the alluvial materials compacted to 98% Mod AASHTO density conforms closely to its 95% Mod AASHTO counterpart. The strong improvement in correlation between the grading parameters and CBR values in particular stands out. Correlation coefficients varied from -0,47 and -0,72 for particle sizes smaller than 13,2mm, with the constituent passing the 2,0mm sieve showing the best correlation (-0,72). As a result, the grading modulus (0,68) and grading coefficient (0,61) also showed good correlations with the CBR. Considering the above, the effect of sorting in alluvial materials is evident, though it must be cautioned again that all the samples analysed were from the same source and as such, may not be representative of alluvial materials as a whole.

In addition to the grading parameters, both the linear shrinkage product and shrinkage product also showed fair correlation, with correlation coefficients of -0,45 and -0,48, respectively.

4.5.9 Colluvium

In the colluvial group four parameters stood out as far as correlation coefficients are concerned. Of the four parameters, three showed good correlations with the fourth showing a fair correlation with CBR values.

The linear shrinkage product, shrinkage product and P075 constituent had correlation coefficients of -0,51, -0,50 and -0,54, respectively. As with basic crystalline materials (section 4.5.2) it appears then that these parameters are associated with deteriorating CBR values, rather than improving values. The final parameter, which showed a fair to poor correlation, was the grading modulus. The parameter had a correlation of 0,36 with CBR values.

4.5.10 Non-Plastic Materials

The non-plastic materials showed enhanced correlation coefficients between grading parameters compared with the other material groups. Constituents passing the 13,2mm sieve, 4,75mm sieve and 2,0mm sieve had correlation coefficients of -0,41, -0,44 and -0,41, respectively. The grading modulus had a poor to fair correlation coefficient of 0,38.

4.6 Principal Component Analysis: Dry Areas: 100% Mod AASHTO

Summaries of the principal component analysis for 100% Mod AASHTO compaction are given in Table 4.6.

4.6.1 All Groups

Only four parameters were noted to show (poor) correlation with the CBR for the group of mixed materials, compacted to 100% Mod AASHTO density. As has been seen in many individual material groups, the linear shrinkage, linear shrinkage product and shrinkage product were found to have correlation coefficients of -0,29, -0,38 and -0,32. Also, the P075 constituent had a correlation of -0,33, which is to be expected, considering the correlation of the linear shrinkage product.

4.6.2 Basic Crystalline Materials

The trend of poor correlations between the CBR and Atterberg limits is continued in the 100% Mod AASHTO density group. The linear shrinkage product and shrinkage product, on the other hand, had fair to good correlation coefficients of -0,48 and -0,51, respectively. The finer particle size distributions also correlated better with the CBR, with the P4,75, P2,0 and P425 constituents having correlation coefficients of -0,47, -0,50 and -0,48, respectively. In addition to these parameters, the grading

Table 4.6 Parameter Correlation with CBR (100% Mod AASHTO, dry)

	All Groups	Basic Crystal -line	Acid Crystal-line	High Silica	Arena-ceous	Argilla-ceous	Calcrete	Allu-vium	Collu-vium	Non-Plastic
LL	-0,21	-0,05	-0,25	-0,14	-0,35	-0,14	-0,35	-0,30	-0,31	-
PI	-0,27	-0,30	-0,22	-0,25	-0,27	-0,22	-0,32	-0,35	-0,26	-
PL	-0,15	0,09	-0,24	-0,07	-0,35	-0,05	-0,34	-0,23	-0,32	-
LS	-0,29	-0,36	-0,26	-0,29	-0,30	-0,15	-0,32	-0,36	-0,31	-
LSP	-0,38	-0,48	-0,18	-0,46	-0,49	-0,37	-0,28	-0,45	-0,54	-
SP	-0,32	-0,51	-0,19	-0,44	-0,39	-0,31	-0,40	-0,48	-0,53	-
P37,5	-0,06	-0,03	0,12	-0,20	-0,03	-0,03	0,01	-0,20	-0,04	-0,18
P26,5	-0,14	-0,18	0,12	-0,30	-0,10	-0,08	-0,04	-0,19	-0,09	-0,29
P19,0	-0,15	-0,19	0,11	-0,31	-0,13	-0,11	-0,12	-0,20	-0,09	-0,34
P13,2	-0,19	-0,30	0,14	-0,34	-0,11	-0,13	-0,22	-0,35	-0,11	-0,39
P4,75	-0,22	-0,47	0,20	-0,35	-0,04	-0,18	-0,32	-0,49	-0,23	-0,42
P2,0	-0,20	-0,50	0,26	-0,31	-0,01	-0,20	-0,28	-0,61	-0,25	-0,40
P425	-0,18	-0,48	0,14	-0,31	-0,08	-0,21	-0,26	-0,41	-0,33	-0,29
P075	-0,33	-0,42	0,01	-0,39	-0,51	-0,29	-0,15	-0,53	-0,58	-0,15
GM	0,24	0,53	-0,21	0,33	0,18	0,23	0,27	0,56	0,43	0,35
GC	0,03	0,40	-0,17	-0,28	-0,28	0,04	0,16	0,61	0,16	0,12

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient

modulus had a correlation coefficient of 0,53 which may be considered as fair to good.

4.6.3 Acid Crystalline Materials

As with the lower compactions, the acid crystalline materials compacted to 100% Mod AASHTO density showed few parameters correlating with CBR values. The four highest correlations are considered to be poor to very poor correlations, at best. The liquid limit, linear shrinkage and grading modulus had correlation coefficients of -0,25, -0,26 and -0,21, respectively. Simultaneously the constituent passing the 2,0mm sieve had a correlation coefficient of 0,26 with the CBR – note again the positive correlation as encountered at lesser compactions. None of these correlations indicates a significant relationship with the CBR values.

4.6.4 High Silica Materials

A number of grading parameters (P13,2 and finer) showed poor correlation with the CBR values, achieving correlation coefficients of -0,39 and less. At the same time the linear shrinkage product and shrinkage product again showed a fair correlation with coefficients of -0,46 and -0,44, respectively. The grading modulus (0,33) was also noted to have a poor correlation with CBR values.

4.6.5 Arenaceous Materials

A good correlation was found between the CBR and the P075 (-0,51) constituent for this group. This can also be related to the fair correlation of the linear shrinkage product (-0,49). The shrinkage product also had a poor to fair correlation coefficient of -0,39, whilst the liquid limit and plastic limit had correlation coefficients of -0,35 in both instances.

4.6.6 Argillaceous Materials

As with the lower compactive efforts, the parameters of the argillaceous materials compacted to 100% Mod AASHTO density showed little correlation with CBR values. Only two parameters had poor correlations with the CBR. The linear shrinkage product and shrinkage product had correlation coefficients of -0,37 and -0,31, respectively. The only other parameter having any correlation with the CBR was the P075 constituent (-0,29).

4.6.7 Calcrete Materials

Conforming to the less densely compacted calcrete materials, the Atterberg Limits were found to have poor, yet notable (compared with other parameters in the material group) correlations with the CBR. The liquid limit, plastic limit and plasticity index had correlation coefficients of -0,35, -0,34 and -0,32, respectively.

The linear shrinkage was found to have a correlation coefficient of -0,32; whilst the shrinkage product (-0,40) showed a fair correlation with CBR values. It is interesting to note that in this instance the P075 constituent and linear shrinkage product had correlation coefficients of only -0,15 and -0,28, with the higher linear shrinkage product correlation being ascribed to the influence of the P075 values.

4.6.8 Alluvial Materials

Alluvial materials at this density (and from the same source area) revealed a good correlation between CBR values and the P4,75 constituent (-0,49) and P2,0 constituent (-0,61). The P075 constituent also had a good correlation coefficient of -0,53, whilst the grading modulus and grading coefficient had correlation coefficients of 0,56 and 0,61, respectively.

Both the linear shrinkage product and shrinkage product also showed fair correlations with the CBR, as indicated by correlation coefficients of -0,45 and -0,48, respectively.

4.6.9 Colluvium

Three parameters were identified that had good correlation with the CBR values. They were the linear shrinkage product (-0,54), the shrinkage product (-0,53) and the P075 constituent (-0,58). In general it was noted that once more, grading coefficients increased (negatively) with a decrease in particle size. The grading modulus confirms this, with a correlation coefficient of 0,43 suggesting that, in general, an increase in coarseness results in an increase in CBR.

4.6.10 Non-Plastic Materials

The non-plastic materials revealed an increasing, negative correlation with the CBR as particle sizes decreased (down to the constituent passing the 2,0mm sieve). The three parameters (P13,2, P4,75 and P2,0) had correlation coefficients of -0,39, -0,42 and -0,40, respectively. Contradicting the fair correlations observed from the P075 constituent thus far, this constituent showed a very poor correlation (-0,15) with the CBR for non-plastic materials.

4.7 Correlation Coefficient Summary

Table 4.7 and Table 4.8 illustrate summaries of the correlation coefficients of moist and dry regions, respectively. The tables provide a comparison between correlations observed between 95%, 98% and 100% Mod AASHTO densities for each material group, in the given climatic zones.

In each table an unspecified number of parameters are highlighted as they were deemed to be the better correlation(s) within a specific group. As mentioned before, the classification (significance) of such correlations is relative to the material group and may not necessarily be directly comparable with other groups; e.g. the best correlation in one group may be 0,35 whilst the best correlation in another group may be 0,72. The identification of the best correlations is therefore relative for individual material groups and must be considered in such a context.

The general conclusion drawn from these tables is that the shrinkage products, grading modulus and percentage passing the finer screen sizes generally appear to

Table 4.7 Correlation Coefficient Summary, Moist Areas

Group	Density	LL	PI	PL	LS	LSP	SP	P37,5	P26,5	P19,0	P13,2	P4,75	P2,0	P425	P075	GM	GC	n
All Groups	95%	-0,36	-0,41	-0,22	-0,39	-0,42	-0,48	-0,29	-0,36	-0,41	-0,44	-0,50	-0,52	-0,54	-0,53	0,57	-0,01	574
	98%	-0,32	-0,37	-0,19	-0,34	-0,37	-0,42	-0,24	-0,33	-0,39	-0,41	-0,46	-0,47	-0,48	-0,48	0,51	0,37	1016
	100%	-0,35	-0,39	-0,22	-0,37	-0,40	-0,46	-0,25	-0,33	-0,38	-0,40	-0,47	-0,49	-0,50	-0,50	0,53	0,41	1179
Basic Crystal-line	95%	-0,35	-0,47	0,04	-0,45	-0,57	-0,62	-0,27	-0,35	-0,48	-0,54	-0,62	-0,68	-0,71	-0,70	0,73	0,53	107
	98%	-0,21	-0,32	0,04	-0,29	-0,41	-0,45	-0,17	-0,29	-0,43	-0,47	-0,53	-0,55	-0,54	-0,53	0,56	0,39	154
	100%	-0,24	-0,34	0,01	-0,32	-0,44	-0,48	-0,21	-0,36	-0,47	-0,50	-0,55	-0,57	-0,56	-0,56	0,59	0,38	178
Acid Crystal-line	95%	-0,40	-0,42	-0,26	-0,43	-0,62	-0,63	-0,34	-0,33	-0,29	-0,33	-0,53	-0,64	-0,64	-0,65	0,68	0,57	53
	98%	-0,44	-0,46	-0,30	-0,46	-0,48	-0,52	-0,20	-0,25	-0,27	-0,39	-0,46	-0,50	-0,49	-0,51	0,53	0,43	100
	100%	-0,53	-0,56	-0,36	-0,57	-0,52	-0,58	-0,24	-0,29	-0,32	-0,37	-0,46	-0,49	-0,49	-0,53	0,54	0,43	109
High Silica	95%	-0,34	-0,44	-0,16	-0,38	-0,46	-0,54	-0,40	-0,53	-0,61	-0,67	-0,71	-0,72	-0,72	-0,58	0,72	0,61	93
	98%	-0,27	-0,35	-0,12	-0,28	-0,36	-0,42	-0,43	-0,51	-0,58	-0,61	-0,62	-0,63	-0,62	-0,48	0,63	0,56	162
	100%	-0,26	-0,34	-0,11	-0,27	-0,36	-0,43	-0,38	-0,46	-0,53	-0,57	-0,61	-0,63	-0,63	-0,50	0,64	0,60	198
Arena-ceous	95%	-0,46	-0,39	-0,48	-0,36	-0,45	-0,51	-0,02	-0,27	-0,30	-0,31	-0,28	-0,23	-0,21	-0,43	0,27	-0,04	26
	98%	-0,42	-0,34	-0,43	-0,34	-0,41	-0,43	0,03	-0,15	-0,21	-0,22	-0,25	-0,23	-0,18	-0,33	0,25	0,12	53
	100%	-0,42	-0,40	-0,39	-0,38	-0,46	-0,46	0,13	-0,04	-0,12	-0,15	-0,23	-0,24	-0,18	-0,31	0,26	0,24	59
Argilla-ceous	95%	-0,47	-0,43	-0,38	-0,45	-0,25	-0,38	-0,14	-0,18	-0,17	-0,19	-0,23	-0,24	-0,22	-0,29	0,26	0,16	73
	98%	-0,60	-0,55	-0,46	-0,41	-0,50	-0,51	-0,09	-0,13	-0,17	-0,22	-0,28	-0,33	-0,33	-0,51	0,40	0,34	96
	100%	-0,47	-0,44	-0,36	-0,37	-0,45	-0,45	-0,05	-0,08	-0,11	-0,14	-0,18	-0,24	-0,24	-0,43	0,31	0,30	106
Calcrete	95%	-0,73	-0,68	-0,72	-0,70	-0,58	-0,64	-0,41	-0,39	-0,41	-0,42	-0,45	-0,44	-0,58	-0,67	0,63	0,42	19
	98%	-0,68	-0,60	-0,69	-0,64	-0,48	-0,57	-0,33	-0,30	-0,30	-0,11	-0,31	-0,32	-0,48	-0,61	0,53	0,31	27
	100%	-0,66	-0,61	-0,65	-0,63	-0,47	-0,57	-0,38	-0,35	-0,33	-0,15	-0,33	-0,32	-0,48	-0,61	0,53	0,31	34

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; n = Number of samples

Table 4.7 Correlation Coefficient Summary, Moist Areas (continued)

Group	Density	LL	PI	PL	LS	LSP	SP	P37,5	P26,5	P19,0	P13,2	P4,75	P2,0	P425	P075	GM	GC	n
Ferri-crete	95%	-0,27	-0,27	-0,23	-0,26	-0,31	-0,36	-0,19	-0,33	-0,38	-0,46	-0,48	-0,44	-0,54	-0,51	0,53	0,29	108
	98%	-0,30	-0,30	-0,25	-0,29	-0,34	-0,37	-0,11	-0,22	-0,26	-0,34	-0,39	-0,34	-0,44	-0,45	0,44	0,26	258
	100%	-0,33	-0,32	-0,28	-0,31	-0,38	-0,43	-0,24	-0,31	-0,36	-0,44	-0,54	-0,50	-0,57	-0,55	0,58	0,39	300
Collu-vium	95%	-0,37	-0,46	-0,16	-0,49	-0,46	-0,50	0,01	0,01	-0,01	-0,03	-0,11	-0,27	-0,40	-0,46	0,45	0,39	95
	98%	-0,31	-0,41	-0,12	-0,42	-0,41	-0,45	0,02	0,01	-0,01	-0,05	-0,18	-0,39	-0,47	-0,43	0,51	0,53	154
	100%	-0,35	-0,43	-0,17	-0,44	-0,41	-0,46	0,04	0,04	0,02	-0,02	-0,16	-0,38	-0,43	-0,42	0,49	0,52	175
Non-Plastic	95%	-	-	-	-	-	-	-0,19	-0,32	-0,41	-0,47	-0,52	-0,52	-0,51	-0,25	0,51	-0,11	62
	98%	-	-	-	-	-	-	-0,20	-0,34	-0,45	-0,51	-0,59	-0,58	-0,49	-0,22	0,52	0,46	120
	100%	-	-	-	-	-	-	-0,19	-0,27	-0,36	-0,43	-0,57	-0,60	-0,55	-0,28	0,56	0,55	135

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; n = Number of samples

Table 4.8 Correlation Coefficient Summary, Dry Areas

Group	Density	LL	PI	PL	LS	LSP	SP	P37,5	P26,5	P19,0	P13,2	P4,75	P2,0	P425	P075	GM	GC	n
All Groups	95%	-0,20	-0,26	-0,13	-0,30	-0,42	-0,35	-0,01	-0,05	-0,06	-0,09	-0,12	-0,13	-0,18	-0,38	0,21	0,08	619
	98%	-0,22	-0,28	-0,15	-0,31	-0,41	-0,35	-0,05	-0,12	-0,14	-0,18	-0,20	-0,19	-0,20	-0,37	0,25	0,05	624
	100%	-0,21	-0,27	-0,15	-0,29	-0,38	-0,32	-0,06	-0,14	-0,15	-0,19	-0,22	-0,20	-0,18	-0,33	0,24	0,03	581
Basic Crystal-line	95%	-0,30	-0,52	-0,15	-0,55	-0,69	-0,72	-0,02	-0,10	-0,13	-0,22	-0,33	-0,37	-0,56	-0,56	0,54	0,28	50
	98%	-0,21	-0,46	-0,06	-0,50	-0,62	-0,66	0,01	-0,17	-0,19	-0,30	-0,43	-0,46	-0,55	-0,52	0,57	0,33	50
	100%	-0,05	-0,30	0,09	-0,36	-0,48	-0,51	-0,03	-0,18	-0,19	-0,30	-0,47	-0,50	-0,48	-0,42	0,53	0,40	50
Acid Crystal-line	95%	-0,08	-0,02	-0,10	-0,10	-0,06	-0,04	0,07	0,06	0,04	0,10	0,23	0,33	0,21	0,06	-0,28	-0,24	66
	98%	-0,17	-0,12	-0,19	-0,18	-0,10	-0,10	0,12	0,12	0,11	0,16	0,26	0,36	0,22	0,08	-0,31	-0,23	66
	100%	-0,25	-0,22	-0,24	-0,26	-0,18	-0,19	0,12	0,12	0,11	0,14	0,20	0,26	0,14	0,01	-0,21	-0,17	66
High Silica	95%	0,01	-0,04	0,03	-0,04	-0,24	0,21	0,00	-0,06	-0,08	-0,14	-0,22	-0,23	-0,27	-0,30	0,26	-0,02	77
	98%	-0,13	-0,17	-0,09	-0,19	-0,46	-0,42	-0,21	-0,32	-0,35	-0,38	-0,40	-0,38	-0,39	-0,47	0,41	-0,26	80
	100%	-0,14	-0,25	-0,07	-0,29	-0,46	-0,44	-0,20	-0,30	-0,31	-0,34	-0,35	-0,31	-0,31	-0,39	0,33	-0,28	80
Arena-ceous	95%	-0,48	-0,44	-0,41	-0,46	-0,60	-0,49	-0,11	-0,15	-0,16	-0,11	-0,04	-0,01	-0,09	-0,57	0,19	-0,27	54
	98%	-0,43	-0,36	-0,39	-0,35	-0,50	-0,35	-0,01	-0,03	-0,04	-0,02	0,02	0,03	-0,02	-0,45	0,11	-0,10	54
	100%	-0,35	-0,27	-0,35	-0,30	-0,49	-0,39	-0,03	-0,10	-0,13	-0,11	-0,04	-0,01	-0,08	-0,51	0,18	-0,28	36
Argilla-ceous	95%	-0,13	-0,19	-0,05	-0,15	-0,46	-0,37	-0,11	-0,16	-0,18	-0,19	-0,23	-0,23	-0,28	-0,41	0,30	-0,06	154
	98%	-0,21	-0,28	-0,10	-0,22	-0,41	-0,32	-0,07	-0,11	-0,13	-0,14	-0,16	-0,16	-0,18	-0,32	0,21	-0,04	155
	100%	-0,14	-0,22	-0,05	-0,15	-0,37	-0,31	-0,03	-0,08	-0,11	-0,13	-0,18	-0,20	-0,21	-0,29	0,23	0,04	131
Calcrete	95%	-0,44	-0,43	-0,40	-0,44	-0,41	-0,47	-0,01	-0,07	-0,12	-0,17	-0,21	-0,17	-0,13	-0,22	0,18	0,05	72
	98%	-0,40	-0,37	-0,38	-0,38	-0,35	-0,44	0,03	-0,04	-0,11	-0,20	-0,29	-0,26	-0,22	-0,16	0,24	0,14	72
	100%	-0,35	-0,32	-0,34	-0,32	-0,28	-0,40	0,01	-0,04	-0,12	-0,22	-0,32	-0,28	-0,26	-0,15	0,27	0,16	72

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; n = number of samples

Table 4.8 Correlation Coefficient Summary, Dry Areas (continued)

Group	Density	LL	PI	PL	LS	LSP	SP	P37,5	P26,5	P19,0	P13,2	P4,75	P2,0	P425	P075	GM	GC	n
Allu-vium	95%	-0,32	-0,40	-0,23	-0,40	-0,49	-0,51	-0,37	-0,37	-0,38	-0,52	-0,64	-0,71	-0,52	-0,60	0,67	0,51	38
	98%	-0,26	-0,34	-0,18	-0,35	-0,45	-0,48	-0,30	-0,30	-0,31	-0,47	-0,61	-0,72	-0,54	-0,60	0,68	0,61	38
	100%	-0,30	-0,35	-0,23	-0,36	-0,45	-0,48	-0,20	-0,19	-0,20	-0,35	-0,49	-0,61	-0,41	-0,53	0,56	0,61	38
Collu-vium	95%	-0,29	-0,29	-0,27	-0,34	-0,48	-0,46	0,07	0,05	0,07	0,06	-0,03	-0,08	-0,14	-0,45	0,23	0,06	81
	98%	-0,30	-0,24	-0,31	-0,30	-0,51	-0,50	0,07	0,03	0,02	0,00	-0,14	-0,19	-0,26	-0,54	0,36	0,15	82
	100%	-0,31	-0,26	-0,32	-0,31	-0,54	-0,53	-0,04	-0,09	-0,09	-0,11	-0,23	-0,25	-0,33	-0,58	0,43	0,16	81
Non-Plastic	95%	-	-	-	-	-	-	-0,11	-0,16	-0,19	-0,23	-0,25	-0,23	-0,18	-0,16	0,22	0,12	103
	98%	-	-	-	-	-	-	-0,23	-0,33	-0,36	-0,41	-0,44	-0,41	-0,31	-0,17	0,38	0,14	113
	100%	-	-	-	-	-	-	-0,18	-0,29	-0,34	-0,39	-0,42	-0,40	-0,29	-0,15	0,35	0,12	113

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; n = number of samples

have the best correlations with the CBR. Certain material groups have better relationships for selected properties other than these. It is also clear that there are little differences in the trends related to density (as would be expected) and no obvious strong trends related to climate.

4.8 Derivation of CBR Prediction Models

After the principal component analyses were completed for each of the material groups, the results were examined to obtain an indication of which parameters showed a stronger correlation within the group of parameters and with the CBR values. Once certain parameters were identified, existing empirical formulae (section 2.8) were applied and results compared to establish if any of the existing formulae proved promising for the datasets developed. For each material group focus was placed on formulae that contained parameters proven to be influential (by the principal component analysis) for that group; however, all of the remaining formulae and parameters were also tested.

After comparing all the existing models, it was found that most of the models showed no potential for accurate prediction using the compiled datasets. This was based on a comparison between the mean measured CBR and the mean predicted CBR, the argument being that a fairly accurate model would deliver a mean CBR close to that of the mean measured CBR. A decision was taken to retain the method of Kleyn (1955) for further comparisons, as the method is still used in the South African context. As a result the empirical equation (Eq 2.6) of Kleyn's (1955) method as derived by Stephens (1988) was included for further comparisons. In addition, it was attempted to use the same model and parameters used by Kleyn (1955) – i.e. the plasticity index and grading modulus – to develop modified models based on his model. The exception was that the model would be derived for individual material groups in an attempt to adjust the model to specific material groups and that it would be derived by a linear regression.

4.9 Weibull Regression

4.9.1 Model Selection and Description

Initial prediction models were derived with stepwise, linear regressions. However, Dr Sonali Das (2008, personal communication, CSIR, Pretoria) pointed out a fundamental flaw in that neither variables nor the predicted value (CBR) were linear functions, based on frequency distributions. Taking only CBR values as an example, normal frequency distributions were not encountered (refer to Addendum A). Such a normal distribution commonly indicates linear data. As such, the linear regression is not strictly applicable to predict the models considering the nature of the data. After trials considering the Probit regression, the method was also abandoned because it is not suitable for the task at hand.

Considering the variability of the predicting parameters and the predicted CBR values, as well as the ranges of the parameters (in conjunction with the nature of respective tests used to determine the parameter values), Dr Das (2008, personal communication, CSIR, Pretoria) recommended the use of the Weibull Regression. The method is commonly used in so-called survival analysis and reliability engineering. Weibull (1951) emphasised the flexibility of the model in application to natural and biological fields. The model can represent a normal or exponential function, with the conditions that the function (or variables) have to be positive and non-decreasing (Weibull, 1951).

The method proposed by Weibull (1951) is ideal for analysis of the project data for a number of reasons:

- It is clear that the data (and hence any predicting model) is not necessarily linear.
- Apart from the first statement, little else is known concerning the models to be derived, particularly with regard to its nature (e.g. logarithmic distribution). Hence a method is required which is flexible enough to“adjust” to the data.
- All parameters have positive values ranging between zero and 100, with the exception of the shrinkage product and linear shrinkage product, which both have maximum values exceeding 100.

4.9.2 Data Manipulation

Prior to performing the Weibull regression a number of matters needed to be addressed. These data modifications were made in duplicate datasets formulated specifically for input into the Statistical Analysis System (SAS® 9.1) package and are not reflected in the master dataset given in Addendum C. The following applies:

- No Modification: Certain parameters were retained from the original data without any alterations or modifications. These parameters include the Atterberg Limits (liquid limit, plastic limit and plasticity index), the linear shrinkage, linear shrinkage product, shrinkage product, dust ratio and grading modulus.
- Grading Coefficient: The grading coefficient was calculated by standard procedure, i.e. grading was normalised to 100% passing the 37,5mm sieve.
- Grading: Grading was normalised to 100% passing the 37,5mm sieve. This was done bearing in mind the size and common particle sizes of the foundation indicator sample.
- Grading Analyses: Cumulative grading compositions proved problematic due to a lack of degrees of freedom in the regression procedures. The problem was ultimately identified to be related to the decreasing percentages of material passing the grading sieves, a condition prohibited by the Weibull method (Weibull, 1951). This decreasing relationship was eliminated by calculating the actual percentage of material retained on each sieve, as opposed to the cumulative percentage passing through it. Table 4.9 illustrates an example of how the decreasing percentages are removed.
- Normalised CBR values: Considering the fact that the CBR classification is in fact a comparison with existing standards, all CBR values exceeding 100% were accepted as having a value of 100%. This was done simply because any CBR value exceeding 100% is probably fairly meaningless with regard to further classifications (e.g. COLTO). In fact, the COLTO system only considers CBR values up to 80% in its classification.

Table 4.9 Decreasing Grain Size Distribution and Grain Size Retention on Sieves

Sieve Size (mm)	**37,5**	**26,5**	**19,0**	**13,2**	**4,75**	**2,0**	**0,425**	**0,075**
% Passing	100	97	91	88	67	50	34	26
% Retained	0	3	6	3	21	17	16	8

- Included Parameters: All parameters were included in the initial regression, even where parameters are derived from the products of included parameters (e.g. the linear shrinkage product was included even though both the linear shrinkage and P075 constituent were also included). The implications of this are discussed later.
- Handling non-plastic materials: It should be noted that non-plastic materials resulted in a number of the properties having values of zero. This affected the distribution of the data significantly. The results tended to be bimodal with a peak at zero.

4.9.3 Parameter Identification by Weibull Regression

After entering data of each material group (at respective densities and climatic groups) into SAS® 9.1, the Weibull regression was performed and a frequency distribution of CBR values produced (to verify the distribution characteristics). Initial results indicated basic information (e.g. number of observations read and used), along with a logarithmic likelihood, which can be viewed as an overall indication of the goodness of fit (subject to the number of observations read).

After the initial regression, progressive results and subject knowledge were used to continuously refine each model with parameters indicated to be significant by the regression and parameters deemed important by the author. The aim was to reduce the number of predicting parameters to between two and five, but still retaining the best regression results.

As mentioned in section 4.9.2 all parameters were initially included, despite interdependency. It was often encountered that interdependent parameters were eliminated by the regression itself during progressive refinement (i.e. one parameter becomes less significant as the model is refined and is eventually discarded). The same applies to parameters conveying similar or correlating properties (e.g. grading modulus and grading coefficient; Atterberg Limits). Where this was not the case, one parameter was removed manually.

Two parameters that required special attention during the regression refinement were the linear shrinkage product and shrinkage product. On more than one occasion both parameters remained significant to the model well into the refinement process. In such an instance the remaining grading parameters were considered before eliminating one or the other. For example, if the linear shrinkage product, shrinkage product and r075 constituent (the constituent retained on the 0,075mm screen) remained significant to the model, the linear shrinkage product was excluded. Though the linear shrinkage is a product of the P075 constituent and not the r075 constituent, interdependency remains. The reasoning behind this is that keeping the linear shrinkage product in the model whilst the r075 parameter is included, may result in a "double error". Removing the linear shrinkage product and rather retaining both the shrinkage product and r075 constituent results in more predicting parameters with less interdependency and hence a lower risk of error. The inclusion of the linear shrinkage, linear shrinkage product and shrinkage product in the same model was also scrutinised and ultimately prohibited. Similar approaches were applied to the parameters such as the dust ratio and Atterberg Limits.

Results obtained from the Weibull regression proved inconsistent and highly variable, though this will be discussed in more detail later. After extensive analyses, comparisons and discussions with Dr Das (and in turn with her colleagues), it was concluded that the poor results could not be ascribed to the model, but rather to the highly variable data.

4.10 Linear Regression

After achieving variable and inconsistent results from the Weibull regression it was decided that based on the variability, the linear regression method should not be excluded from consideration. As a result a linear regression was performed on each of the material groups at respective densities and different climatic regions. Considering the problems identified related to cumulative percentages in the grading analyses as described in section 4.9.2, the percentages retained on individual sieves were used, rather than percentages passing the sieves. Identical datasets analysed with the Weibull regression were entered into SPSS® 15.0 and subjected to linear regressions. Whereas the Weibull regression was continuously refined, the linear regression was not. All parameters were entered into the regression as the stepwise regression eliminates insignificant parameters by processing. Consequently some parameters showing similarity (e.g. linear shrinkage and shrinkage product) may be included in one equation, where this was avoided with the Weibull regression.

4.11 Model Derivation Procedure Summary

After initial analyses it became evident that predicting models (Weibull and linear regressions) produced variable results. The data ranges analysed were therefore revised based on practical application:

- Moist Areas: The CBR classification range considered for the COLTO classification for selected natural gravels (G6 to G9) was applied to the CBR ranges to be predicted in moist areas. As such, CBR values between 7% and 25% were considered for regression and prediction. CBR values of less than 7% (i.e. materials poorer than G9) were excluded as CBR values between 1% and 5%, in particular, were found to be highly inconsistent.
- Dry Areas: The same range of CBR values was initially considered for materials from dry regions; however CBR values from the dry regions are considerably higher than those from moist areas. This resulted in insufficient data for (sensible) regressions. As such, the range of CBR values considered

for dry areas was increased from 25% to 50%; hence CBR values between 7% and 50% were considered.

After derivation of the empirical formulae, the predicted values of each model (Weibull regression model, linear regression model, Kleyn's model and adapted Kleyn model) were plotted against measured CBR values. In addition, residual values were derived by subtracting the estimated CBR from the measured CBR. These residuals were used to calculate the mean square prediction error (MSPE). This measure of error was used as it allows direct comparison between the four models, but was not used as the sole decisive factor when selecting the most suitable model for each group. Figure 4.1 illustrates schematically the procedure followed in deriving the most suitable empirical prediction equation for individual material groups.

Model verification consists only of derived confidence intervals, as the restricted ranges of CBR values used resulted in availability of little (previously unused) data for verification. The confidence intervals were set at 95%. The method proposed by Kleyn (1955) does not include confidence intervals, though, but all derived equations have these intervals included.

An example of the entire derivation process for one material group is included in Addendum B. The example given contains results that include two models that have similar MSPE values. This model was specifically selected to illustrate the approach used when results are too close to select a model based only on the MSPE. This is vital, as the MPSE only considers the mean of residuals and not e.g. the predicted range of a model.

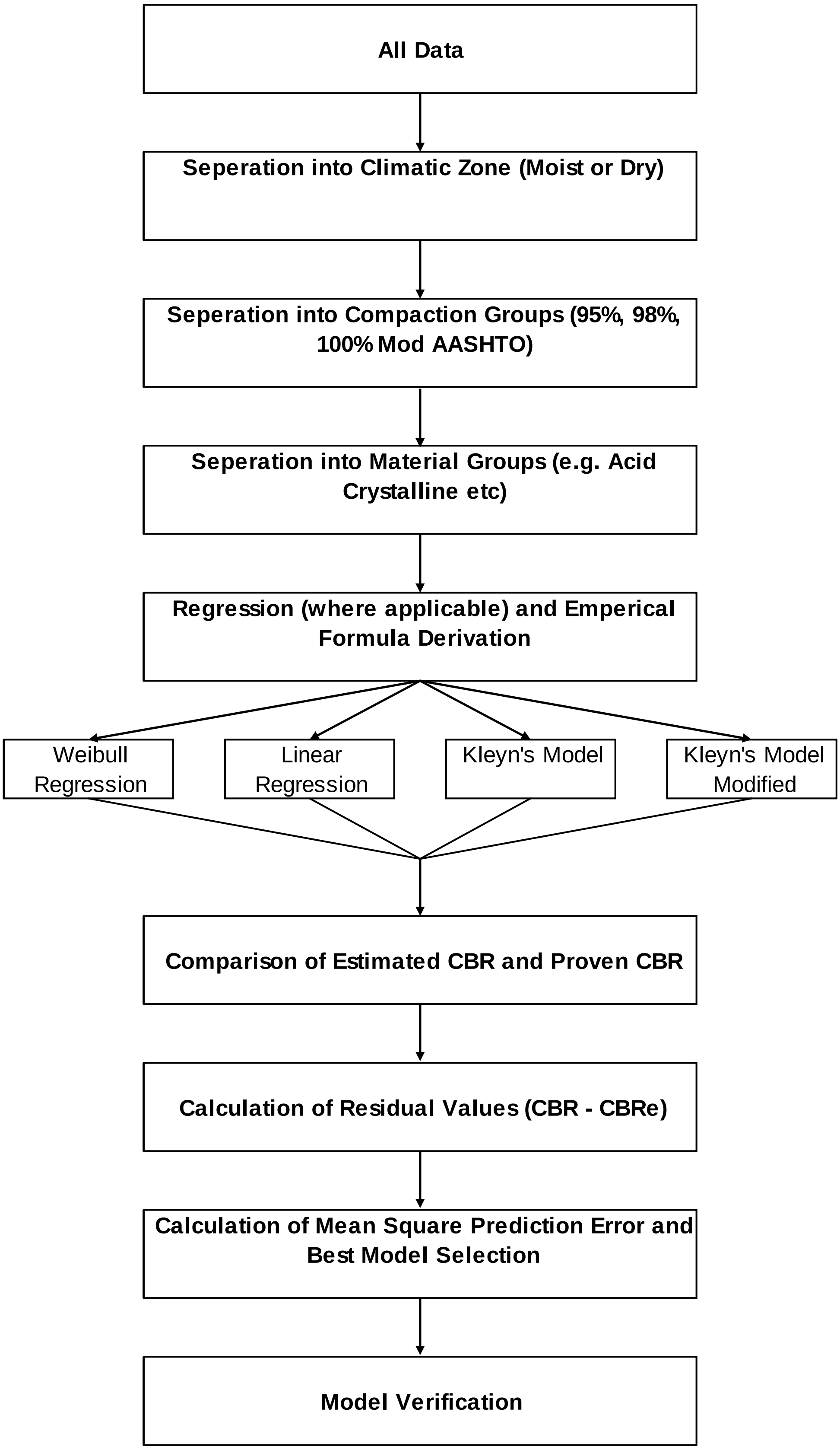

Figure 4.1 Schematic Model of Model Derivation and Selection

5. Discussion

The purpose of this project is to develop a model(s) that will allow the prediction of the CBR of materials from index test results. Hence, certain parameters (e.g. maximum dry density, optimum moisture content etc.) were not considered in the analyses. In addition, as the material test results were almost exclusively from natural gravels, it must be anticipated that the results are likely to address materials of natural gravel quality only (G4-G10), as crushed stone samples may not necessarily be included in the data. Crushed stone typically, however, would not require the estimation of the CBR as it would be expected to exceed the normal minimum of 80% for base course materials. Crushed stone would also usually be non-plastic or slightly plastic at worst.

5.1 Test Methods

As the predicted CBR depends so much on the quality of the test results, it is considered necessary to discuss some of the background and implications of the test methods that influence the predictions.

5.1.1 CBR Reproducibility

The CBR test is notorious for its poor repeatability and reproducibility. An example of this was observed whilst collecting and entering data, where a single sample was compacted to the same compactive effort on two occasions (with an identical test). While most of the other parameters (e.g. plasticity index, etc.) correlated closely, the first CBR value measured could be up to ten times greater than the second. This clearly illustrates the significant challenge posted by the repeatability and reproducibility of the test. This was also confirmed by a discussion with Mr Dave Ventura (2008, personal communication, CSIR, Pretoria).

The implications of the problem have far-reaching consequences, not only for testing, but also for real-life project economics and road quality. Consider the following two scenarios for the example described above:

- The first (higher) CBR value is caused (for arguments' sake) by a 19,0mm diameter piece of gravel directly beneath the penetrating piston. This may result in a higher CBR than would be obtained on the matrix. Hence, the material is in reality considerably weaker than indicated by test. If this CBR value is considered for design, it could result in under-performance of the material and possibly subsequent premature failure or poor road performance.
- Should the second (lower) CBR value be considered to be true whilst it is not representative of the material (e.g. due to low or improper compaction), the strength of the material may be considered to be too poor. Such a material may then possibly be rejected for use and other materials imported at a higher cost due to underestimation of the gravel quality.

Considering the repeatability and reproducibility issue, it would therefore be ideal to conduct multiple penetrations at the same compactive effort for each sample and determining an average CBR value. However, practice at most commercial laboratories is to conduct between three and five CBR tests at different compactive efforts (95%, 98% and 100% Mod AASHTO densities) and extrapolate the results to give the CBR strengths at 100%, 98%, 95%, 93% and 90% Mod AASHTO density. The amount of material required for such testing consumes nearly the entire CBR sample (sometimes even the sample supplied is insufficient in volume – this will be discussed separately). Simply stated, to conduct three CBR tests at a single compactive effort to derive an average CBR value would require a sample three times larger to supply enough material. One could however loosen and recompact materials already used (provided the preparation and testing does not cause excessive degradation of the material) and penetrated again, though this is not recommended. In addition, such testing would be three times as costly and time-consuming.

5.1.2 CBR Testing Methods

Two aspects need to be considered regarding CBR testing methods. Firstly, it seems that practical limitations in industry often necessitate laboratories to improvise during testing. One common problem includes insufficient material quantities being supplied for testing. In such instances laboratories would then re-use material already tested, i.e. after compacting and penetrating a mould, the material is broken apart (loosened), recompacted to the next density and penetrated again.

It must be considered that depending on the material type and strength, certain material particles are likely to break under compaction (e.g. brittle or slaking shale or sandstone gravel). If such a sample is then loosened and recompacted for an additional test, the properties of the sample are likely to have been altered; hence a direct comparison would not be truly representative.

Observations have been made on visits to a number of commercial laboratories. For the most part, laboratories visited in large metropolitan areas (e.g. Pretoria) seem to comply with the requirements of the test methods. Two SANAS accredited laboratories visited, in particular, were found to follow test procedures diligently and comprehensively. The commercial laboratories commonly compile weekly schedules based on the number of samples that require soaking. In general, soaking is scheduled to coincide with weekends to optimise time usage. It also appeared that the laboratories visited had well-trained and diligent staff, executing the test procedures with consistency.

A different scenario was observed elsewhere at some of the smaller laboratories. At one laboratory, it was noted that CBR samples were simply compacted by a laboratory assistant taking no cognisance of the specified falling distance of the compacting hammer. This leads the author to have serious doubts about the results produced by the laboratory, as well as the laboratory’s competence with any other type of sample testing.

The second aspect to consider regarding the CBR test, concerns grading. The CBR test currently also produces a certain bias regarding the grading. The existing test method requires any particles retained on the 19,0mm sieve to be lightly crushed to pass the 19,0mm sieve. Theoretically this results in an underestimation of the material's true CBR value, as in most cases, the larger particles provide the strength to the material. Hence, by removing coarser particles – or crushing them to comply with the test specification – the strength of the material may be under-estimated. Also, the crushing results in a modified grading that does not necessarily represent the sampled material correctly. It should be noted that the underestimation of strength is more acceptable than overestimation in the context of pavement engineering.

5.1.3 Atterberg Limits Determination

With regard to Atterberg Limits, results may vary considerably from laboratory to laboratory or between individuals conducting the tests. This is because the Atterberg Limits are strongly operator-dependent, particularly the plastic limit. At local laboratories it was observed that only a few individuals determined the Atterberg Limits. The values determined are, however, subject to the operator's experience, which results in poor reproducibility.

When considering the Casagrande test used for South African determination of the liquid limit (TMH 1, 1986) and the cone penetrometer used for British Standard testing (BSI, 1990), the penetrometer is likely to deliver more reliable and reproducible results. The results obtained from the penetrometer test are dependent on the shear strength of the material tested (BSI, 1990) and are therefore less susceptible to any bias introduced due to operator influence or interpretation. A limited bias may still prevail due to variable material preparation by the operator, though such a bias is limited by the use of preparation guidelines.

It has been clearly shown that the material preparation of calcretes can affect the Atterberg limits. Oven drying of the materials reduces the liquid limit compared with materials that have only been air-dried (Netterberg, 1978b). Though no evidence of similar testing could be found for ferricrete materials, there is a possibility that a similar effect may occur, though this can not be substantiated.

5.1.4 Grading

Correlating foundation indicator tests with CBR tests is subject to a practical bias, with reference to sample sizes. Given the purposes of the foundation indicator and CBR tests, the samples selected for testing vary accordingly – specifically in size. This presents yet another bias: When gathering a CBR sample, the material is generally loaded by shovel and particles of all sizes are included as the sample itself is large. With foundation indicator samples, however, a considerably smaller sample is taken. As a result, the sampler would often not include larger particles such as coarse gravel or pebbles, much less any material deemed as "over-sized" by CBR guidelines. It must therefore be anticipated that the foundation indicator samples may be biased toward focussing on the finer constituent of the materials – the primary purpose of foundation indicator testing. This biased grading has a direct influence, for instance, on the grading modulus, and as such should be normalised to 100% passing the 37,5mm sieve to allow direct comparisons (Paige-Green, 1999). It is therefore clear that the grading modulus, which is an important parameter in many of the empirical systems tested, may not correlate truly with CBR prediction, unless handled in a standard manner.

On the opposite end of the size scale, the influence of fine particles, particularly silt and clay, can influence also analysis. A presentation delivered by Prof P Savage at a course on compaction (13 March 2007, Kempton Park) included a discussion of an experiment he conducted. According to Savage a compacted sample of montmorillonite clay was allowed to soak in a water bath. After eighteen months the sample was removed from the tub and broken open. Even after this extended period of soaking, the sample was apparently not fully saturated to the core. Though it is very unlikely that such a sample of clayey material would be considered or tested for road layer works, it gives a clear indication of the influence that significant clay content can have on limiting the saturation effect of the four day soaked CBR test. Also, elevated levels of finer constituents, particularly clay minerals, would mostly result in an increase in the plasticity index. An increase in the plasticity index reduces the material classification according to e.g. the COLTO G-class system. Despite this, research has been done on the CBR prediction of clay materials (Stephens, 1992).

5.1.5 Scale Effect

A scale effect needs to be considered when interpreting CBR results. It is essential to keep in mind that the moulds used to compact the CBR samples result in confinement of the materials during and after compaction. Materials situated in-situ (as tested by e.g. the plate load test) are not confined by a rigid boundary such as the CBR mould to the same extent and as such, some lateral or shear movements can occur. The effect of compaction and confinement must therefore also be considered when analysing CBR properties in terms of Coulomb's Law or when using Mohr circles to estimate soil strengths. The Iowa bearing value (section 2.6), which uses a smaller mould than the South African standard, is likely to have results that are even more biased as a result of the scale of the test.

Considering the point above, it is therefore likely that the scale bias of the CBR test results in an over-estimation of material strengths compared with the true, in-situ conditions. However, even though a plate load test is likely to be more representative of in-situ conditions, the practicality of conducting numerous such tests needs to be considered. Also, CBR samples can easily and rapidly be extracted from depth when conducting a test pit survey, whereas it may prove challenging (and costly) to erect the plate load test apparatus to conduct testing at the required depth and at multiple locations.

5.1.6 Other Factors

Many researchers and practitioners feel that the CBR test is outdated, insufficient, inadequate or incomplete. One such researcher is Savage (2008), who feels that alternative aspects and methods should be considered. Savage (2008) emphasises the influence of particle interlock and porosity as indicators of materials' road building properties and also compares their advantages over conventional CBR testing (e.g. damage to existing layer works during remedial centre line investigations, etc.). The reference to particle interlock was discussed by Croney (1977) on the basis that such interlock provides strength to non-plastic materials. Despite the in-depth discussion and thorough motivation of the theory behind such a method, no evidence of application in industry has been found, which suggests that the method has not yet been attempted or accepted in practice.

Simultaneously Sezer *et al* (2008) investigated the correlation between the fractal dimensions of (uniform) sands and the bearing strength, as determined by the CBR test. The authors state that factors such as the particle shape, size and grain properties are pivotal in determining the strength or bearing capacity of soils. Although the research conducted by Sezer *et al* (2008) can not be directly compared with the current research (due to the aim and scale of materials considered), it is interesting to note that a number of points raised have been echoed, though not substantiated in practice, by Savage (2008).

5.2 Materials

5.2.1 General Material Properties

This section highlights certain material properties that have an influence on the material strength. Individual material groups are discussed at a later stage. The specific materials discussed here exhibit particular characteristics or properties that require careful consideration when attempting to draw general conclusions.

- Igneous rocks that have weathered chemically (decompose) often contain strong, competent gravel clasts but also residual clay constituents. These materials have often been found to develop favourable CBR results, but are classified as poor materials due to the clay constituent which produces inadequate plasticity indices. To illustrate the point, consider a moderately weathered dolerite material in a moist environment: although the material may have competent gravel clasts with acceptable crushing values, it will also contain typical clays found in residual dolerites. A CBR test alone may produce an acceptable result. Regardless of the strength of the dolerite rock clasts, it is the plasticity index of the residual clay that would result in its ultimate classification (e.g. COLTO G-class) where the plasticity index plays a pivotal part in the classification.

- A second important consideration, involving igneous materials particularly, is the degree of weathering. Considering dolerite as an example again, many unweathered dolerites are generally considered ideal, strong materials for road construction. However, the further chemical weathering (decomposition) proceeds, the larger the variability of the material properties becomes. Theoretically, in such a scenario the plasticity index will increase as decomposition continues. Hence, the degree of decomposition (and in fact clay content) in igneous materials requires careful consideration and the materials should not merely be accepted for use based on their geological and/or geotechnical classification.
- Certain sedimentary materials, such as shale and mudstone, are susceptible to slaking (Venter, 1989). Such materials are considered to be non-durable when used in roads. This often leads to misconceptions regarding the material, as it may yield acceptable results when sampled and tested. However, after exposure to the elements (moisture and temperature variations in particular), the material begins breaking down physically and the cementation and lithification is lost. This results from dissolution of cementing materials or loss of physico-chemical bonding (e.g., van der Waals forces etc.). Once the material has weakened, the additional traffic stresses accelerate the material's breakdown by disintegration. Consequently, premature failure or poor performance ensues.
- Conglomerate, breccia and tillite deserve distinction from other materials as well. These materials may display highly variable constituent sizes that may vary over short distances, depending on the original depositional environment or mode of genesis. For example, consider conglomerate: the material may occur as matrix-supported, gravel-sized clasts hosted in a very fine matrix at one location. However, at another location it may be encountered as clast-supported, pebble-sized clasts in a sandy matrix. The example points out that even though both materials are conglomerate, they may have totally different characteristics. Based on grading and the Atterberg Limits of the matrix, its behaviour will vary significantly. These materials are therefore too variable to

include in the analysis under one grouping and would likely require further subdivision and a large number of samples (which were not obtained during data collection for the research at hand).

5.2.2 Material Groups

As previously discussed, all the samples obtained were grouped according to climatic region and material type using the scheme proposed by Weinert (1980). It must be emphasised that not all materials comprising the groups could be obtained e.g. test results on basalt and andesite were commonly found amongst the data obtained, however phonolite, another basic crystalline material, for instance was never indicated.

Another factor to be considered is that an accurate in-situ field identification of geological materials often proves difficult. In some regions, for example, it may prove difficult to distinguish non-amygdaloidal basalt from slightly weathered dolerite when the geological setting is not known. Also, accurate material identification and classification often requires the results of mineralogical analyses, a procedure not routinely used during the investigation of road construction materials. Nevertheless, the material groups can generally be distinguished on site by visual sample identification e.g. granite vs. dolerite. As a result, if non-amygdaloidal basalt was indeed mistaken for dolerite during sampling, the implications for this research are not too severe as both materials are analysed as part of Weinert's basic crystalline material group.

Experience has also shown that the rock identification skills of many involved in material sampling is basic at best and incorrect classification is frequently encountered. This even extends as far as classifying the materials within incorrect groups according to Weinert's classification. Instances have been encountered in industry where (technical) individuals could not distinguish between shale and dolerite.

5.2.3 Material Sources

The data used for this research were obtained from sources that involved purpose-specific sampling. As a result, many of the sample results used came from material targets (e.g. existing or proposed borrow pits) that are not necessarily representative of all natural materials. The same applies to materials extracted from existing layer works (e.g. centre line surveys for rehabilitation projects). As a result the data analysed can to a certain extent be considered as "idealised" or slightly biased information; however this does not mean that less ideal materials are not included at all, particularly as the results include random borrow materials for potential use in fills, selected layers, sub-grades, sub-bases and bases.

5.3 CBR Prediction Model Derivation

This section contains a general description of the models derived by four methods (for individual material groups). The four methods include the Weibull regression, the existing Kleyn (1955) model, a model developed by linear regression based on Kleyn's method (from this point referred to as the adapted Kleyn model) and a model developed by a stepwise, linear regression. For the final analysis more than 130 regressions were done, including the Weibull, linear and adapted Kleyn (linear) model derivations. The methodology followed in deriving the models are described in section 4.11 and a worked example is included in Addendum B. When analysing the models the following must be considered:

- The number of samples used in model development for each group is indicated in each discussion. In some instances the data available was not substantial enough to permit a regression. On other occasions regressions proceeded to completion but with limited samples. In general it must be considered that the fewer samples used to derive a model, the less likely it is to be representative.
- A number of linear regressions did not proceed to completion. This was particularly true for non-plastic groups. This is not necessarily ascribed to insufficient data, but may be due to the fact that there simply is not a predictive relationship. The fact that this occurred predominantly in non-

plastic groups is sensible, as Atterberg Limits and shrinkage related parameters were excluded from regressions for these groups.

- Considering the variability in data described in sections 4.9 and 4.10, a prevalent trend was observed in all the predicting models. This trend, which is clearly visible in residual plots, indicates that the models over-estimate lower CBR values and under-estimate higher CBR values (relative to the ranges considered in the analyses).
- The MSPE allows a direct comparison between models developed, but can not be used as the sole parameter for model selection. For example, a model can have an MSPE of zero (indicating an ideal model), but only predict a range of CBR values between 15% and 18% whilst the aim is to predict values between e.g. 7% and 25%. In general the MSPE was used (in conjunction with the mean predicted CBR) to identify the two best models which were then further analysed considering, amongst other things, the range predicted etc. It is important to note that there is a large difference in the MSPE values for groups in moist and dry settings. Where a MSPE value of zero was commonly achieved by at least one model per group in a moist region, this was not the case for models for dry regions.
- The mean CBR calculated for the adapted Kleyn and linear models were mostly identical to the mean CBR measured. In fact, all three regression models were fairly accurate in predicting the mean CBR. The Kleyn (1955) model, though, was far less accurate with regard to the mean predicted CBR calculated, as the model was not derived for the data used.
- For non-plastic materials the adapted Kleyn model used only the grading modulus as a variable, as the plasticity index was assumed to be zero.
- A number of material groups in dry regions contained insufficient data to perform meaningful regressions and analyses. This lack of data prevailed even after the included range of CBR values was increased (to 7% - 50%) from the range used for moist areas. The lack of data in dry regions is particularly pronounced in the 98% and 100% Mod AASHTO groups. This is ascribed to the fact that the majority of samples had CBR values in the excess of 50% and often in the excess of 75% at these compactions.

5.3.1 Moist Areas: 95% Mod AASHTO

A summary of predictive models derived is illustrated in Table 5.1. As the table is fairly comprehensive and self-explanatory, few points will be highlighted and discussed below.

- All groups: The adapted Kleyn model was found to be the most suitable model for the mixed materials. Whilst the linear model showed nearly the same potential and an identical predicted mean CBR, the adapted Kleyn model was marginally better.
- Acid crystalline materials: Both the adapted Kleyn and Weibull models had MSPE values of zero. The Weibull was selected as the most suitable model, though, as it became apparent during analysis that the model has smaller residual values compared than the adapted Kleyn model (i.e. the model was less variable).
- Arenaceous materials: A limited sample population for this group excluded the Weibull regression from contention. Of the remaining three models the linear model proved the most suitable.
- Argillaceous materials: The linear and adapted Kleyn models were identified as the two most suitable models for the argillaceous group. In terms of the best model, there was very little between the two models. The adapted Kleyn model was selected, though, based on MSPE values.

  Basic crystalline materials: Analysis showed that the Weibull model and adapted Kleyn model held potential for the group at hand. The adapted Kleyn model showed less scatter than the Weibull model, though, and a smaller MSPE.
- Calcrete materials: Insufficient data was obtained to do any meaningful analysis of this group.
- Colluvium: The adapted Kleyn model proved most suitable for predicting colluvial materials. A limited range predicted by the model is ascribed to the strong trend prevailing in all the models as discussed earlier.

Table 5.1 Predicting Model Summary for Moist Areas, 95% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	292	15	Weibull	CBR = Exp[log(-log(0,5)) × 0,3146 + (3,6481 – (0,0003×SP) – (0,0114×r075) – (0,8485×DR))]	14	144
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	26	38939
			Adapted Kleyn	CBR = 10,900 – (0,252×PI) + (4,635×GM)	15	0
			Linear	CBR = 30,478 – (0,010×SP) – (0,196×r075) – (14,465×DR)	15	2
Acid Crystalline	32	16	Weibull	CBR = Exp[log(-log(0,5)) × 0,3003 + (3,2393 – (0,0086×PL) – (0,0016×LSP) – (0,0548×r26,5))]	16	0
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	28	4564
			Adapted Kleyn	CBR = 8,096 – (0,297×PI) + (6,858×GM)	16	0
			Linear	CBR = 21,909 – (0,026×SP)	21	982
Arenaceous	14	18	Weibull	Insufficient Data	N/A	N/A
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	36	4765
			Adapted Kleyn	CBR = 8,750 – (0,551×PI) + (7,744×GM)	18	0
			Linear	CBR = 29,010 – (0,089×SP) + (3,385×PI) – (22,130×DR) – (3,475×LS)	18	<1
Argillaceous	50	15	Weibull	CBR = Exp[log(-log(0,5)) × 0,2944 + (2,8521 – (0,0002×SP) + (0,0017×r075))]	14	86
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	32	13899
			Adapted Kleyn	CBR = 16,832 – (0,275×PI) + (0,649×GM)	15	0
			Linear	CBR = 18,427 – (0,671×LS)	15	<1
Basic Crystalline	46	17	Weibull	CBR = Exp[log(-log(0,5)) × 0,2280 + (3,4259 – (0,0015×SP) – (0,0049×r26,5) – (0,0078×r075)]	17	14
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	28	5595
			Adapted Kleyn	CBR = 8,598 – (0,303×PI) + (7,111×GM)	17	0
			Linear	CBR = 26,857 – (0,034×SP) – (0,012×r075)	19	218

Table 5.1 Predicting Model Summary for Moist Areas, 95% Mod AASHTO (continued)

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
Calcrete	5	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Adapted Kleyn	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Colluvium	52	13	Weibull	CBR = Exp[log(-log(0,5)) × 0,3223 + (2,6954 + (0,0243×PL)– (0,0573×LS) – (0,1436×DR))]	12	26
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	18	1503
			Adapted Kleyn	CBR = 13,984 – (0,254×PI) + (1,963×GM)	13	0
			Linear	CBR = 17,181 – (7,394×DR)	13	<1
Ferricrete	56	13	Weibull	CBR = Exp[log(-log(0,5)) × 0,2608 + (2,6192 – (0,0013×LSP) + (0,0710×r19,0) + (0,0321×r13,2) + (0,0084×r425))]	13	12
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	24	6941
			Adapted Kleyn	CBR = 6,523 – (0,315×PI) + (7,482×GM)	13	0
			Linear	CBR = 6,523 + (7,482×GM) – (0,315×PI)	13	<1
High Silica	14	14	Weibull	CBR = Exp[log(-log(0,5)) × 0,3341 + (2,5398 – (0,0003×SP) + (0,0129×r26,5) + (0,1870×GM))]	13	48
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	25	4822
			Adapted Kleyn	CBR = 10,185 – (0,356×PI) + (5,653×GM)	14	0
			Linear	CBR = 6,513 + (6,483×GM)	14	<1
Non-Plastic	26	19	Weibull	CBR = Exp[log(-log(0,5)) × 0,1979 + (3,2291 – (0,0080×r475) + (0,0039×r425) – (0,0044×r075) – (0,0014×GC))]	18	3
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	41	12507
			Adapted Kleyn	CBR = 13,455 + (3,968×GM)	19	0
			Linear	CBR = 13,455 + (3,968×GM)	19	<1

- Ferricrete materials: The adapted Kleyn and linear models delivered identical prediction equations, both of which were most suitable for the ferricrete materials.
- High silica materials: The adapted Kleyn model was again chosen over the linear model, though there was very little to choose from between the two models.
- Non-plastic materials: As with ferricrete materials, the linear and adapted Kleyn models were identical.

5.3.2 Moist Areas: 98% Mod AASHTO

Table 5.2 illustrates the modelling results. The adapted Kleyn and linear models again accounted for the majority of most suitable models.

- All groups: The adapted Kleyn and linear models showed the most potential for the mixed materials. The latter had a slightly lower MSPE though, and was selected on this basis. The results are strongly influenced by the prevailing trend in the data.
- Acid crystalline materials: The adapted Kleyn model was again identified as most suitable compared with the remaining three models.
- Arenaceous materials: The limited number of samples included did not permit a Weibull regression. The linear model was chosen above the adapted Kleyn model (which has a lower MSPE) because the model has a larger, more sensible predicted range (11% to 22%).
- Argillaceous materials: The linear model was selected over the adapted Kleyn model for the same reasons explained above.
- Basic crystalline materials: The argument given for arenaceous materials holds true for the group at hand.
- Calcrete materials: As before, insufficient data was obtained for meaningful analysis.

Table 5.2 Predicting Model Summary for Moist Areas, 98% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	422	14	Weibull	CBR = Exp[log(-log(0,5)) × 0,3179 + (2,8697 + (0,0063×PL) - (0,0009×SP) + (0,1209×DR))]	14	236
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	24	37340
			Adapted Kleyn	CBR = 11,938 – (0,262×PI) + (4,079×GM)	14	0
			Linear	CBR = 14,81 – (0,010×SP) + (1,937×GM)	14	3
Acid Crystalline	51	16	Weibull	CBR = Exp[log(-log(0,5)) × 0,2686 + (3,0088– (0,0013×LSP) + (0,0439×r19,0))]	15	14
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	25	4058
			Adapted Kleyn	CBR = 6,773 – (0,028×PI) + (6,691×GM)	16	0
			Linear	CBR = 7,025 – (5,699×GM) + (0,688×r19,0)	16	<1
Arenaceous	16	16	Weibull	Insufficient Data	N/A	N/A
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	32	4024
			Adapted Kleyn	CBR = 14,635 – (0,363×PI) + (2,424×GM)	16	0
			Linear	CBR = 8,531 + (0,4200×r425)	16	<1
Argillaceous	43	16	Weibull	CBR = Exp[log(-log(0,5)) × 0,2883 + (2,6458– (0,0003×r075) + (0,1513×GM))]	15	22
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	28	6091
			Adapted Kleyn	CBR = 10,859 – (0,150×PI) + (4,349×GM)	16	0
			Linear	CBR = 17,54 + (4,218×GM) – (0,2700×LL)	16	0
Basic Crystalline	47	14	Weibull	CBR = Exp[log(-log(0,5)) × 0,2336 + (2,2649– (0,0120×PI) + (0,057×r13,2) + (0,0182×r425))]	13	3
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	26	7615
			Adapted Kleyn	CBR = 5,916 – (0,032×PI) + (4,989×GM)	14	0
			Linear	CBR = 5,6100 + (4,9160×GM)	14	<1

Table 5.2 Predicting Model Summary for Moist Areas, 98% Mod AASHTO (continued)

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
Calcrete	7	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Adapted Kleyn	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Colluvium	59	13	Weibull	CBR = Exp[log(-log(0,5)) × 0,3426 + (3,1814 - (0,0645×PI) + (0,0011×LSP) + (0,0304×r475)– (0,2122×DR))]	13	43
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	17	694
			Adapted Kleyn	CBR = 18,930– (0,429×PI) - (0,432×GM)	13	0
			Linear	CBR = 18,500– (0,424×PI)	13	<1
Ferricrete	129	14	Weibull	CBR = Exp[log(-log(0,5)) × 0,2524 + (2,5447– (0,0011×LSP) - (0,0544×r26,5) + (0,3321×GM))]	13	32
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	22	9449
			Adapted Kleyn	CBR = 10,810– (0,361×PI) + (5,781×GM)	14	0
			Linear	CBR = 16,277 - (0,024×SP) + (0,219×LL)	14	<1
High Silica	65	14	Weibull	CBR = Exp[log(-log(0,5)) × 0,3308 + (2,2819– (0,0415×r475) - (0,0112×r425) + (0,7400×GM))]	13	37
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	26	9293
			Adapted Kleyn	CBR = 16,321– (0,571×PI) + (1,863×GM)	14	0
			Linear	CBR = 18,071 - (0,617×PI) + (0,370×r19,0)	14	<1
Non-Plastic	35	17	Weibull	CBR = Exp[log(-log(0,5)) × 0,2518 + (2,6187– (0,0040×r20) + (0,0096×r425) + (0,0038×r075) – (0,0061×GC))]	16	6
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	36	13464
			Adapted Kleyn	CBR = 20,120 - (3,015×GM)	17	0
			Linear	Regression Incomplete	0	-

- Colluvium: The adapted Kleyn and linear models used nearly the same product with the plasticity index in the predictive equation. However, the adapted Kleyn model also included the grading modulus. Considering that the latter model has more than one predictor and a marginally lower MSPE, it was selected as the most suitable model for the group.
- Ferricrete materials: The adapted Kleyn model was again selected over the linear model, but is only marginally better according to the MSPE.
- High silica materials: The same argument as for ferricrete materials applies to the high silica group. The adapted Kleyn model was therefore identified as the most suitable.
- Non-plastic: Though the adapted Kleyn model showed a better MSPE than the Weibull model, the former had a very restricted predicted range. The Weibull regression was therefore selected as most suitable, with predicted values between 12% and 19%.

5.3.3 Moist Areas: 100% Mod AASHTO

Table 5.3 summarises the predictive models derived for this compaction group. The following applies to the 100% Mod AASHTO compacted group:

- All groups: Despite the adapted Kleyn model having a much lower MSPE than the Weibull model, the latter predicts a more sensible range (5% to 24%) and as such was selected as the most suitable model.
- Acid crystalline materials: The adapted Kleyn model proved most suitable for this group compared with the remaining models.
- Arenaceous materials: As before, insufficient data prevented a Weibull regression. However, the linear and adapted Kleyn models resulting from the linear regressions are identical.
- Argillaceous materials: The linear model was selected as the most suitable model for this material group, despite having a slightly larger MSPE than the adapted Kleyn model.
- Basic crystalline materials: The same reasoning discussed above applies to the basic crystalline materials and hence the linear model was also selected.

- Calcrete materials: Though insufficient data was available to perform a Weibull regression, the linear and adapted Kleyn regressions proceeded. The latter was deemed the more suitable model.
- Colluvium: The adapted Kleyn model had a MSPE of zero, whilst all other models' values were noticeably larger. The model was selected on this basis.
- Ferricrete materials: Once more the adapted Kleyn and linear models were identified as having potential. The adapted Kleyn model was selected though, and predicts values between 3% and 23%, which means the lower bound falls below the real range.
- High silica materials: The Weibull model was selected for this group, despite the fact that the adapted Kleyn model had a lower MSPE. Reasoning for this is that the Weibull model delivered a better fit and residual plot than the adapted Kleyn model. The model predicted CBR values between 7% and 34%. The point plotting at 34% was initially deemed to be an outlier, but closer analysis revealed that the sample was particularly coarse (as depicted by the grading modulus). The model may therefore possibly exclude coarse gravels, though this could not be substantiated with the data at hand.
- Non-plastic materials: The linear regression for this group did not reach completion. In addition to this, none of the remaining three models delivered satisfactory results, particularly with regard to the predicted range. Though the adapted Kleyn model was selected as the most suitable, the model only predicted CBR values between 20% and 23%, where the real values ranged from 16% to 25%.

Table 5.3 Predicting Model Summary for Moist Areas, 100% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	611	15	Weibull	CBR = Exp[log(-log(0,5)) × 0,2734 + (3,1232 + (0,0122×LL) - (0,0012×SP) - (0,4269×DR))]	14	238
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	20	14654
			Adapted Kleyn	CBR = 12,644 – (0,430×PI) + (6,538×GM)	15	0
			Linear	CBR = 24,228 + (4,121×GM) - (18,846×DR) – (0,282×PI) + (0,653×LS) – (0,143×r26,5)	18	6231
Acid Crystalline	59	16	Weibull	CBR = Exp[log(-log(0,5)) × 0,2497 + (3,6262 – (0,0754×LS) + (0,0008×r425) – (0,0129×r075))]	16	8
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	20	1010
			Adapted Kleyn	CBR = 10,314 – (0,352×PI) + (8,020×GM)	16	0
			Linear	CBR = 0,881 + (10,257×GM) - (0,417×PI) + (0,417×PL)	16	<1
Arenaceous	16	19	Weibull	Insufficient Data	N/A	N/A
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	27	1088
			Adapted Kleyn	CBR = 9,227 – (0,531×PI) + (10,239×GM)	19	0
			Linear	CBR = 9,227 + (10,239×GM) – (0,531×PI)	19	<1
Argillaceous	50	16	Weibull	CBR = Exp[log(-log(0,5)) × 0,2628 + (2,9809 – (0,0007×SP) + (0,0299×r13,2) + (0,0254×DR))]	15	14
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	22	1821
			Adapted Kleyn	CBR = 11,871 – (0,254×PI) + (5,288×GM)	16	0
			Linear	CBR = 16,742 + (3,010×GM) – (0,217×LL) + (0,616×r13,2)	16	<1
Basic Crystalline	70	15	Weibull	CBR = Exp[log(-log(0,5)) × 0,2621 + (1,5423 + (0,0123×r425) + (0,0127×r075) + (0,5281×GM))]	15	20
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	22	3397
			Adapted Kleyn	CBR = 8,374 – (0,202×PI) + (6,768×GM)	15	0
			Linear	CBR = 14,423 – (0,012×SP) + (3,541×GM)	15	<1

Table 5.3 Predicting Model Summary for Moist Areas, 100% Mod AASHTO (continued)

Material	**n**	**Mean CBR (%)**	**Model**	**Equation**	**Estimated Mean CBR (%)**	**MSPE**
Calcrete	16	13	Weibull	Insufficient Data	N/A	N/A
			Kleyn	$CBR = Exp[(((12\times GM) - PI) \div 18,5) + \ln(16,7)]$	17	325
			Adapted Kleyn	$CBR = 4,371 - (0,337\times PI) + (11,327\times GM)$	13	0
			Linear	$CBR = 19,289 - (0,023\times SP) + (1,274\times r19,0)$	13	<1
Colluvium	100	12	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,2972 + (2,9308 - (0,0387\times PI) + (0,0457\times r475) + (0,1214\times GM))]$	12	28
			Kleyn	$CBR = Exp[(((12\times GM) - PI) \div 18,5) + \ln(16,7)]$	15	672
			Adapted Kleyn	$CBR = 12,992 - (0,386\times PI) + (5,564\times GM)$	12	0
			Linear	$CBR = 55,312 + (0,021\times LSP) - (52,725\times DR) + (0,435\times PL) + (1,651\times r26,5) - (1,645\times r13,2) - (0,367\times r075) - (2,160\times LS)$	11	56
Ferricrete	199	15	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,2141 + (3,201 - (0,0345\times PI) + (0,0281\times r19,0) + (0,0165\times GC) - (0,6018\times DR))]$	15	23
			Kleyn	$CBR = Exp[(((12\times GM) - PI) \div 18,5) + \ln(16,7)]$	20	6066
			Adapted Kleyn	$CBR = 13,424 - (0,561\times PI) + (6,925\times GM)$	15	0
			Linear	$CBR = 19,792 - (0,042\times SP) + (0,059\times LSP) + (9,823\times GM) - (20,567\times DR) + (0,538\times PL) - (0,308\times LL) - (0,133\times GC)$	15	2
High Silica	94	15	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,2028 + (2,5887 - (0,045\times PI) - (0,0994\times r13,2) - (0,0055\times r425) + (0,7947\times GM))]$	15	1
			Kleyn	$CBR = Exp[(((12\times GM) - PI) \div 18,5) + \ln(16,7)]$	20	2055
			Adapted Kleyn	$CBR = 17,375 - (0,702\times PI) + (4,709\times GM)$	15	0
			Linear	$CBR = 14,614 - (0,669\times PI) - (0,614\times r26,5) + (7,819\times GM)$	15	<1
Non-Plastic	23	21	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,0992 + (3,1768 + (0,0049\times r475) - (0,1820\times DR))]$	22	6
			Kleyn	$CBR = Exp[(((12\times GM) - PI) \div 18,5) + \ln(16,7)]$	32	13464
			Adapted Kleyn	$CBR = 12,492 + (9,077\times GM)$	21	0
			Linear	Regression Incomplete	-	-

5.3.4 Dry Areas: 95% Mod AASHTO

A summary of the derived models is included in Table 5.4. The materials from dry areas appear to be even more variable than those from moist areas, with regard to statistical analyses. The following was observed in the analyses:

- All groups: The Weibull model was deemed the most suitable model for this group. The model has a MSPE of 3210, and though this is very high, it was the lowest of the four predicting models. A strong trend was observed in the model(s) and values between 17% and 38% were predicted, despite the real range being 7% to 50%.
- Acid crystalline materials: The linear model was marginally better than the adapted Kleyn model and therefore chosen as the most suitable model.
- Arenaceous materials: The adapted Kleyn model proved more accurate than the linear model, despite having the same MSPE. The former model predicted the mean CBR accurately whilst the latter model did not.
- Argillaceous materials: The adapted Kleyn model was again found to be marginally better than the linear model. The prevalent trend, however, results in a reduced predicted range (18% to 30%).
- Basic crystalline materials: Only the adapted Kleyn model showed a reduced MSPE of less than one. The other models varied in MSPE between 85 and 5602. The adapted Kleyn model was subsequently selected as the most suitable model.
- Calcrete materials: The linear, adapted Kleyn and Kleyn's (1955) models were identified as potential predictive models. All three models had an MSPE value of less than one. The linear model was ultimately selected as it predicted a less random range of values (particularly compared with Kleyn's model).
- Colluvium: The adapted Kleyn model was the most suitable predicting model for this group. The model predicted values between 15% and 35% however, restricting the effective use of the model significantly.

Table 5.4 Predicting Model Summary for Dry Areas, 95% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	448	29	Weibull	CBR = Exp[log(-log(0,5)) × 0,3357 + (3,7801 + (0,0042×PL) - (0,0014×LSP) - (0,5708×DR))]	27	3210
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	40	54984
			Kleyn Adapted	CBR = 25,501 – (0,549×PI) + (4,180×GM)	29	7543
			Linear	CBR = 49,740 – (0,038×LSP) - (27,766×DR) – (0,213×r075)	28	5797
Acid Crystalline	50	34	Weibull	CBR = Exp[log(-log(0,5)) × 0,1996 + (4,6514 + (0,0313×PI) - (0,0021×SP) + (0,0302×r13,2)– (0,5591×GM))]	33	24
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	47	8275
			Kleyn Adapted	CBR = 51,100 + (0,274×PI) - (8,956×GM)	34	<1
			Linear	CBR = 53,051 – (0,782×r2,0) – (1,026×r26,5)	34	<1
Arenaceous	46	25	Weibull	CBR = Exp[log(-log(0,5)) × 0,3808 + (3,663 - (0,0053×LSP) - (0,0266×r2,0) + (0,0184×GC))]	23	228
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	45	18900
			Kleyn Adapted	CBR = 32,105 – (1,159×PI) + (1,231×GM)	25	<1
			Linear	CBR = 23,495 - (0,095×LSP) + (0,795×r425)	27	<1
Argillaceous	131	24	Weibull	CBR = Exp[log(-log(0,5)) × 0,3617 + (3,6728 + (0,0044×LL) + (0,0149×r26,5) + (0,0044×r475)– (1,1265×DR))]	23	370
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	42	40915
			Kleyn Adapted	CBR = 16,771 – (0,357×PI) + (5,184×GM)	24	<1
			Linear	CBR = 30,546 – (0,079×LSP)	24	<1
Basic Crystalline	41	30	Weibull	CBR = Exp[log(-log(0,5)) × 0,2734 + (3,6662– (0,0578×PI) + (0,0329×r13,2))]	29	85
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	42	5602
			Kleyn Adapted	CBR = 14,520 – (1,415×PI) + (13,168×GM)	30	<1
			Linear	CBR = 38,173 – (0,044×SP) + (1,452×r13,2) – (0,927×r19,0)	36	1228

Table 5.4 Predicting Model Summary for Dry Areas, 95% Mod AASHTO (continued)

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
Calcrete	35	35	Weibull	CBR = Exp[log(-log(0,5)) × 0,1802 + (3,7015 - (0,0087×LL) + (0,0193×r13,2) + (0,0082×r2,0))]	35	8
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	35	<1
			Kleyn Adapted	CBR = 29,773 - (0,619×PI) + (6,139×GM)	35	<1
			Linear	CBR = 43,732 – (0,437×PL)	35	<1
Colluvium	65	27	Weibull	CBR = Exp[log(-log(0,5)) × 0,3311 + (3,4001 - (0,002×LSP) + (0,1015×GM))]	25	142
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	30	646
			Kleyn Adapted	CBR = 17,363 – (0,695×PI) + (10,313×GM)	27	<1
			Linear	CBR = 19,242 - (0,110×LSP) + (44,367×DR)	27	<1
Alluvium	18	38	Weibull	Insufficient Data	N/A	N/A
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	24	3538
			Kleyn Adapted	CBR = 29,180 – (0,664×PI) + (11,730×GM)	38	<1
			Linear	Insufficient Data	N/A	N/A
High Silica	51	37	Weibull	CBR = Exp[log(-log(0,5)) × 0,2167 + (3,8540 - (0,0011×SP) - (0,0034×r075))]	37	37
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	58	24091
			Kleyn Adapted	CBR = 14,456 - (0,042×PI) + (9,692×GM)	37	<1
			Linear	CBR = 27,321 + (0,94×r13,2)	37	<1
Non-Plastic	72	32	Weibull	CBR = Exp[log(-log(0,5)) × 0,2850 + (3,2579 - (0,0115×r19,0) - (0,0030×r4,75) - (0,0103×r2,0) + (0,2768×GM))]	31	135
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	51	26194
			Kleyn Adapted	CBR = 24,812 + (4,524×GM)	32	<1
			Linear	CBR = 37,833 – (0,153×r075)	32	<1

- Alluvium: The data available for the linear and Weibull regressions was not sufficient. Consequently only the adapted Kleyn and Kleyn's (1955) models were considered for analysis. The former proved most suitable and predicted CBR values between 30% and 48%. It should be noted, though, that all samples used in this group are from the same location and as such may not be representative of all alluvial materials.
- High silica materials: The adapted Kleyn model was again preferred to the linear model for this group.
- Non-plastic materials: As with the high silica group, the adapted Kleyn model proved most suitable. The prevalent trend again resulted in a restricted predicted range (28% to 37%).

5.3.5 Dry Areas: 98% Mod AASHTO

As mentioned earlier, a lack of data became more pronounced in dry regions, particularly for compactions above (and including) 98% Mod AASHTO. This is illustrated in Table 5.5 below. The group's characteristics are as follows:

- All groups: The linear and adapted Kleyn models were identified as models with potential. The adapted Kleyn model was subsequently selected. The model shows significant limitations, as it only predicts CBR values between 28% and 40%.
- Acid Crystalline materials: only thirteen samples were included in this group, preventing any sensible analysis.
- Arenaceous materials: Whilst the linear and adapted Kleyn models had a similar MSPE, the linear model predicted a slightly larger range and was selected on this basis.
- Argillaceous materials: The adapted Kleyn model proved more suitable for data from this group.
- Basic crystalline materials: Kleyn's (1955) model was found to be the most suitable model for the basic crystalline group. This is the only instance in this research where the model was selected. Though the trend observed thus far is

Table 5.5 Predicting Model Summary for Dry Areas, 98% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	252	32	Weibull	CBR = Exp[log(-log(0,5)) × 0,3068 + (3,6024 - (0,0015×LSP) + (0,0041×r425) + (0,013×GM))]	30	701
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	36	3864
			Kleyn Adapted	CBR = 30,286 – (0,691×PI) + (4,099×GM)	32	<1
			Linear	CBR = 34,778 – (0,064×LSP) + (0,173×r425)	32	<1
Acid Crystalline	13	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Arenaceous	31	27	Weibull	CBR = Exp[log(-log(0,5)) × 0,3182 + (1,8449 + (0,0496×LS) - (0,0522×r13,2) – (0,0355×r475) + (1,0787×GM))]	25	74
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	44	8864
			Kleyn Adapted	CBR = 8,285 – (0,126×PI) + (8,897×GM)	27	<1
			Linear	CBR = 7,779 + (1,528×r19,0) + (0,421×r075)	27	<1
Argillaceous	106	30	Weibull	CBR = Exp[log(-log(0,5)) × 0,2036 + (3,6721 – (0,0018×SP) + (0,1404×GM))]	29	229
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	41	13446
			Kleyn Adapted	CBR = 20,165 – (0,752×PI) + (8,151×GM)	30	<1
			Linear	CBR = 39,356 – (0,110×LSP)	30	<1
Basic Crystalline	22	34	Weibull	CBR = Exp[log(-log(0,5)) × 0,2954 + (3,6453 – (0,0036×LSP) + (0,029×r26,5) – (0,0285×r19,0) + (0,0074×GC))]	34	8
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	34	3
			Kleyn Adapted	CBR = 5,916 – (0,032×PI) + (4,989×GM)	14	9348
			Linear	CBR = 5,61 + (4,916×GM)	14	9524

Table 5.5 Predicting Model Summary for Dry Areas, 98% Mod AASHTO (continued)

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
Calcrete	15	38	Weibull	Insufficient Data	N/A	N/A
			Kleyn	$CBR = \mathrm{Exp}[(((12\times GM) - PI) \div 18{,}5) + \ln(16{,}7)]$	33	369
			Kleyn Adapted	$CBR = 59{,}201 - (0{,}223\times PI) - (9{,}995\times GM)$	38	<1
			Linear	Insufficient Data	N/A	N/A
Colluvium	50	32	Weibull	$CBR = \mathrm{Exp}[\log(-\log(0{,}5)) \times 0{,}2726 + (4{,}0807 - (0{,}0024\times LSP) - (0{,}1222\times r19{,}0) - (0{,}0054\times r075))]$	31	104
			Kleyn	$CBR = \mathrm{Exp}[(((12\times GM) - PI) \div 18{,}5) + \ln(16{,}7)]$	27	1258
			Kleyn Adapted	$CBR = 37{,}102 - (0{,}988\times PI) + (1{,}065\times GM)$	32	<1
			Linear	$CBR = 36{,}753 - (0{,}058\times LSP) - (4{,}709\times r19{,}0) + (0{,}462\times GC)$	32	<1
Alluvium	4	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
High Silica	8	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Non-Plastic	30	38	Weibull	$CBR = \mathrm{Exp}[\log(-\log(0{,}5)) \times 0{,}1728 + (3{,}6571 - (0{,}0297\times r13{,}2) - (0{,}0386\times r2{,}0) + (0{,}0293\times GC))]$	38	7
			Kleyn	$CBR = \mathrm{Exp}[(((12\times GM) - PI) \div 18{,}5) + \ln(16{,}7)]$	47	2280
			Kleyn Adapted	$CBR = 30{,}407 + (5{,}090\times GM)$	38	<1
			Linear	Regression Incomplete	N/A	N/A

less pronounced in the model, the predicted range is fairly large, ranging from 17% to 66%.

- Calcrete materials: A lack of sufficient data again prevented the inclusion of the Weibull and linear regressions. As a result the adapted Kleyn model showed the most potential.
- Colluvium: The linear model was deemed most suitable for this group, despite the adapted Kleyn model having a lower MSPE. The linear model accommodates a larger predicted range (11% to 47%) than the adapted Kleyn model.
- Alluvium: This analysis was discontinued due to insufficient data.
- High silica materials: As above, insufficient data prohibited further analysis of this group.
- Non-plastic materials: The adapted Kleyn model (using only the grading modulus) was identified as the most suitable model for this group. The model predicted CBR values between 35% and 43%, again indicating the restrictions of the model.

5.3.6 Dry Areas: 100% Mod AASHTO

Only five of the material groups had sufficient data to permit analyses (Table 5.6). Groups that had sufficient data for analysis revealed the following:

- All groups: The linear model proved the most suitable for this group. Though the model is less restricted than the adapted Kleyn model, it still only predicted values between 18% and 37%.
- Acid crystalline materials: Insufficient data prevented further analysis of this group.
- Arenaceous materials: The linear model was selected as the most suitable model for this group.

Table 5.6 Predicting Model Summary for Dry Areas, 100% Mod AASHTO

Material	n	Mean CBR (%)	Model	Equation	Estimated Mean CBR (%)	MSPE
All	160	32	Weibull	$\mathrm{CBR} = \mathrm{Exp}[\log(-\log(0,5)) \times 0,3361 + (3,3295 - (0,0063\times \mathrm{PI}) - (0,0098\times r475) + (0,2471\times \mathrm{GM}))]$	30	635
			Kleyn	$\mathrm{CBR} = \mathrm{Exp}[(((12\times \mathrm{GM}) - \mathrm{PI}) \div 18,5) + \ln(16,7)]$	35	2117
			Kleyn Adapted	$\mathrm{CBR} = 26,382 - (0,458\times \mathrm{PI}) + (5,278\times \mathrm{GM})$	32	<1
			Linear	$\mathrm{CBR} = 36,764 - (0,051\times \mathrm{LSP})$	32	<1
Acid Crystalline	6	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Arenaceous	28	20	Weibull	$\mathrm{CBR} = \mathrm{Exp}[\log(-\log(0,5)) \times 0,3611 + (2,0156 + (0,0835\times r13,2) + (0,0723\times r425))]$	27	33
			Kleyn	$\mathrm{CBR} = \mathrm{Exp}[(((12\times \mathrm{GM}) - \mathrm{PI}) \div 18,5) + \ln(16,7)]$	50	7844
			Kleyn Adapted	$\mathrm{CBR} = 0,162 - (0,414\times \mathrm{PI}) + (13,886\times \mathrm{GM})$	28	<1
			Linear	$\mathrm{CBR} = 5,628 + (1,880\times r19,0) + (0,497\times r075)$	28	<1
Argillaceous	75	30	Weibull	$\mathrm{CBR} = \mathrm{Exp}[\log(-\log(0,5)) \times 0,3528 + (3,6129 - (0,0024\times \mathrm{LSP}) + (0,1704\times \mathrm{DR}))]$	28	392
			Kleyn	$\mathrm{CBR} = \mathrm{Exp}[(((12\times \mathrm{GM}) - \mathrm{PI}) \div 18,5) + \ln(16,7)]$	40	7020
			Kleyn Adapted	$\mathrm{CBR} = 19,418 - (0,580\times \mathrm{PI}) + (8,035\times \mathrm{GM})$	30	<1
			Linear	$\mathrm{CBR} = 38,722 - (0,095\times \mathrm{LSP})$	30	<1
Basic Crystalline	10	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A

Table 5.6 Predicting Model Summary for Dry Areas, 100% Mod AASHTO (continued)

Material	**n**	**Mean CBR (%)**	**Model**	**Equation**	**Estimated Mean CBR (%)**	**MSPE**
Calcrete	8	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Colluvium	27	31	Weibull	CBR = Exp[log(-log(0,5)) × 0,2125 + (4,3385 - (0,1218×LS) + (0,0345×r475) + (0,0363×r2,0)– (0,6455×GM))]	30	13
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	25	881
			Kleyn Adapted	CBR = 33,257 – (1,265×PI) + (5,912×GM)	31	<1
			Linear	CBR = 40,717 - (2,675×LS)	31	<1
Alluvium	2	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
High Silica	6	N/A	Weibull	Insufficient Data	N/A	N/A
			Kleyn	Insufficient Data	N/A	N/A
			Kleyn Adapted	Insufficient Data	N/A	N/A
			Linear	Insufficient Data	N/A	N/A
Non-Plastic	18	40	Weibull	CBR = Exp[log(-log(0,5)) × 0,1013 + (3,6383 + (0,0395×r26,5) - (0,0764×r19,0) + (0,0079×GC))]	39	<1
			Kleyn	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	46	699
			Kleyn Adapted	CBR = 3,309 + (34,732×GM)	40	<1
			Linear	Regression Incomplete	N/A	N/A

- Argillaceous materials: The linear and adapted Kleyn models were identified as being partially suitable for predicting argillaceous materials. After further analysis, the adapted Kleyn model was selected.
- Basic crystalline materials: Insufficient data prevented further analysis of this group.
- Calcrete materials: Insufficient data prevented further analysis of this group.
- Colluvium: The linear model was chosen as most suitable for colluvial materials, rather than the adapted Kleyn model. The linear model predicts CBR values between 15% and 40%.
- High silica materials: Insufficient data prevented further analysis of this group.
- Non-plastic materials: The Weibull model was found to be most representative for this material group. As mentioned before, one outlier was encountered, but this outlier had a high grading modulus. It is therefore anticipated that the model may be restricted to finer and medium-coarse materials only. Again, this could not be substantiated with the data available.

5.3.7 Selected Model Summary

Table 5.7 and Table 5.8 summarise the models selected for individual material groups at respective compactions in the moist and dry climatic regions. From the tables it is clear that the predicted CBR ranges are often far off the actual CBR ranges. This also illustrates how poor the majority of the models are, despite having low MSPE values and mean CBR values nearly similar (if not identical) to the actual mean CBR.

It was initially intended to verify the models using data that was not included in the derivation of the models. The author's personal data collection was considered to verify models for moist regions, whilst additional data from the Namibian Roads Department was to be used for dry regions. It soon became apparent, though, that due to the restrictions imposed on the CBR ranges tested, the verification data would not suffice, either due to the quality of the material or due to the quantity of available datasets in the required range. It is necessary, though, that some measure of model reliability must be included. As such, the upper and lower confidence intervals (set at 95%) will be provided, but will be included in the next chapter. It must be noted that for regressions derived during the research these confidence intervals can be provided. However, the confidence intervals of Kleyn's (1955) model are not known and can therefore not be supplied. In addition, the range of parameters used in each selected model will also be specified with the results.

5.4 Parameters of Note

During the analyses of respective materials and consideration of different parameters, it became apparent that statistical methods often failed to identify parameters (or combinations of parameters) that proved more promising for prediction. On numerous occasions the adapted Kleyn model proved more suitable than both the linear regression and the Weibull regression. Though the adapted Kleyn models were also derived by linear regressions, the regression was forced to use the plasticity index and grading modulus. Whereas such models often proved more suitable, the associated linear regression (or Weibull regression) often did not identify either of the two parameters as variables to be considered.

Three parameters in particular were identified during data processing and regression analyses by considering descriptive statistics and correlation characteristics. It must be emphasised that the author does not suggest that the three parameters are the only significant parameters, but merely that they were notable in the given data analyses. The three parameters are the plasticity index, linear shrinkage and grading modulus. To illustrate the point to be made, the data set containing all the materials compacted to 100% Mod AASHTO density in a moist region was considered for the following discussion.

Table 5.7 Selected Models for Individual Material Groups, Moist Areas

Group	Compaction (% Mod AASHTO)	n	CBR Range (%)	Estimated CBR Range (%)	Model Type	Equation	MSPE
All	95	292	7 - 25	4 - 22	Adapted Kleyn	$CBR = 10{,}900 - (0{,}252 \times PI) + (4{,}635 \times GM)$	0
	98	422	7 - 25	5 - 20	Adapted Kleyn	$CBR = 11{,}938 - (0{,}262 \times PI) + (4{,}079 \times GM)$	0
	100	611	7 - 25	5 - 24	Weibull	$CBR = \mathrm{Exp}[\log(-\log(0{,}5)) \times 0{,}2734 + (3{,}1232 + (0{,}0122 \times LL) - (0{,}0012 \times SP) - (0{,}4269 \times DR))]$	238
Acid Crystalline	95	32	7 - 25	11 - 23	Weibull	$CBR = \mathrm{Exp}[\log(-\log(0{,}5)) \times 0{,}3003 + (3{,}2393 - (0{,}0086 \times PL) - (0{,}0016 \times LSP) - (0{,}0548 \times r26{,}5))]$	0
	98	51	7 - 25	9 - 22	Adapted Kleyn	$CBR = 6{,}773 - (0{,}028 \times PI) + (6{,}691 \times GM)$	0
	100	59	7 - 25	5 - 23	Adapted Kleyn	$CBR = 10{,}314 - (0{,}352 \times PI) + (8{,}020 \times GM)$	0
Arenaceous	95	14	7 - 25	8 - 25	Linear	$CBR = 29{,}010 - (0{,}089 \times SP) + (3{,}385 \times PI) - (22{,}130 \times DR) - (3{,}475 \times LS)$	<1
	98	16	7 - 22	11 - 22	Linear	$CBR = 8{,}531 + (0{,}4200 \times r425)$	<1
	100	16	9 - 25	12 - 25	Adapted Kleyn / Linear	$CBR = 9{,}227 - (0{,}531 \times PI) + (10{,}239 \times GM)$	0
Argillaceous	95	50	7 - 24	9 - 18	Adapted Kleyn	$CBR = 16{,}832 - (0{,}275 \times PI) + (0{,}649 \times GM)$	0
	98	43	7 - 25	7 - 20	Linear	$CBR = 17{,}54 + (4{,}218 \times GM) - (0{,}2700 \times LL)$	0
	100	50	7 - 25	9 - 22	Linear	$CBR = 16{,}742 + (3{,}010 \times GM) - (0{,}217 \times LL) + (0{,}616 \times r13{,}2)$	<1
Basic Crystalline	95	46	7 - 25	9 - 23	Adapted Kleyn	$CBR = 8{,}598 - (0{,}303 \times PI) + (7{,}111 \times GM)$	0
	98	47	7 - 25	8 - 18	Linear	$CBR = 5{,}6100 + (4{,}9160 \times GM)$	<1
	100	70	7 - 25	5 - 21	Linear	$CBR = 14{,}423 - (0{,}012 \times SP) + (3{,}541 \times GM)$	<1

Table 5.7 Selected Models for Individual Material Groups, Moist Areas (continued)

Group	Compaction (% Mod AASHTO)	n	CBR Range (%)	Estimated CBR Range (%)	Model Type	Equation	MSPE
Calcrete	95	Insufficient Data					
	98	Insufficient Data					
	100	16	7 - 24	7 - 19	Adapted Kleyn	CBR = 4,371– (0,337×PI) + (11,327×GM)	0
Colluvium	95	52	7 - 25	10 - 16	Adapted Kleyn	CBR = 13,984– (0,254×PI) + (1,963×GM)	0
	98	59	7 - 25	5 - 19	Adapted Kleyn	CBR = 18,930– (0,429×PI) - (0,432×GM)	0
	100	100	7 - 25	3 - 18	Adapted Kleyn	CBR = 12,992– (0,386×PI) + (5,564×GM)	0
Ferricrete	95	56	7 - 25	2 - 20	Adapted Kleyn	CBR = 6,523– (0,315×PI) + (7,482×GM)	0
	98	129	7 - 25	5 - 21	Adapted Kleyn	CBR = 10,810– (0,361×PI) + (5,781×GM)	0
	100	199	7 - 25	2 - 23	Adapted Kleyn	CBR = 13,424– (0,561×PI) + (6,925×GM)	0
High Silica	95	14	7 - 25	8 - 21	Adapted Kleyn	CBR = 10,185– (0,356×PI) + (5,653×GM)	0
	98	65	7 - 25	7 - 19	Adapted Kleyn	CBR = 16,321– (0,571×PI) + (1,863×GM)	0
	100	94	7 - 25	7 - 34	Weibull	CBR = Exp[log(-log(0,5)) × 0,2028 + (2,5887 – (0,045×PI) - (0,0994×r13,2) - (0,0055×r425) + (0,7947×GM))]	1
Non-Plastic	95	26	11 - 25	15 - 23	Linear	CBR = 13,455 + (3,968×GM)	0
	98	35	7 - 25	12 - 19	Weibull	CBR = Exp[log(-log(0,5)) × 0,2518 + (2,6187 – (0,0040×r20) + (0,0096×r425) + (0,0038×r075) – (0,0061×GC))]	6
	100	23	16 - 25	20 - 23	Adapted Kleyn	CBR = 12,492 + (9,077×GM)	0

Table 5.8 Selected Models for Individual Material Groups, Dry Areas

Group	Compaction (% Mod AASHTO)	n	CBR Range (%)	Estimated CBR Range (%)	Model Type	Equation	MSPE
All	95	448	7 - 50	17 - 38	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,3357 + (3,7801 + (0,0042 \times PL) - (0,0014 \times LSP) - (0,5708 \times DR))]$	3210
	98	252	7 - 50	28 - 40	Adapted Kleyn	$CBR = 30,286 – (0,691 \times PI) + (4,099 \times GM)$	<1
	100	160	7 - 50	18 - 37	Linear	$CBR = 36,764 – (0,051 \times LSP)$	<1
Acid Crystalline	95	50	14 - 50	28 - 45	Linear	$CBR = 53,051 – (0,782 \times r2,0) – (1,026 \times r26,5)$	<1
	98	Insufficient Data					
	100	Insufficient Data					
Alluvium	95	18	14 - 50	30 - 48	Adapted Kleyn	$CBR = 29,180 – (0,664 \times PI) + (11,730 \times GM)$	<1
	98	Insufficient Data					
	100	Insufficient Data					
Arenaceous	95	46	7 - 50	14 - 35	Weibull	$CBR = Exp[\log(-\log(0,5)) \times 0,3808 + (3,663 - (0,0053 \times LSP) - (0,0266 \times r2,0) + (0,0184 \times GC))]$	228
	98	31	8 - 49	16 - 39	Linear	$CBR = 7,779 + (1,528 \times r19,0) + (0,421 \times r075)$	<1
	100	28	7 - 49	20 - 40	Linear	$CBR = 5,628 + (1,880 \times r19,0) + (0,497 \times r075)$	<1
Argillaceous	95	131	7 - 50	18 - 30	Adapted Kleyn	$CBR = 16,771 – (0,357 \times PI) + (5,184 \times GM)$	<1
	98	106	8 - 50	20 - 41	Adapted Kleyn	$CBR = 20,165 – (0,752 \times PI) + (8,151 \times GM)$	<1
	100	75	7 - 49	20 - 40	Adapted Kleyn	$CBR = 19,418 – (0,580 \times PI) + (8,035 \times GM)$	<1
Basic Crystalline	95	41	8 - 50	12 - 44	Adapted Kleyn	$CBR = 14,520 – (1,415 \times PI) + (13,168 \times GM)$	<1
	98	22	12 - 50	17 - 66	Kleyn	$CBR = Exp[(((12 \times GM) - PI) \div 18,5) + \ln(16,7)]$	3
	100	Insufficient Data					

Table 5.8 Selected Models for Individual Material Groups, Dry Areas (continued)

Group	Compaction (% Mod AASHTO)	n	CBR Range (%)	Estimated CBR Range (%)	Model Type	Equation	MSPE
Calcrete	95	35	12 - 49	25 - 44	Linear	CBR = 43,732– (0,437×PL)	<1
	98	15	9 - 50	28 - 48	Adapted Kleyn	CBR = 59,201 - (0,223×PI) - (9,995×GM)	<1
	100	Insufficient Data					
Colluvium - Aeolian	95	65	8 - 49	15 - 35	Adapted Kleyn	CBR = 17,363– (0,695×PI) + (10,313×GM)	<1
	98	50	7 - 50	11 - 47	Linear	CBR = 36,753 - (0,058×LSP)– (4,709×r19,0) + (0,462×GC)	<1
	100	27	7 - 48	15 - 40	Linear	CBR = 40,717 - (2,675×LS)	<1
High Silica	95	51	9 - 50	24 - 41	Adapted Kleyn	CBR = 14,456 - (0,042×PI) + (9,692×GM)	<1
	98	Insufficient Data					
	100	Insufficient Data					
Non-Plastic	95	72	9 - 50	28 - 37	Adapted Kleyn	CBR = 24,812 + (4,524×GM)	<1
	98	30	17 - 50	35 - 43	Adapted Kleyn	CBR = 30,407 + (5,090×GM)	<1
	100	18	20 - 50	30 - 47	Weibull	CBR = Exp[log(-log(0,5)) × 0,1013 + (3,6383 + (0,0395×r26,5) - (0,0764×r19,0) + (0,0079×GC))]	<1

5.4.1 Linear Shrinkage

Figure 5.1 indicates the relationship between the linear shrinkage and CBR for the group under discussion. Though a few samples may arguably be dubbed as outliers, a clear trend can be observed, which seems compliant with the point made by Netterberg (1969). This trend indicates that (in general) high linear shrinkage values are associated with low CBR values. This is evident when considering the CBR range between 0% and 10%, which clearly illustrates elevated linear shrinkage values compared with the remainder of the CBR range. Critically, though, low linear shrinkage values (e.g. 0% to 5%) are not exclusively associated with high CBR values, i.e. low linear shrinkage values occur with CBR values between 5% and 100%. Hence, the trend observed is not mutually exclusive.

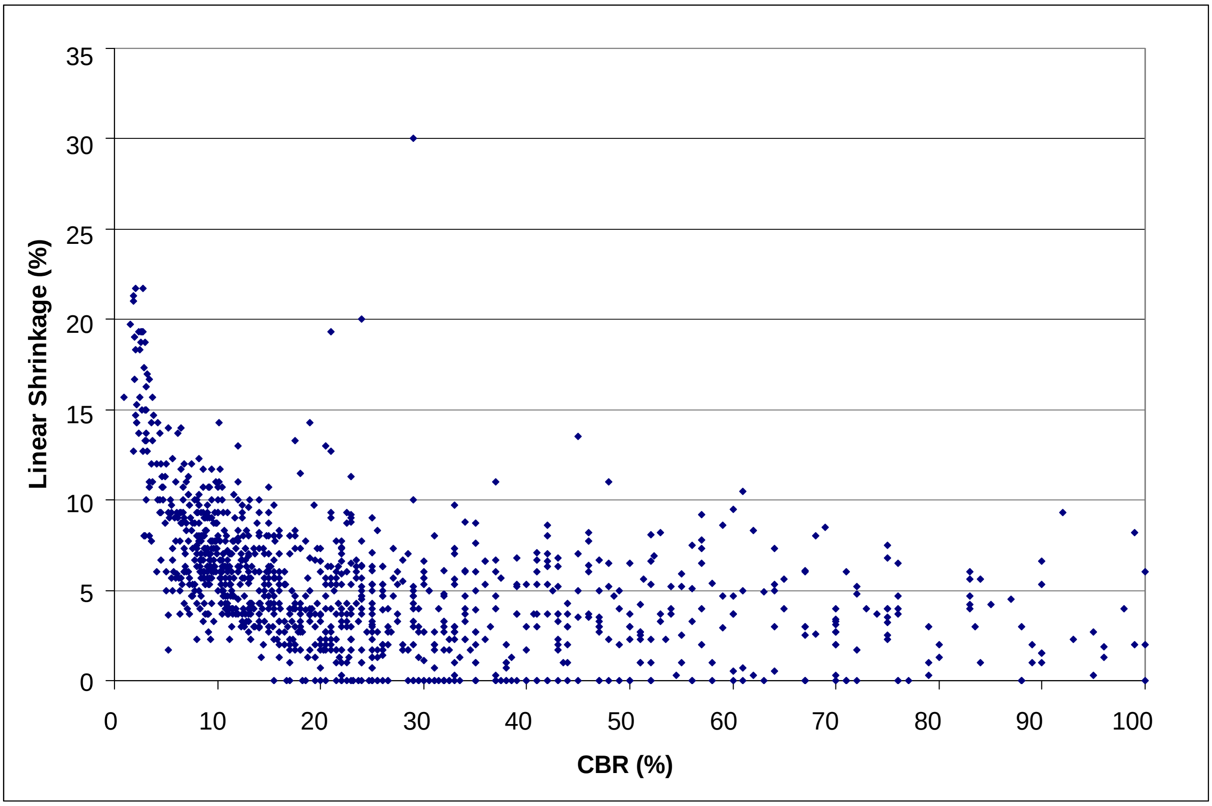

Figure 5.1 Relationship between the linear shrinkage and CBR

5.4.2 Plasticity Index

A similar trend is observed for the plasticity index, when comparing it with the linear shrinkage discussed above. Though the range of the plasticity index is greater than that of the linear shrinkage, the trend also indicates that high plasticity indices are associated with low CBR values (refer to Figure 5.2). It is also apparent that the relationship between CBR values and plasticity indices are not mutually exclusive. (Points along the base of the graph result from non-plastic materials which were awarded a plasticity index of 0%).

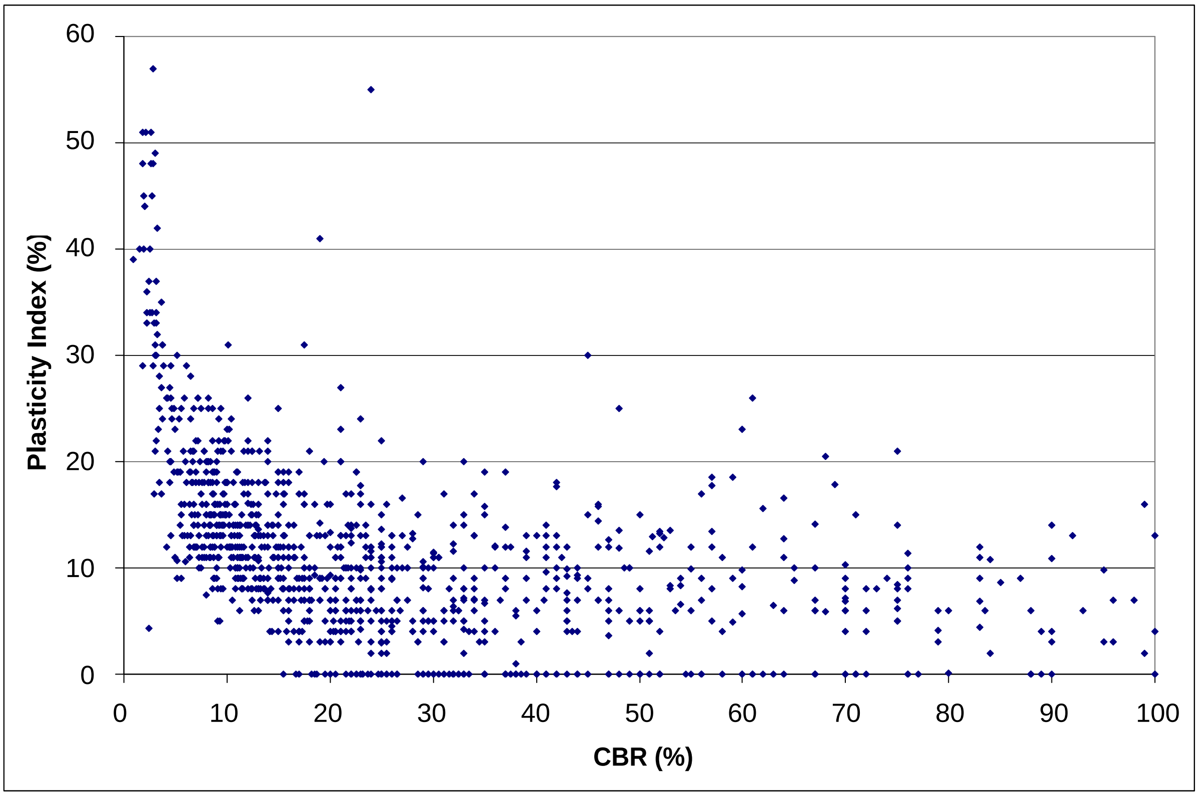

Figure 5.2 Relationship between the plasticity index and CBR

5.4.3 Grading Modulus

The grading modulus, which has long been correlated with CBR values, also revealed a particular, non-exclusive relationship with the CBR. For example, Figure 5.3 illustrates that CBR values in the excess of 60% generally have a grading modulus greater than 1,00. But once again, the relationship is not exclusive, as a number of sample with CBR values less than 10% also have a grading modulus larger than 1,00. The trend is present, though, and is worth considering (as many authors e.g. Kleyn have).

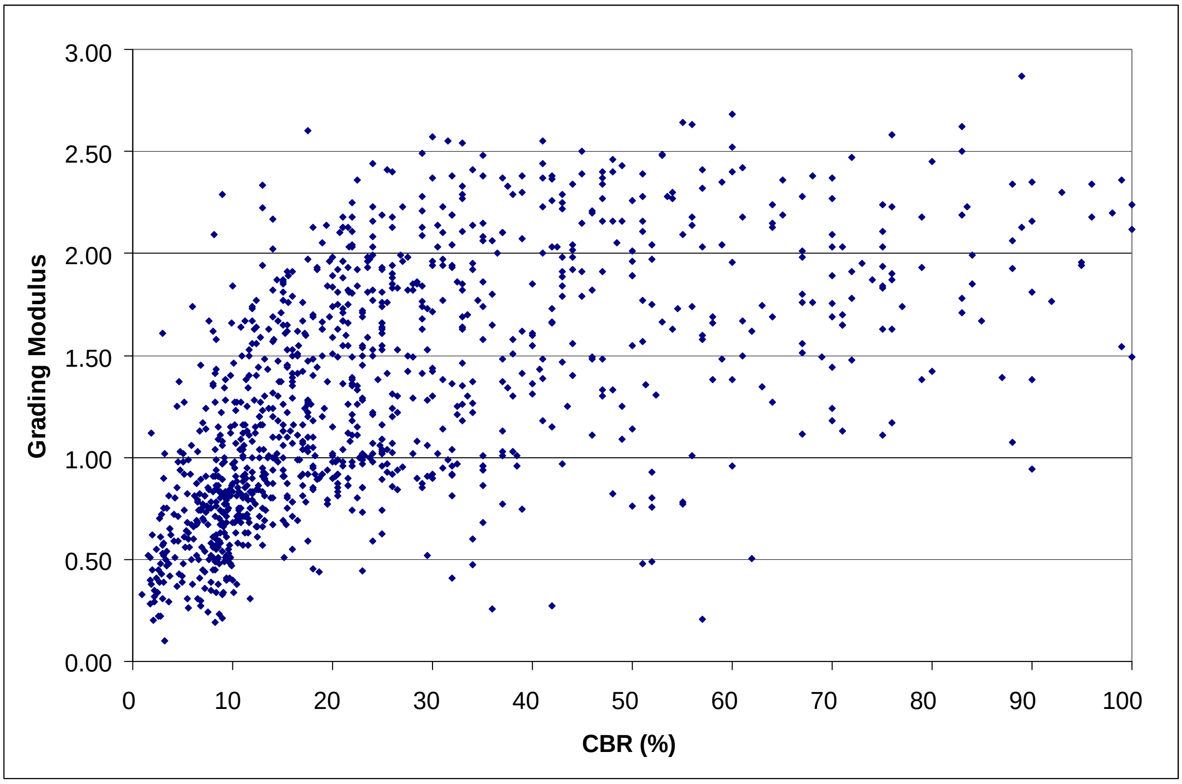

Figure 5.3 Relationship between the grading modulus and CBR

6. Results

Analyses of the existing models (discussed in section 2.8) with the data at hand indicated that none of the models was accurate in its prediction for the database created. As such none of the existing models, with the exception of Kleyn's (1955) model, were retained for further analyses. Kleyn's model was included in the empirical form derived by Stephens (1988). Although the model did not show particular potential, it was retained as it is still used in South Africa.

The aim of the dissertation was achieved, but with poor results. Table 6.1 and Table 6.2 summarise the models predicting CBR in moist and dry regions, respectively. Each table indicates the material group and compaction of the samples tested. In addition the real range of CBR values and the predicted range of CBR values are also indicated. The tables also include the upper and lower bounds (set at a 95% confidence interval) for each model, where applicable. The only model for which confidence intervals are not given, is the existing model proposed by Kleyn (1955) for which no intervals were provided. The remaining models were derived from regressions and as such, the confidence intervals are known.

By far the biggest limitation of all the models is the prevalent trend observed when analysing the data. Despite attempting to limit this trend by using smaller, selected ranges of data, the trend remained. This trend, however, is not related to statistical anomalies, but rather to test results and tests used (particularly the CBR test). Practically, the trend often resulted in severe restrictions in the predicted range of the models derived by regression. The model proposed by Kleyn (1955) and described empirically by Stephens (1988) was the exception, although this model predicted random results.

The retention of results derived by linear regressions (including the adapted Kleyn models) proved rewarding, as such models proved to be the overall best predictors. This also indicates that the statistical methods applied based on a theoretical and statistical approach, do not necessarily respond to the data as well as expected.

Table 6.1 Model and confidence interval summary, moist regions

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Equation Type	Equation	Range of Parameters	
All	95	292	7 - 25	4 - 22	**Model**	CBR = 10,900 – (0,252×PI) + (4,635×GM)	PI	0 – 55
					Upper Confidence	CBR = 12,578 – (0,167×PI) + (5,658×GM)	GM	0,17 – 2,63
					Lower Confidence	CBR = 9,221 – (0,338×PI) + (3,613×GM)		
	98	422	7 - 25	5 - 20	**Model**	CBR = 11,938 – (0,262×PI) + (4,079×GM)	PI	0 - 55
					Upper Confidence	CBR = 13,379 – (0,190×PI) + (4,975×GM)	GM	0,21 – 2,50
					Lower Confidence	CBR = 10,498 – (0,335×PI) + (3,183×GM)		
	100	611	7 - 25	5 - 24	**Model**	CBR = Exp[log(-log(0,5)) × 0,2734 + (3,1232 + (0,0122×LL) - (0,0012×SP) - (0,4269×DR))]	LL	0 – 81
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,2892 + (3,2102 + (0,0159×LL) - (0,0011×SP) - (0,2113×DR))]	SP	0 – 1288
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,2585 + (3,0362 + (0,0086×LL) - (0,0014×SP) - (0,6424×DR))]	DR	0,12 – 0,99
Acid Crystalline	95	32	7 - 25	11 - 23	**Model**	CBR = Exp[log(-log(0,5)) × 0,3003 + (3,2393 – (0,0086×PL) – (0,0016×LSP) – (0,0548×r26,5))]	PL	0 – 30
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,3921 + (3,6230 + (0,0196×PL) + (0,0003×LSP) + (0,0235×r26,5))]	r26,5	0 – 7
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,2300 + (2,8556 – (0,0369×PL) – (0,0035×LSP) – (0,1331×r26,5))]	LSP	0 – 288
	98	51	7 - 25	9 – 22	**Model**	CBR = 6,773 – (0,028×PI) + (6,691×GM)	PI	0 – 22
					Upper Confidence	CBR = 12,886 + (0,264×PI) + (10,000×GM)	GM	0,44 – 2,35
					Lower Confidence	CBR = 0,660 – (0,320×PI) + (3,383×GM)		
	100	59	7 - 25	5 - 23	**Model**	CBR = 10,314 – (0,352×PI) + (8,020×GM)	PI	4 – 25
					Upper Confidence	CBR = 14,776 – (0,109×PI) + (10,280×GM)	GM	0,38 – 2,25
					Lower Confidence	CBR = 5,852 – (0,596×PI) + (5,760×GM)		

Table 6.1 Model and confidence interval summary, moist regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Model	Equation	Range of Parameters	
Arenaceous	95	14	7 - 25	8 - 25	**Model**	CBR = 29,010 – (0,089×SP) + (3,385×PI) – (22,130×DR) – (3,475×LS)	SP PI	0 – 407 0 – 19
					Upper Confidence	CBR = 33,637 – (0,061×SP) + (4,620×PI) – (7,537×DR) – (0,615×LS)	DR	0,19 – 0,82
					Lower Confidence	CBR = 24,384 – (0,116×SP) + (2,150×PI) – (36,724×DR) – (6,331×LS)	LS	0 – 8,3
	98	16	7 - 22	11 - 22	**Model**	CBR = 8,531 + (0,4200×r425)	r425	6 – 31
					Upper Confidence	CBR = 14,147 + (0,721×r425)		
					Lower Confidence	CBR = 2,915 + (0,119×r425)		
	100	16	9 - 25	12 - 25	**Model**	CBR = 9,227 – (0,531×PI) + (10,239×GM)	PI	3 – 19
					Upper Confidence	CBR = 16,118 – (0,112×PI) + (15,451×GM)	GM	0,77 – 1,92
					Lower Confidence	CBR = 2,335 – (0,950×PI) + (5,028×GM)		
Argilla-ceous	95	50	7 - 24	9 - 18	**Model**	CBR = 16,832 – (0,275×PI) + (0,649×GM)	PI	0 – 29
					Upper Confidence	CBR = 22,419 + (0,010×PI) + (3,162×GM)	GM	0,17 – 2,63
					Lower Confidence	CBR = 11,245 – (0,559×PI) - (1,865×GM)		
	98	43	7 - 25	7 - 20	**Model**	CBR = 17,54 + (4,218×GM) – (0,270×LL)	LL	18 – 48
					Upper Confidence	CBR = 26,495 + (6,838×GM) – (0,016×LL)	GM	0,46 – 2,50
					Lower Confidence	CBR = 8,586 + (1,598×GM) – (0,523×LL)		
	100	50	7 - 25	9 - 22	**Model**	CBR = 16,742 + (3,010×GM) – (0,217×LL) + (0,616×r13,2)	GM	0,39 – 2,60
					Upper Confidence	CBR = 22,301 + (5,829×GM) – (0,069×LL) + (1,174×r13,2)	LL	18 – 58
					Lower Confidence	CBR = 11,183 + (0,191×GM) – (0,365×LL) + (0,058×r13,2)	r13,2	0 - 13

Table 6.1 Model and confidence interval summary, moist regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Model	Equation	Range of Parameters	
Basic Crystalline	95	46	7 - 25	9 - 23	**Model**	CBR = 8,598 – (0,303×PI) + (7,111×GM)	PI	0 – 55
					Upper Confidence	CBR = 13,563 – (0,130×PI) + (10,268×GM)	GM	0,68 – 2,46
					Lower Confidence	CBR = 3,633 – (0,477×PI) + (3,955×GM)		
	98	47	7 - 25	8 - 18	**Model**	CBR = 5,610 + (4,9160×GM)	GM	0,57 – 2,46
					Upper Confidence	CBR = 9,211 + (7,006×GM)		
					Lower Confidence	CBR = 2,827 + (7,006×GM)		
	100	70	7 - 25	5 - 21	**Model**	CBR = 14,423 – (0,012×SP) + (3,541×GM)	SP	0 – 913
					Upper Confidence	CBR = 19,578 – (0,006×SP) + (5,959×GM)	GM	0,41 – 2,44
					Lower Confidence	CBR = 9,269 – (0,018×SP) + (1,122×GM)		
Calcrete	95	Insufficient data						
	98	Insufficient data						
	100	16	7 - 24	7 - 19	**Model**	CBR = 4,371 – (0,337×PI) + (11,327×GM)	PI	0 -41
					Upper Confidence	CBR = 10,762 – (0,071×PI) + (17,017×GM)	GM	0,69 – 2,05
					Lower Confidence	CBR = -2,020 – (0,603×PI) + (5,637×GM)		
Colluvium	95	52	7 - 25	10 - 16	**Model**	CBR = 13,984 – (0,254×PI) + (1,963×GM)	PI	0 – 21
					Upper Confidence	CBR = 18,113 – (0,019×PI) + (5,284×GM)	GM	0,21 – 1,97
					Lower Confidence	CBR = 9,854 – (0,490×PI) - (1,359×GM)		
	98	59	7 - 25	5 - 19	**Model**	CBR = 18,930 – (0,429×PI) - (0,432×GM)	PI	0 – 31
					Upper Confidence	CBR = 23,621 – (0,221×PI) + (3,362×GM)	GM	0,21 – 1,97
					Lower Confidence	CBR = 14,239 – (0,637×PI) - (4,226×GM)		
	100	100	7 - 25	3 - 18	**Model**	CBR = 12,992 – (0,386×PI) + (5,564×GM)	PI	0 – 31
					Upper Confidence	CBR = 16,260 – (0,242×PI) + (8,012×GM)	GM	0,19 – 1,97
					Lower Confidence	CBR = 9,723 – (0,529×PI) + (3,116×GM)		

Table 6.1 Model and confidence interval summary, moist regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Model	Equation	Range of Parameters	
Ferricrete	95	56	7 - 25	2 - 20	**Model**	CBR = 6,523 – (0,315×PI) + (7,482×GM)	PI	0 – 26
					Upper Confidence	CBR = 10,409 – (0,127×PI) + (9,865×GM)	GM	0,38 – 2,06
					Lower Confidence	CBR = 2,636 – (0,503×PI) + (5,100×GM)		
	98	129	7 - 25	5 - 21	**Model**	CBR = 10,810 – (0,361×PI) + (5,781×GM)	PI	0 – 24
					Upper Confidence	CBR = 13,412 – (0,229×PI) + (7,455×GM)	GM	0,31 – 2,06
					Lower Confidence	CBR = 8,208 – (0,492×PI) + (4,106×GM)		
	100	199	7 - 25	2 - 23	**Model**	CBR = 13,424 – (0,561×PI) + (6,925×GM)	PI	0 – 26
					Upper Confidence	CBR = 15,104 – (0,480×PI) + (8,130×GM)	GM	0,30 – 2,03
					Lower Confidence	CBR = 11,745 – (0,643×PI) + (5,720×GM)		
High Silica	95	14	7 - 25	8 - 21	**Model**	CBR = 10,185 – (0,356×PI) + (5,653×GM)	PI	0 – 18
					Upper Confidence	CBR = 16,196 + (0,063×PI) + (9,162×GM)	GM	0,59 – 2,08
					Lower Confidence	CBR = 4,175 – (0,775×PI) + (2,144×GM)		
	98	65	7 - 25	7 - 19	**Model**	CBR = 16,321 – (0,571×PI) + (1,863×GM)	PI	0 – 18
					Upper Confidence	CBR = 19,805 – (0,360×PI) + (4,193×GM)	GM	0,33 – 2,29
					Lower Confidence	CBR = 12,838 – (0,781×PI) - (0,467×GM)		
	100	94	7 - 25	7 - 34	**Model**	CBR = Exp[log(-log(0,5)) × 0,2028 + (2,5887 – (0,045×PI) - (0,0994×r13,2) - (0,0055×r425) + (0,7947×GM))]	PI r13,2	0 – 23 0 – 7
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,2375 + (2,7484 – (0,0362×PI) - (0,0600×r13,2) + (0,0011×r425) + (0,9778×GM))]	r425	0 – 39
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,1731 + (2,4289 – (0,0538×PI) - (0,1388×r13,2) - (0,0121×r425) + (0,6117×GM))]	GM	0,33 – 2,29

Table 6.1 Model and confidence interval summary, moist regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Model	Equation	Range of Parameters	
Non-Plastic	95	26	11 - 25	15 - 23	**Model**	CBR = 13,455 + (3,968×GM)	GM	0,48 – 2,29
					Upper Confidence	CBR = 18,678 + (7,764×GM)		
					Lower Confidence	CBR = 8,233 + (0,173×GM)		
	98	35	7 - 25	12 - 19	**Model**	CBR = Exp[log(-log(0,5)) × 0,2518 + (2,6187 – (0,0040×r20) + (0,0096×r425) + (0,0038×r075) – (0,0061×GC))]	r2,0 r425	0 – 33 1 – 40
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,3333 + (3,8627 + (0,0296×r20) + (0,0310×r425) + (0,0197×r075) + (0,0251×GC))]	r075	13 – 83
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,1902 + (1,3747 – (0,0377×r20) - (0,0117×r425) - (0,0121×r075) – (0,0373×GC))]	GC	0 - 37
	100	23	16 - 25	20 - 23	**Model**	CBR = 12,492 + (9,077×GM)	GM	0,79 – 1,18
					Upper Confidence	CBR = 23,553 + (20,297×GM)		
					Lower Confidence	CBR = 1,430 - (2,144×GM)		

Table 6.2 Model and confidence interval summary, dry regions

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Equation Type	Equation	Range of Parameters	
All	95	448	7 - 50	17 - 38	**Model**	CBR = Exp[log(-log(0,5)) × 0,3357 + (3,7801 + (0,0042×PL) - (0,0014×LSP) - (0,5708×DR))]	PL LSP DR	0 - 43 0 - 375 0,10 – 1,00
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,3615 + (3,8805 + (0,0090×PL) - (0,0008×LSP) - (0,3597×DR))]		
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,3117 + (3,6796 - (0,0005×PL) - (0,0020×LSP) - (0,7819×DR))]		
	98	252	7 - 50	28 - 40	**Model**	CBR = 30,286 – (0,691×PI) + (4,099×GM)	PI	0 – 28
					Upper Confidence	CBR = 35,373 – (0,389×PI) + (6,895×GM)	GM	0,44 – 2,73
					Lower Confidence	CBR = 25,199 – (0,992×PI) + (1,303×GM)		
	100	160	7 - 50	18 - 37	**Model**	CBR = 36,764 – (0,051×LSP)	LSP	0 – 375
					Upper Confidence	CBR = 39,755 – (0,027×LSP)		
					Lower Confidence	CBR = 33,773 – (0,075×LSP)		
Acid Crystalline	95	50	14 - 50	28 - 45	**Model**	CBR = 53,051 – (0,782×r2,0) – (1,026×r26,5)	r2,0	10 – 32
					Upper Confidence	CBR = 63,357 – (0,365×r2,0) – (0,200×r26,5)	r25,5	0 - 11
					Lower Confidence	CBR = 42,745 – (1,198×r2,0) – (1,851×r26,5)		
	98	Insufficient Data						
	100	Insufficient Data						
Alluvium	95	18	14 - 50	30 - 48	**Model**	CBR = 29,180 – (0,664×PI) + (11,730×GM)	PI	0 – 20
					Upper Confidence	CBR = 62,062 – (0,281×PI) + (35,969×GM)	GM	0,97 – 1,92
					Lower Confidence	CBR = –3,701 – (1,609×PI) – (12,508×GM)		
	98	Insufficient Data						
	100	Insufficient Data						

Table 6.2 Model and confidence interval summary, dry regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Equation Type	Equation	Range of Parameters	
Arenaceous	95	46	7 - 50	14 - 35	**Model**	CBR = Exp[log(-log(0,5)) × 0,3808 + (3,663 - (0,0053×LSP) - (0,0266×r2,0) + (0,0184×GC))]	LSP	0 – 234
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,4741 + (4,0011 - (0,0031×LSP) + (0,0197×r2,0) + (0,0419×GC))]	r2,0	1 – 14
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,30598 + (3,3250 - (0,0074×LSP) - (0,0728×r2,0) - (0,0052×GC))]	GC	2 – 30
	98	31	8 - 49	16 - 39	**Model**	CBR = 7,779 + (1,528×r19,0) + (0,421×r075)	r19,0	0 – 20
					Upper Confidence	CBR = 19,332 + (2,442×r19,0) + (0,755×r075)	r075	1 - 55
					Lower Confidence	CBR = -3,775 + (0,615×r19,0) + (0,088×r075)		
	100	28	7 - 49	20 - 40	**Model**	CBR = 5,628 + (1,880×r19,0) + (0,497×r075)	r19,0	1 – 20
					Upper Confidence	CBR = 17,976 + (2,865×r19,0) + (0,927×r075)	r075	1 - 51
					Lower Confidence	CBR = -6,721 + (0,895×r19,0) + (0,068×r075)		
Argillaceous	95	131	7 - 50	18 - 30	**Model**	CBR = 16,771 – (0,357×PI) + (5,184×GM)	PI	0 – 19
					Upper Confidence	CBR = 25,517 + (0,153×PI) + (9,076×GM	GM	0,46 – 2,85
					Lower Confidence	CBR = 8,025 – (0,866×PI) + (1,292×GM		
	98	106	8 - 50	20 - 41	**Model**	CBR = 20,165 – (0,752×PI) + (8,151×GM)	PI	0 – 19
					Upper Confidence	CBR = 30,336 – (0,182×PI) + (12,599×GM)	GM	0,46 – 2,78
					Lower Confidence	CBR = 9,993 – (1,322×PI) + (3,703×GM)		
	100	75	7 - 49	20 - 40	**Model**	CBR = 19,418 – (0,580×PI) + (8,035×GM)	PI	0 – 19
					Upper Confidence	CBR = 31,552 + (0,149×PI) + (13,325×GM)	GM	0,46 – 2,73
					Lower Confidence	CBR = 7,284 – (1,308×PI) + (2,745×GM)		
Basic Crystalline	95	41	8 - 50	12 - 44	**Model**	CBR = 14,520 – (1,415×PI) + (13,168×GM)	PI	0 – 15
					Upper Confidence	CBR = 27,627 – (0,794×PI) + (20,072×GM)	GM	0,58 – 2,77
					Lower Confidence	CBR = 1,412 – (2,036×PI) + (6,263×GM)		
	98	22	12 - 50	17 - 66	**Model**	CBR = Exp[(((12×GM) - PI) ÷ 18,5) + ln(16,7)]	PI	0 – 15
					Upper Confidence	None Given	GM	0,58 – 2,11
					Lower Confidence	None Given		
	100	Insufficient Data						

Table 6.2 Model and confidence interval summary, dry regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Equation Type	Equation	Range of Parameters	
Calcrete	95	35	12 - 49	25 - 44	**Model**	CBR = 43,732 – (0,437×PL)	PL	0 - 43
					Upper Confidence	CBR = 50,008 – (0,144×PL)		
					Lower Confidence	CBR = 37,432 – (0,731×PL)		
	98	15	9 - 50	28 - 48	**Model**	CBR = 59,201 - (0,223×PI) - (9,995×GM)	PI	0 – 28
					Upper Confidence	CBR = 98,086 + (0,935×PI) + (14,927×GM)	GM	1,12 – 2,49
					Lower Confidence	CBR = 20,317 - (1,380×PI) - (34917×GM)		
	100	Insufficient Data						
Colluvium	95	65	8 - 49	15 - 35	**Model**	CBR = 17,363 – (0,695×PI) + (10,313×GM)	PI	0 – 17
					Upper Confidence	CBR = 26,705 – (0,178×PI) + (17,654×GM)	GM	0,63 – 2,41
					Lower Confidence	CBR = 8,022 – (1,212×PI) + (2,972×GM)		
	98	50	7 - 50	11 - 47	**Model**	CBR = 36,753 - (0,058×LSP) – (4,709×r19,0) + (0,462×GC)	LSP	0 – 375
					Upper Confidence	CBR = 41,226 - (0,031×LSP) – (2,622×r19,0) + (0,853×GC)	r19,0	0 – 6
					Lower Confidence	CBR = 32,279 - (0,086×LSP) – (6,795×r19,0) + (0,070×GC)	GC	0 - 29
	100	27	7 - 48	15 - 40	**Model**	CBR = 40,717 - (2,675×LS)	LS	0 – 9,5
					Upper Confidence	CBR = 45,996 - (1,498×LS)		
					Lower Confidence	CBR = 35,437 - (3,852×LS)		
High Silica	95	51	9 - 50	24 - 41	**Model**	CBR = 14,456 - (0,042×PI) + (9,692×GM)	PI	0 – 14
					Upper Confidence	CBR = 34,746 + (0,613×PI) + (18,003×GM)	GM	1,05 – 2,70
					Lower Confidence	CBR = -5,835 - (0,697×PI) + (1,381×GM)		
	98	Insufficient Data						
	100	Insufficient Data						

Table 6.2 Model and confidence interval summary, dry regions (continued)

Material	% Mod AASHTO	n	CBR Range (%)	Estimated CBR Range (%)	Equation Type	Equation	Range of Parameters	
Non-Plastic	95	72	9 - 50	28 - 37	**Model**	CBR = 24,812 + (4,524×GM)	GM	0,65 – 2,61
					Upper Confidence	CBR = 34,073 + (9,888×GM)		
					Lower Confidence	CBR = 15,551 - (0,840×GM)		
	98	30	17 - 50	35 - 43	**Model**	CBR = 30,407 + (5,090×GM)	GM	0,85 – 2,46
					Upper Confidence	CBR = 41,863 + (12,314×GM)		
					Lower Confidence	CBR = 18,951 - (2,133×GM)		
	100	18	20 - 50	30 - 47	**Model**	CBR = Exp[log(-log(0,5)) × 0,1013 + (3,6383 + (0,0395×r26,5) - (0,0764×r19,0) + (0,0079×GC))]	r26,5	0 – 18
					Upper Confidence	CBR = Exp[log(-log(0,5)) × 0,1462 + (3,7315 + (0,0646×r26,5) - (0,0406×r19,0) + (0,0141×GC))]	r19,0	0 – 14
					Lower Confidence	CBR = Exp[log(-log(0,5)) × 0,0702 + (3,5450 + (0,0145×r26,5) - (0,1122×r19,0) + (0,0017×GC))]	GC	0 - 43

7. Conclusion

Considering all the factors analysed and discussed in this dissertation, a number of conclusions were reached. As the aim of the research was to find ways of predicting CBR values from index testing, the main focus will be placed on this outcome.

7.1 Material Nature and Data

One of the main requirements of data used for this research was that it had to represent a variety of material properties. As such, a database with multiple parameters (or in statistical terms, variables) was created. Each parameter shows a large range of values. This objective was therefore achieved.

In hindsight it is anticipated that the large variability and range of parameters perhaps hampered the analyses. Where seventeen variables (each showing significant variation) were used to predict the CBR, it is possible (and perhaps likely) that this large range of variable input parameters did not permit regression analyses to identify and isolate parameters truly critical in prediction. In other words, the range in parameter values may have been too large for sensible analyses, and a further breakdown of the data (e.g., by soil classification) may prove more useful.

Doing similar analyses with limited ranges for the parameters would mean using only selected data, eliminating the statistical validity. The ranges of these parameters would then also be dependent on the extent of weathering and the material type. The example of weathering dolerite and granite applies, as weathered dolerite and granite would not usually have similar property ranges (e.g. consider the plasticity index of a clayey, highly weathered dolerite and a sandy, highly weathered granite). Hence, if prediction with limited ranges for predicting variables is to be done, strict input selection based on classification of the extent of weathering will be required. Unfortunately, the latter is also subjective to descriptions by different individuals involved in the material classification (i.e. one person may describe a material as moderately weathered, and the next as highly weathered as many of those involved in this work have little or no geotechnical training).

7.2 Nature of Predicting Models

Analysis using the existing models revealed poor results with the database created. None of the models delivered satisfactory results using the database and as a result, none of the models were considered for further analysis. This excludes Kleyn's (1955) model, that most widely used in southern Africa.

The results derived from the subsequent research are not satisfactory on a practical or statistical basis either. Strictly speaking, all data should yield similar results when processed by the same method. This, however, was not the case in this research. Four methods were included for predicting CBR values, with the best of the four predictions being selected for individual material groups (at respective densities and in respective climatic regions). Each of the four models included in the analyses (derived by different means) was identified at least once as being the most suitable model.

Considering the above, it is apparent then that neither linear nor Weibull regressions can be excluded, as both were tested and both found to be the most suitable (note: not the best) predictors for certain groups. The same applies to the method proposed by Kleyn (1955) which was derived empirically by Stephens (1988). In theory the data at hand should be ideal for Weibull analysis as the method can accommodate a range of functions; however this proved not to be the case. Though a linear model is also not strictly applicable to the data, the method did prove more successful than the Weibull analyses on a number of occasions.

It is highly likely, then, that the issue does not lie with the methods used, but rather with the database, which in turn depends on test results. The data does not have a strictly linear, logarithmic or exponential distribution. Another possibility that is also likely (and that may be linked to the variability of the data), is the challenge of relating real life data to statistics. It is anticipated that a combination of data variability and data conversion into model variables are jointly responsible for poor results. This is confirmed, at least partially, by the fact that similar material groups in similar climate regions but at different compactions were best predicted by different models (i.e. under ideal circumstances e.g. basic crystalline materials in a moist region should be predicted by the same model type for 95%, 98% and 100% Mod AASHTO compaction).

7.3 Parameter Identification by Regression

A point that raised concern regarding the regressions analyses is that regressions often failed to identify parameters that proved significant. This is illustrated by the number of times that the Kleyn model proved significant despite neither the linear nor the Weibull regression identifying the plasticity index and grading modulus as significant parameters. Yet despite this, forcing the two parameters into a linear regression delivered the best model in many instances.

It was also observed that parameters identified by the regressions to have a relationship with the CBR, did not necessarily correspond with the results of the principal component analyses. This may be ascribed to the different statistical methods used to derive the parameters.

7.4 Parameter Interdependency and Correspondence

Another challenge faced during the analysis was the interdependency between the parameters, e.g. Atterberg Limits, cumulative grading, etc. From a statistical point of view, this is far from ideal as regressions often rejected numerous predicting parameters (variables).

With regard to grading, the problem was solved by using percentages retained on different sieves which are more independent than cumulative percentages passing; however, no such simple solution can be applied for Atterberg Limits. Two options are given when using the Atterberg Limits, the first being to select only one of the parameters, based on subject knowledge. The second option was to remove the plasticity index from the input variables, as its value depends on the liquid limit and plastic limit, and use only the latter two parameters for analysis (regression).

By manual refining of the Weibull regressions, care was taken not to include correlated parameters (e.g. the linear shrinkage product and shrinkage product). With the stepwise linear regression, this was not always the case as the regression automatically tests each parameter entered and either retains or rejects it. Ultimately, the most suitable models selected rectified this issue, as none of the final models contain such correlated parameters (with the exception of the arenaceous group, 95% Mod AASHTO, moist regions, which contained both the shrinkage product and linear shrinkage).

7.5 Data Trends

The applicability of (all) the predictive equations is severely restricted due to a prevalent trend in each of the models and as such, the models can not be considered as reliable. This trend is ascribed to the data and is not associated with the regression methods used. Relative to the ranges of CBR values analysed for the climatic zones (i.e. 7% to 25% for moist regions and 7% to 50% for dry regions), lower CBR values are over-estimated and higher CBR values under-estimated. This trend is evident in both linear and Weibull regressions and was clearly observed in residual plots for each material group analysed.

The result of this trend is illustrated in the limited predicted CBR ranges included in Table 6.1 and Table 6.2 in the previous chapter. These ranges, as well as the real CBR ranges, were specifically included to emphasise the limitations of the models. Before refining the models, predicted ranges were as small as 3%. Yet, despite extensive refinement to the regressions and models (which included limiting the predicted ranges) the trend could not be removed.

7.6 Sample Material Selection

Despite making every possible attempt within practical limitations to use only trusted material identifications, it is likely that some materials included in the analysis were wrongly identified (e.g. arenaceous materials identified as argillaceous).

Unfortunately a compromise had to be reached between the amount of data and the quality (in terms of material identification which could not be corroborated from the available records) of the data used.

Under ideal circumstances the author would have preferred using his own data and the data of individuals who are known to be competent in material identification; however, the number of samples available (and the spread of material origins) was not sufficient.

7.7 Test Reproducibility and Reliability

The question often raised about the CBR's reproducibility and repeatability is again highlighted by this research. Considering all the points discussed thus far, it is suspected that the variability of data is the single biggest impediment to accurate predictions.

The issue is not just restricted to the CBR test, though. The repeatability of Atterberg Limits is also questionable. The issue then becomes apparent when trying to predict a poorly reproducible test with low reliability (i.e. the CBR) with input parameters that are already subject to inherent discrepancies (i.e. Atterberg Limits).

7.8 Non-Exclusive Parameters

As discussed in section 4.4, the effect of non-exclusive parameter correlations must be considered when attempting to produce prediction models. For example, a grading modulus above 1,00 could be associated with CBR values below 10%, but could also apply to materials with CBR values exceeding 60% (refer to section 4.4.3). It is therefore important to consider that even though certain parameters are often associated with e.g. high CBR values, these associations are not exclusive to those CBR ranges. As such, the parameters serve as good indicators of CBR properties, but are not to be used as the only indication of such properties.

8. Recommendations

8.1 CBR Prediction Models

Considering the nature of the models including the confidence intervals, model trends, predicted ranges, etc., the prediction of CBR from index properties by industry can not be recommended. The models derived (and those already in use) are simply too variable and inconsistent. Simply stated, the models are not reliable. The models may be used to check spurious laboratory CBR results, but also within limitations.

As with most other applications, result interpretation must be done with the application of experience (e.g. it is probably often possible to visually estimate material quality in the field better than using models based on index properties). This so-called "gut-feel" often proves very significant in industry and must be used in conjunction with testing and verification to obtain sensible results.

Considering the results obtained from the research, the use of any (other) empirical CBR prediction can not be recommended. This was confirmed by initial comparisons of data with existing models.

8.2 Future Research

Despite the poor results obtained from the research, meaningful and important insight was gained.

8.2.1 Weibull Regression

It is recommended that the Weibull regression be considered for similar research in future, even if just for a reference. The model proved robust and flexible and is suitable for application of natural science data. It must be borne in mind, though, that whilst the linear regression models tend to produce lower MSPE values, the Weibull regression delivers models that tend to be more representative of the entire range of data. As such, the method is suitable for variable data, but within practical and statistical limits. That being stated, it is also recommended that linear regressions not be dismissed on a theoretical basis only, but that it also be included in future work, if only for comparative purposes.

Furthermore, it is recommended that regression results be scrutinised and evaluated with subject knowledge throughout statistical analyses. Particular care must be taken to identify interdependent parameters. On this subject it is also recommended that regression analyses be done using percentages retained on the individual sieves rather than the less independent cumulative passing the sieves used for grading analysis. Experience shows that this removes modelling errors and regression difficulties related to the (cumulative) grading.

8.2.2 Recommendations for Future Research

Based on insight gained from this research, it is recommended that if similar work is undertaken in future, specific focus be placed on the grading modulus, plasticity index and linear shrinkage. Of all the parameters analysed in this dissertation, these three parameters were found to show a significant, constant relationship with the CBR, even though the relationship is not mutually exclusive (refer to section 4.4).

8.2.3 Limited Input Ranges

Results of this project suggest that limiting the number and range of input parameters may yet prove a decisive factor in deriving prediction models. It is therefore recommended that analyses similar to those performed in this research be done, but with selected parameters and ranges only. For example, a model can be derived for materials with grading moduli between 1,00 and 2,00 and plasticity indices between 2% and 6% in an attempt to derive CBR values between 20% and 50%.

The approach of using material rock type as a grouping method should also be retained. It is anticipated that factors such as weathering, mineralogy and material behaviour have an important role to play in CBR prediction, if these properties can be isolated by the parameters analysed. However, the use of other classification systems must also be considered. For example, instead of using the rock material classification, the Unified Soil Classification System (USCS) or AASHTO soil classification system may be considered for data grouping.

8.2.4 Nature of Material Testing

Though the issue of test reproducibility and repeatability has been discussed, it is wise to pursue ways of improving test methods with specific reference to the CBR test. Though the method may be dated and criticised, it remains the most commonly used method for evaluating gravel for road construction, despite its limitations.

Points raised by authors such as Savage (2008) emphasising the limitations of the CBR test are valid. Also, the proposed alternative use of particle interlock and porosity (Savage, 2008) is also sensible; however, no evidence has been found in the literature on testing to support this approach. It is therefore recommended that research be undertaken to study the effects and viability of particle interlock (and possibly relate them to the CBR test). In addition, particle shape, texture and hardness evaluations could probably also prove valuable in such an evaluation.

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Addendum A: Data Analysis and Verification

As discussed under the methodology, a considerable amount of refining was done on the dataset(s) prior to performing the regression analyses. Apart from the physical refinements upon entering the data, the descriptive statistics for the entire dataset were derived and compared with the descriptive statistics derived for the individual material groups using Microsoft® Excel 2002. After this comparison, a principal component analysis was performed to determine which parameters, if any, showed significant relationships with the CBR values within material groups. Subsequently, the regression analyses were performed on the individual material groups.

The purpose of this section is to discuss and compare the descriptive statistics derived for each material group compared with that of the entire dataset, as well as considering the statistical distribution of each parameter. Table 3.2 earlier in the text summarises the division of data into climate and material groups.

Prior to considering the descriptive statistics of each material group, it must be noted that as wide a variation in material properties as possible is expected and is in fact required to improve the statistical significance of any models. The variation is possible as the data considered spans a wide range of material weathering grades. In other words, the data includes results from both unweathered materials and highly or completely weathered (residual) materials. Properties such as the Atterberg Limits are expected to vary significantly, even within the same material group.

A.1 Descriptive Statistics: Moist Areas: 95% Mod AASHTO

A.1.1 All Groups

As one would expect, descriptive statistics for the entire group – that includes a range of materials from Weinert's nine rock groups (Weinert, 1980), compacted to 95% Mod AASHTO density – showed a large variation in nearly every parameter summarised. For the analysis, the pedogenic group was split into ferricrete and calcrete groups for individual assessment. For the purposes of this section, the group comprising all the samples compacted to 95% Mod AASHTO density shall be referred to as the "entire group" or "entire dataset". A summary of the descriptive statistics is included in Table A.1. From the table the following was observed:

- *Liquid Limit:* A mean value of 26,5% was recorded for the entire collective liquid limit, which consisted of 574 samples. As anticipated, the statistics delivered a large standard deviation of 13,93. This is not surprising if one considers that both non-plastic materials and highly weathered, clayey materials were included in the analysis. This is emphasised by a minimum liquid limit of 0% (assumed for non-plastic materials) and a maximum liquid limit of 88%. A more descriptive indicator is the coefficient of variation, which was 0,53. This normalised value emphasises that the material spans a range of values that can be ascribed to the variability of all the materials. The histogram (Figure A.1) for this parameter indicates a slightly skewed distribution, except for a second peak at zero, indicating the non-plastic materials.
- *Plastic Limit:* Descriptive statistics of the plastic limit resemble the variation in the liquid limit. A mean value of 15,3% was obtained with a standard deviation of 6,76 and a minimum and maximum of 0% and 44%, respectively. The coefficient of variation, however, showed a notable refinement compared with the liquid limit (and plasticity index discussed below). The coefficient of variation was 0,44 and although it was smaller than that of the liquid limit, the variation is still large. The histogram (Figure A.2) indicates that no values less than ten were recorded (disregarding non-plastic materials entered as zero), leaving a large gap in the otherwise positively skewed histogram. The second peak ascribed to non-plastic materials is present again.

Table A.1 Descriptive Statistics Summary: Basic Crystalline (Moist regions, 95% Mod AASHTO)

	LL	**PI**	**PL**	**LS/BLS**	**LSP**	**SP**	**GM**	**GC**	**CBR**
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Basic Crystalline : 95% Mod AASHTO									
Mean	33,0	13,8	19,2	6,7	221,9	317,8	1,72	20,8	22,2
Standard Deviation	12,98	9,91	5,23	4,31	308,24	364,94	0,67	10,76	16,29
Coefficient of Variation	0,39	0,72	0,27	0,65	1,39	1,15	0,39	0,52	0,73
Minimum	0	0	0	0	0	0	0,26	1	1
Maximum	72	55	31	21	1722	1953	2,63	44	64
n	107	107	107	107	107	107	107	107	107

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

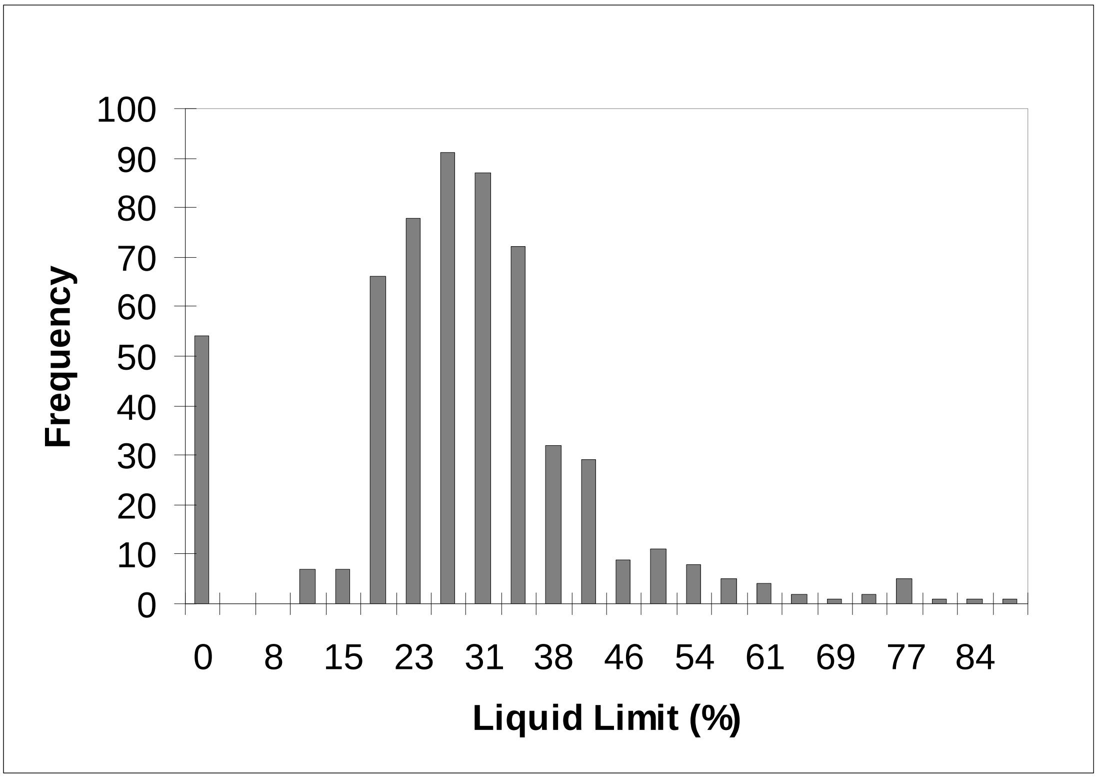


Figure A.1 Frequency Distribution of Liquid Limit (All groups, 95% Mod AASHTO)

- *Plasticity Index:* As with the liquid limit, the plasticity indices of the entire group were also highly variable, with values between 0% (non-plastic) and 57%. Once more, this can be ascribed to the wide variation in both material types and the variable degree of weathering of the materials. A mean value of 11,1% was recorded, with a standard deviation of 8,74. The coefficient of variation also indicates a wide spread of plasticity indices, with a value of 0,78. It should be noted that the plasticity index is subject to a "double error", as it is derived from two tests, the liquid limit and the plastic limit, which are both subject to errors themselves. The histogram (Figure A.3) for the parameter is positively skewed. This is ascribed to the fact that the majority of materials in a moist area will have a plasticity index, but not all materials produce elevated plasticity indices. Also, as a large portion of the data analysed was obtained from road construction documents, where materials with lower Atterberg Limits were most probably targeted during sampling.

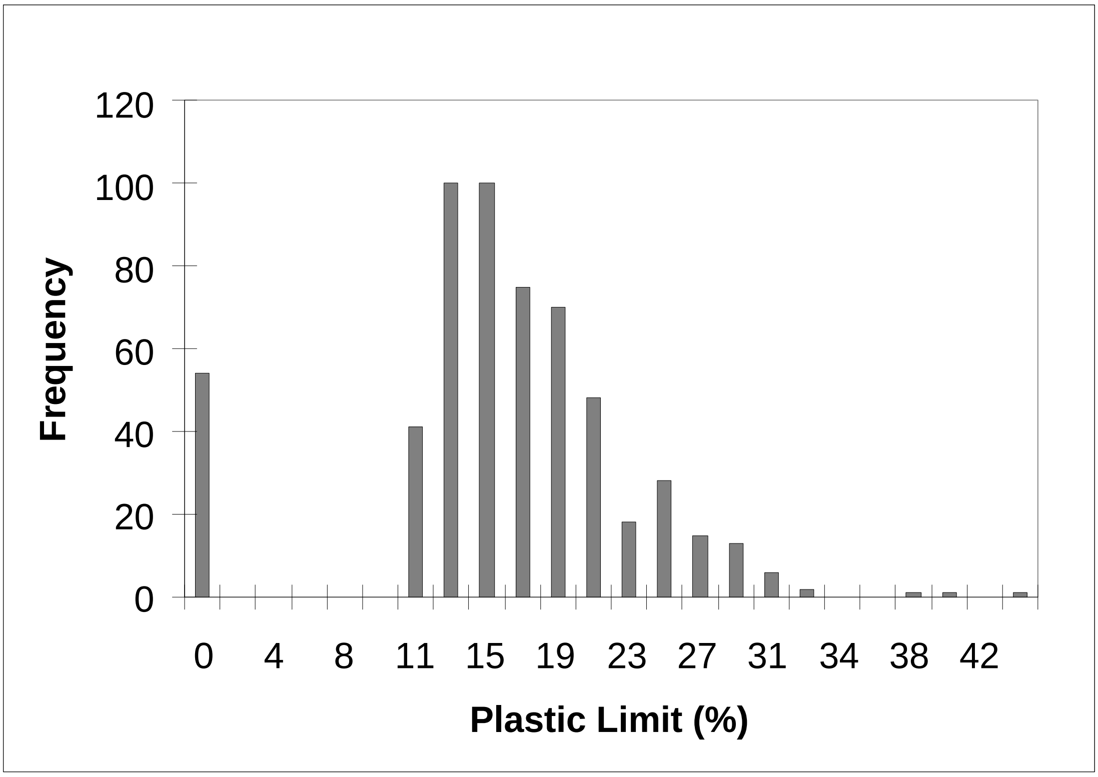


Figure A.2 Frequency Distribution of Plastic Limit (All groups, 95% Mod AASHTO)

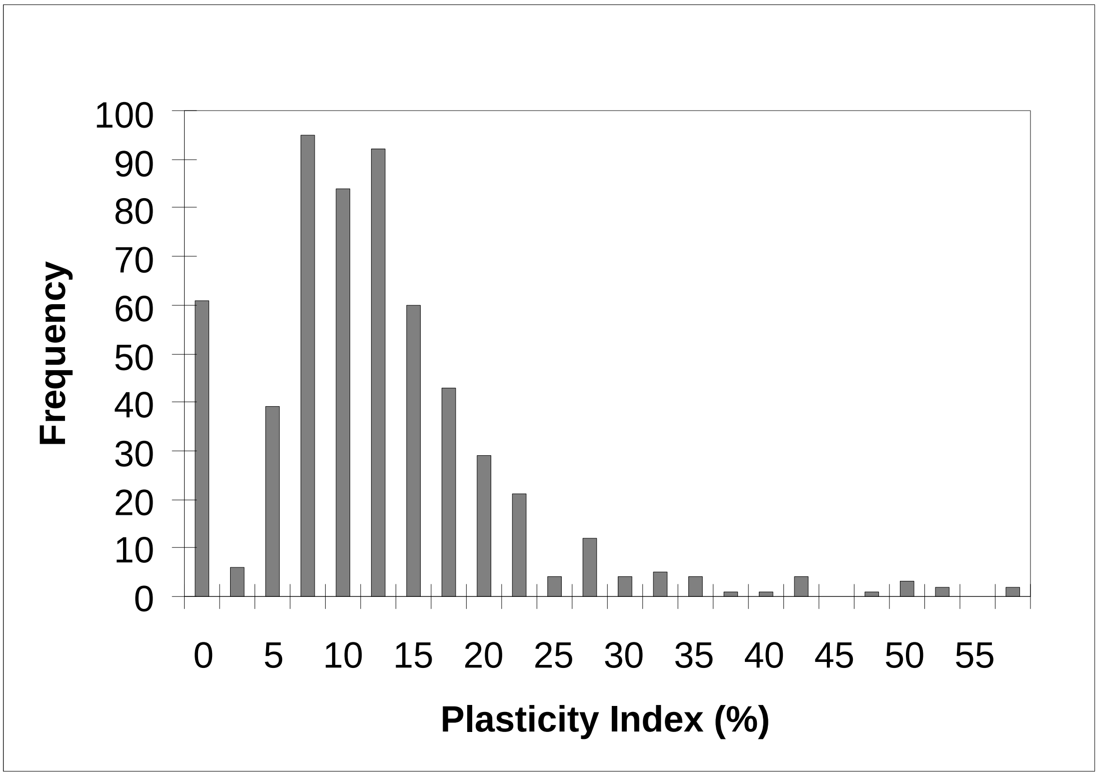


Figure A.3 Frequency Distribution of Plasticity Index (All groups, 95% Mod AASHTO)

- *Linear Shrinkage:* It would be expected that the linear shrinkage would display a large range, specifically as the material plasticity can be likened to a materials potential to permit volume changes. As a result, it is not surprising to note the high variability of the linear shrinkage when considering the properties of the plasticity index discussed above. The entire group revealed a mean linear shrinkage of 5,3%, ranging from 0% to a maximum of 30%. The standard deviation was 3,97, whilst the coefficient of variation was 0,75. It is interesting to note that this coefficient of variation closely correlates with the coefficient of variation of 0,78 recorded for the plasticity index. As with the plasticity index, a positively skewed histogram (Figure A.4) indicates that many samples shrunk, but not all of them produced large volume changes.

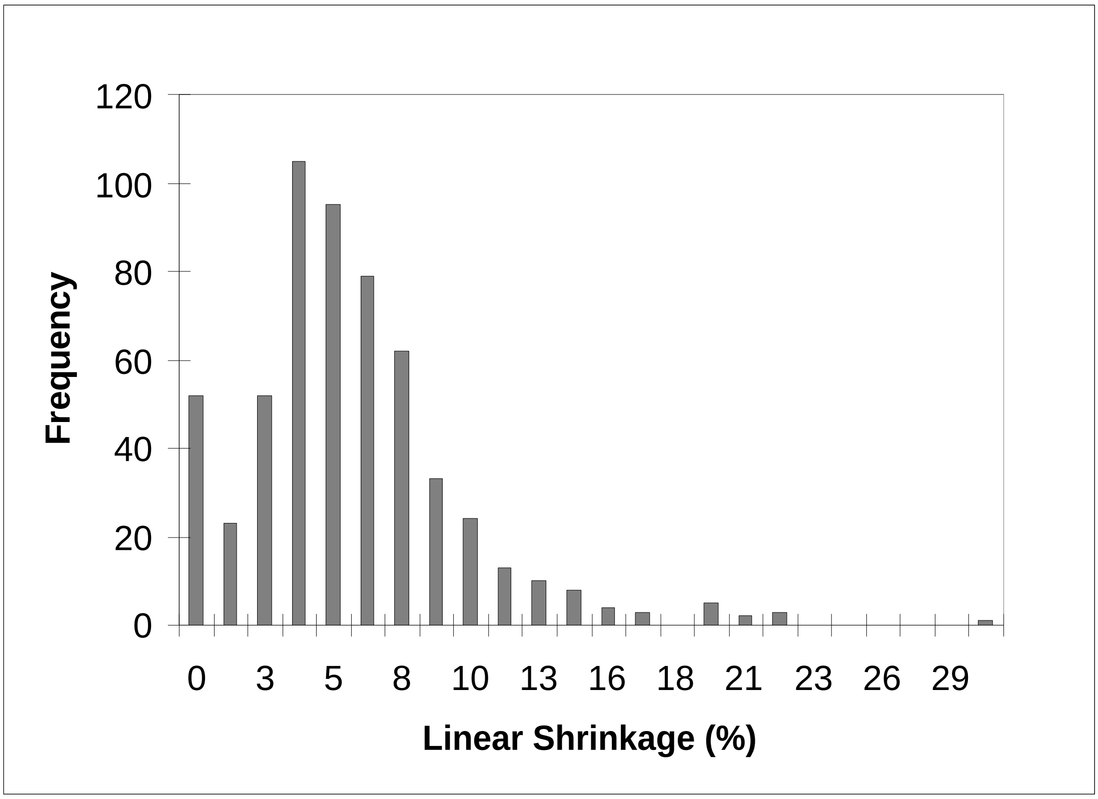


Figure A.4 Frequency Distribution of Linear Shrinkage (All groups, 95% Mod AASHTO)

- *Linear Shrinkage Product:* The linear shrinkage product – as referred to by Netterberg and Paige-Green (1988) - is calculated from the product of linear shrinkage and the P075 constituent; hence it can be expected that the range in values will be larger than other parameters that were determined by physical testing as opposed to mathematical calculation. This is evident when considering the minimum and maximum values of zero and 1823, respectively. Though the mean was indicated to be 205,5 the standard variation is 272,49. The coefficient of variation confirms this, with a value of 1,33. As with plasticity index, the linear shrinkage product is also subject to a double error, as it is calculated from the product of two other parameters.

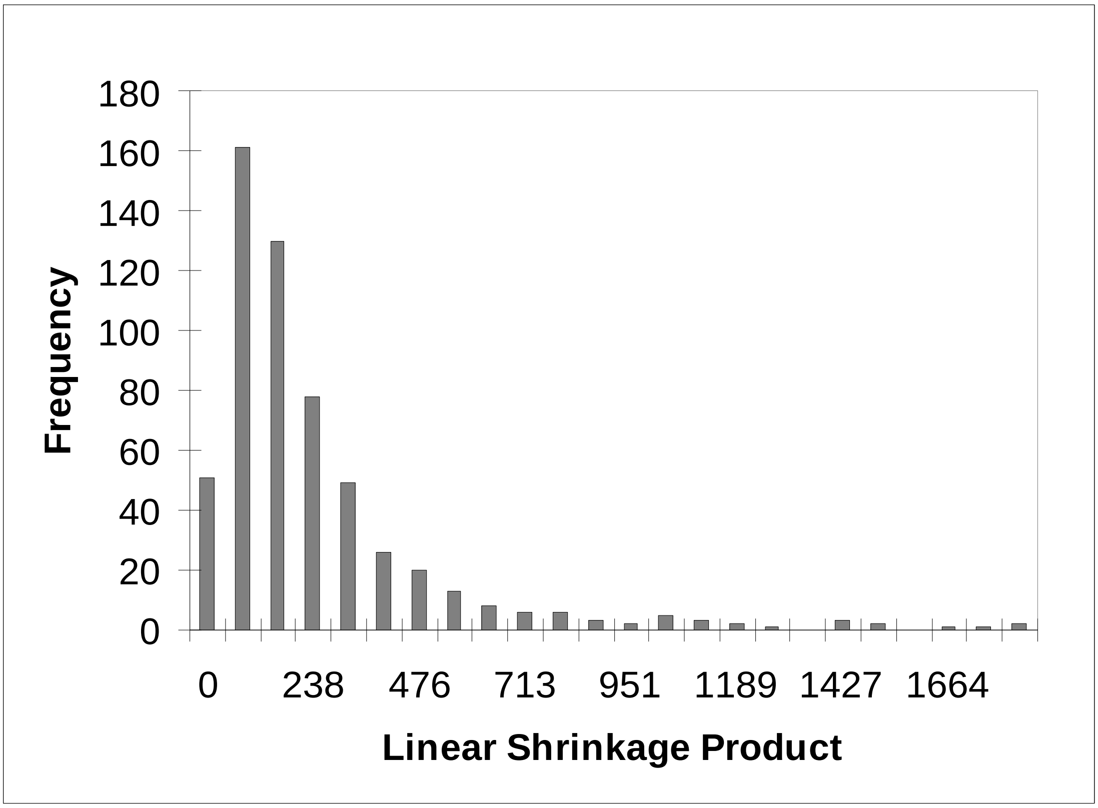


Figure A.5 Frequency Distribution of Linear Shrinkage Product (All groups, 95% Mod AASHTO)

Considering the positively skewed distribution of the linear shrinkage, it is not surprising to note that the linear shrinkage product is also positively skewed (Figure A.5), though it can be noted that the graph transition within the selected intervals is smoother than that of the linear shrinkage histogram.

- *Shrinkage Product:* This parameter is calculated similarly to the product described above, except the P425 constituent is used instead of the P075 component (Paige-Green, 1989); hence the parameter is directly weighted by the fraction used for the test. Consequently the parameter is also subject to a double error and high variability. A mean of 307,3 was calculated, with a range between zero and 2083, emphasising the large range produced by the product. The standard deviation was 326,14 with the coefficient of variation being 1,06. This, once again, confirms the variability of data in the set analysed. A histogram for the parameter delivered a smooth, positively skewed histogram (Figure A.6). This seems to conform to the material properties of heave described for the linear shrinkage and the linear shrinkage product.

- *Grading Modulus:* Rather unexpectedly the grading modulus revealed the smallest coefficient of variation of all the parameters: 0,43. It was expected that, like the Atterberg Limits, the grading modulus would deliver a wide spread of values due to the variation in coarseness of the materials tested. A good spread was obtained, though, with recorded values ranging between 0,17 and 2,64. It is worth noting that CBR sampling is usually selective; hence there is a bias towards selecting those materials that appear to be likely to provide the required CBR result. Materials with excessive fines or oversized clasts are often either not sampled, or sampled selectively (i.e. oversized clasts are not included in the sample). A mean grading modulus of 1,43 was recorded, with a standard deviation of 0,62. The histogram illustrates the sampling bias clearly. A much smaller number of fine materials (GM<0,60) are included than coarser materials. The histogram indicates a highly variable composition otherwise (Figure A.7). This simply indicates the variety of materials encountered, but is essentially bimodal with sandy materials and normal road construction gravels.
- *Grading Coefficient:* The grading coefficient showed poorer distribution than the grading modulus. A mean of 17,7 was recorded, with a standard deviation of 11,10. Recorded values ranged between zero and 46, whilst the coefficient of variation was 0,63. It is expected that the grading coefficient– and grading modulus for that matter – will display a more refined influence within individual groups, particularly when considering the particle sizes resulting

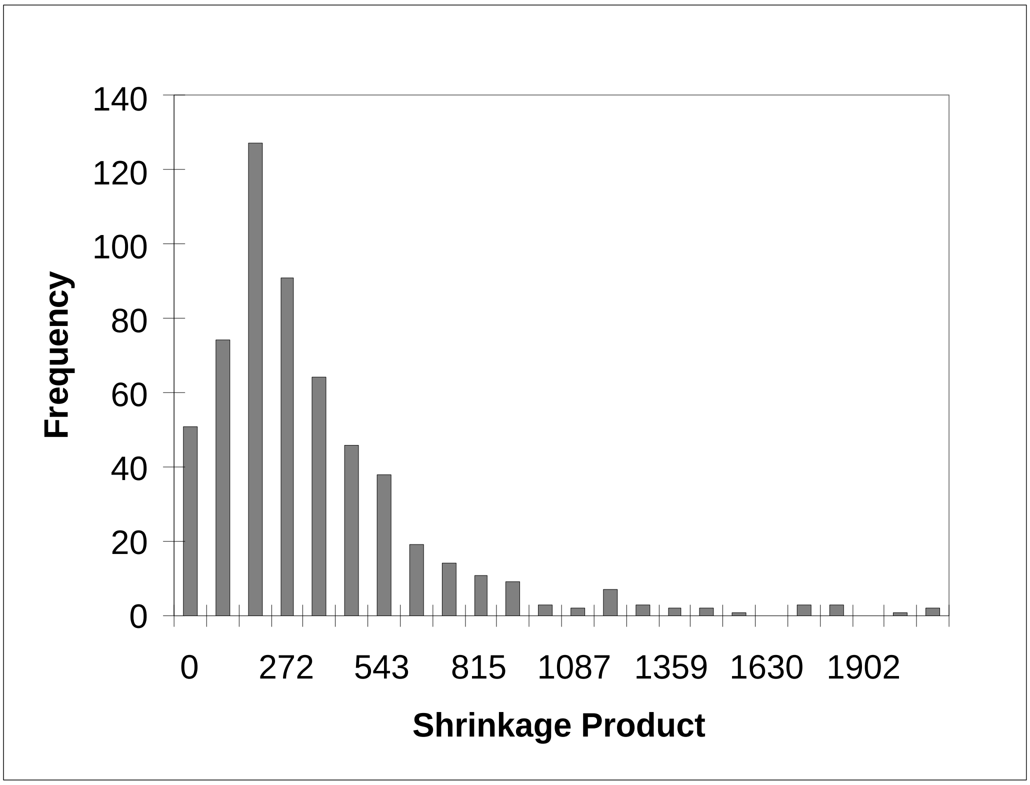


Figure A.6 Frequency Distribution of Shrinkage Product (All groups, 95% Mod AASHTO)

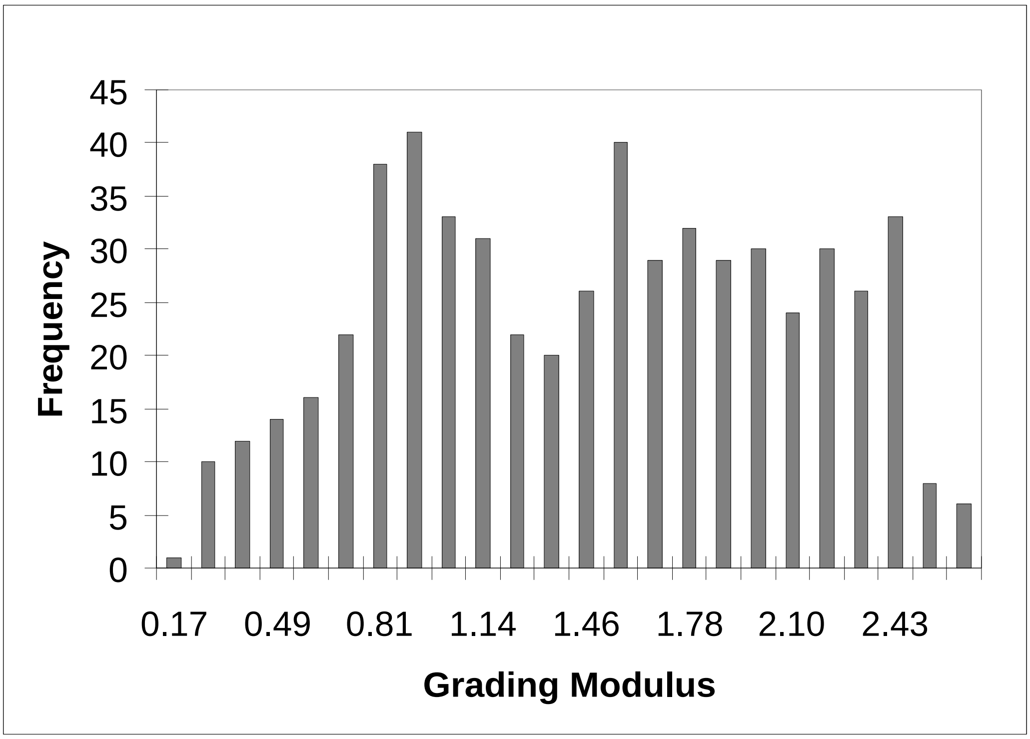


Figure A.7 Frequency Distribution of Grading Modulus (All groups, 95% Mod AASHTO) from chemical weathering and mechanical weathering in the two climatic regions (and also weathering products of different material groups). As with the grading modulus, the histogram (Figure A.8) indicates a wide spreads with a bimodal distribution.

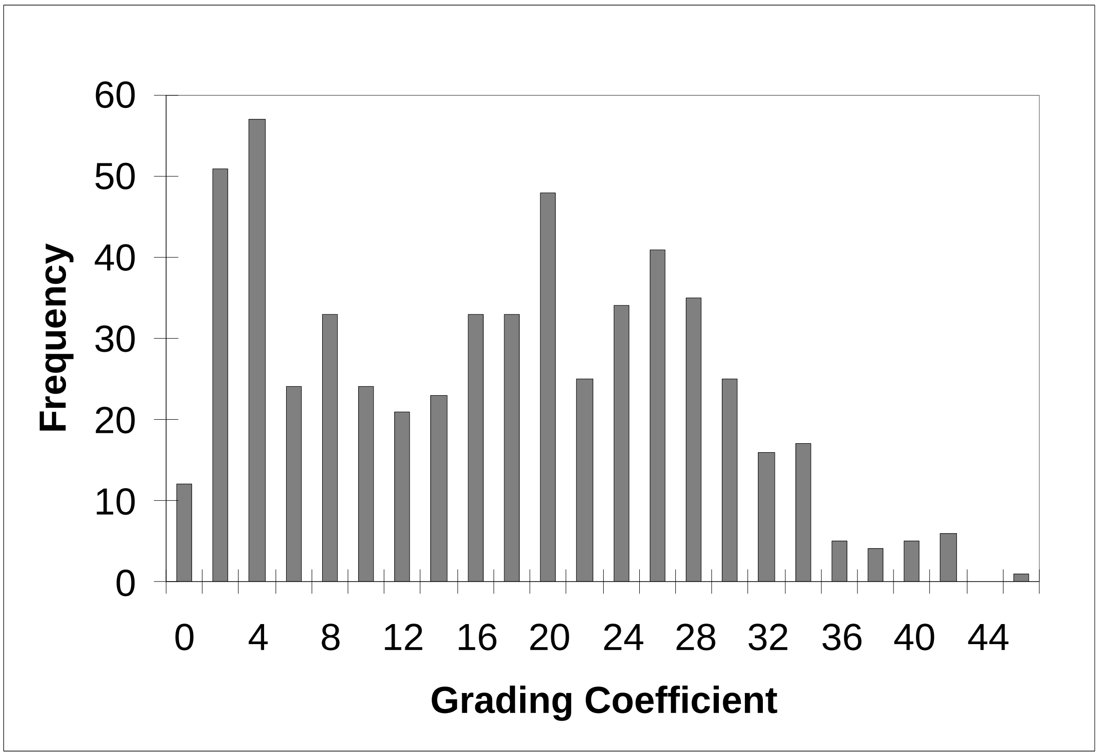


Figure A.8 Frequency Distribution of Grading Coefficient (All groups, 95% Mod AASHTO)

- *CBR at 95% Mod AASHTO (PSCBR):* The range of CBR values recorded once again serves as evidence of the spread of samples analysed. The CBR values recorded ranged from 0% to 110%. The mean CBR value was 20%, with the standard deviation being 17,10. The coefficient of variation was 0,87 once more confirming a wide spread of data. The histogram (Figure A.9) for the CBR values indicates a positively skewed distribution, which indicates that the majority of CBR values recorded were lower rather than having higher values as confirmed by the mean CBR value.

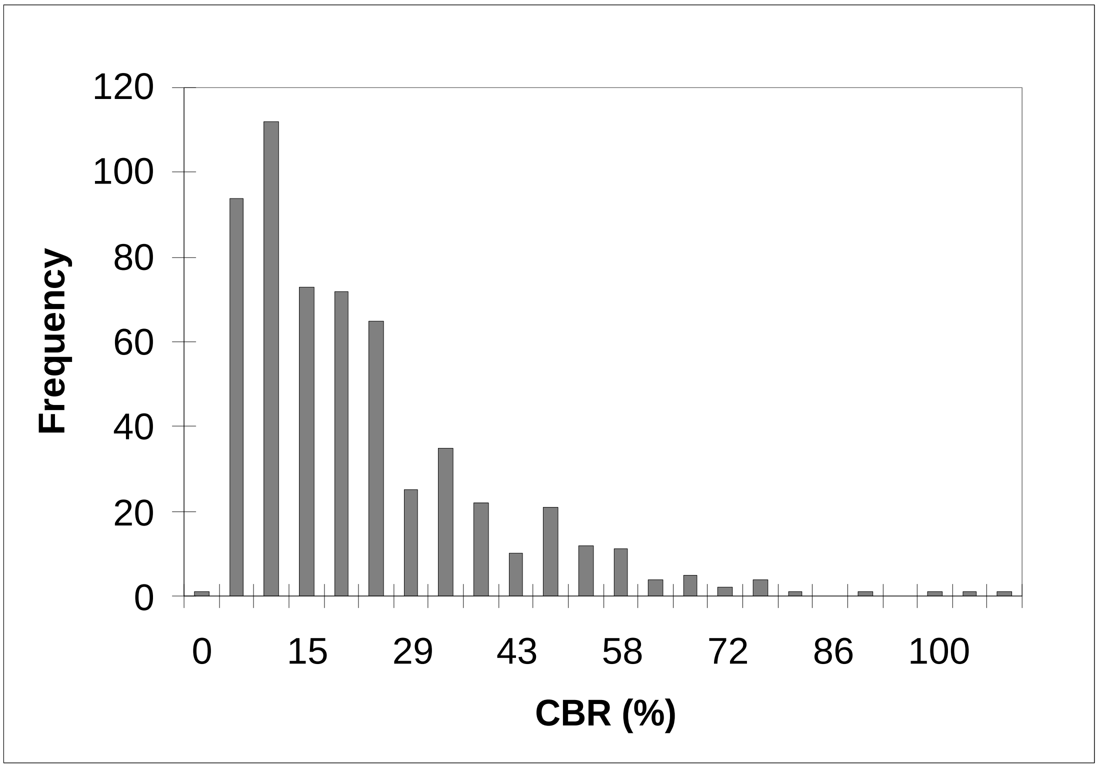


Figure A.9 Frequency Distribution of CBR (All groups, 95% Mod AASHTO)

A.1.2 Basic Crystalline Materials

The descriptive statistics of the basic crystalline group revealed a refinement from the total group, as was anticipated. 107 of the samples analysed were from this group and a summary is given in Table A.1. Perhaps the single most notable difference observed is that the Atterberg Limits show higher means than the entire dataset. This is to be expected, as basic crystalline materials are known for the clayey products produced by chemical weathering in moist areas (Weinert, 1980). Both the plasticity index and liquid limit showed larger standard deviations, although they had improved coefficient of variation.

Considering the tendency of basic crystalline materials to weather to clayey products, it is also not surprising to note that the means of the linear shrinkage, linear shrinkage product and shrinkage product are higher than those of the entire dataset. However, although the linear shrinkage has a higher standard deviation, the coefficient of variation is lower than that of all of the samples. Both the linear shrinkage product and shrinkage product, on the other hand, showed larger standard deviations as well as poorer coefficients of variation. The double error of the linear shrinkage products mentioned earlier therefore needs to be considered here, as the first parameter (linear shrinkage) showed an improvement in its coefficient of variation. The linear shrinkage product revealed a peculiar histogram. Compared with the histogram of the entire group, the basic crystalline linear shrinkage product also had a positively skewed distribution (with the majority of its results lying in the 172 – 344 range), but the histogram is far more peaked than the entire group's histogram, when viewed in proportion (Figure A.10a).

As far as grading is concerned, both the grading modulus and grading coefficient showed increased means, compared with the entire dataset. Though the grading modulus had a slightly larger standard deviation, the grading coefficient showed a slight decrease in the same parameter. Both the grading coefficient and grading modulus showed improved coefficients of variation. Consequently, an improvement in this regard can be ascribed to the refinement of the material group out of the entire dataset. Also, whilst the grading coefficient seemed to conform to that of the entire dataset, the grading modulus produced a histogram in which a marked bimodal distribution is present; however the lower peak (i.e. sandy materials) has a frequency less than half that of the second peak (i.e. gravelly materials). Refer to Figure A.10b.

The basic crystalline group indicated a slightly improved mean CBR. Though the standard deviation did not indicate a notable improvement, the coefficient of variation once more showed improvement, serving as evidence of refinement within the group properties. The histogram also indicates two peaks that may be ascribed to the variability of materials sampled, rather than a definitive bimodal distribution (Figure A.10c).

A.1.3 Acid Crystalline Materials

The Atterberg Limits and the linear shrinkage of the acid crystalline group showed little variation from the entire group with regard to means calculated. All four

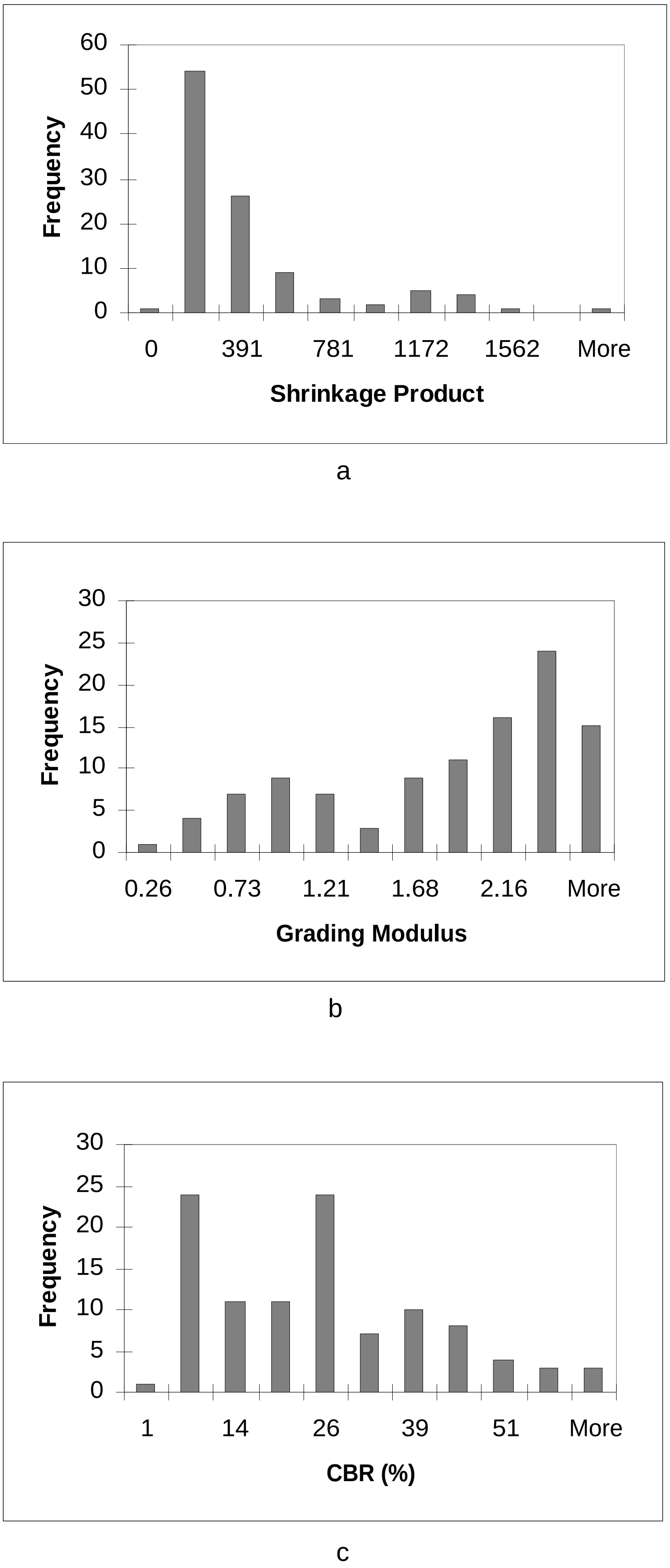


Figure A.10 Frequency Distributions: Basic Crystalline, 95% Mod AASHTO (Moist regions)

parameters, however, showed a markedly reduced standard deviation, as well as an improved coefficient of variation, confirming the smaller range. The linear shrinkage product and shrinkage product revealed lower means than the entire group which suggests that the acid crystalline group materials are less susceptible to swelling and shrinkage compared with the entire dataset. Considering that weathered granite materials generally form a more sandy material, this is expected although it will not necessarily hold true for all cases analysed. At the same time a negatively skewed histogram was produced for the liquid limit and a normally distributed histogram for the plasticity index (Figure A.11a and Figure A.11b). In both histograms the peak values very nearly coincided with the peak values for the entire group's histograms. The linear shrinkage was found to have a near normal distribution that is distorted only by the inclusion of non-plastic samples in the analysis (Figure A.11c). The linear shrinkage product and shrinkage product both had improved coefficients of variation, showing a large improvement in the data which can be ascribed to the rock material group properties (Table A.2).

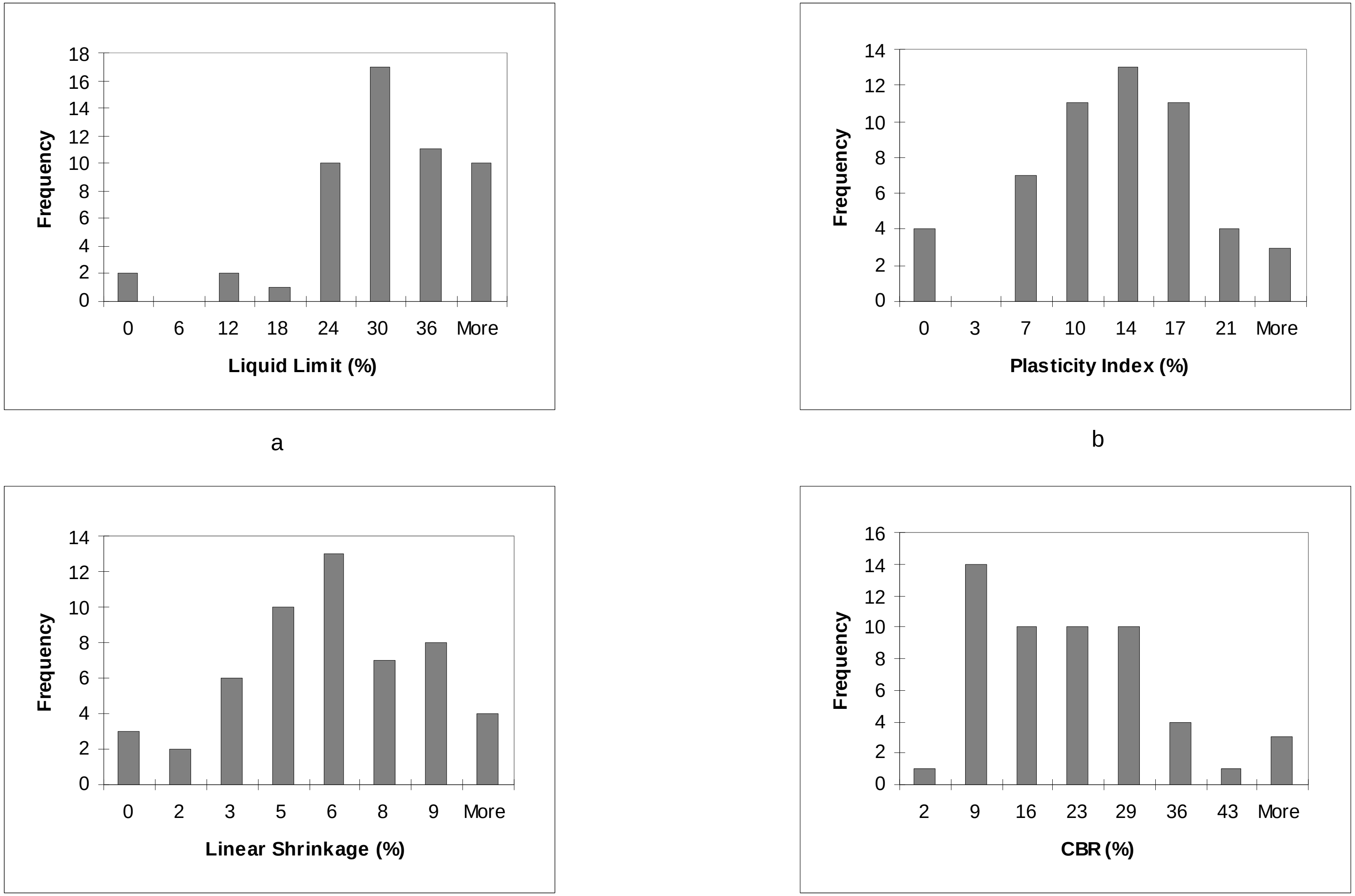
The grading modulus and grading coefficient indicate coarser grading for the acid crystalline group, than the entire group. Considering the example mentioned above, a granitic material weathers to (sometimes coarse) sand in a moist environment, whereas a doleritic material, for example, mostly weathers to a clayey product. Whilst the grading coefficient showed little improvement in terms of standard deviation, that of the grading modulus improved noticeably to 0,45 from the entire group standard deviation of 0,62. Both the grading modulus and grading coefficient showed considerable improvement with regard to the coefficient of variation too. The grading modulus, in particular, had a coefficient of variation of 0,28.

The last parameter analysed – the CBR – had a mean value slightly lower than the entire group. Simultaneously the standard deviation and coefficient of variation showed some improvement, though the coefficient of variation of 0,63 still suggests

Table A.2 Descriptive Statistics Summary: Acid Crystalline (M[illegible]TO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,7	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,50	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Acid Crystalline : 95% Mod AASHTO									
Mean	27,9	11,3	16,6	5,3	153,9	252,3	1,59	22,1	18,2
Standard Deviation	9,11	5,57	5,31	2,70	132,90	176,79	0,45	10,97	11,49
Coefficient of Variation	0,33	0,50	0,32	0,51	0,86	0,70	0,28	0,50	0,63
Minimum	0	0	0	0	0	0	0,71	0	2
Maximum	42	24	30	11	531	792	2,35	42	50
n	53	53	53	53	53	53	53	53	53

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



a

b

c

d

Figure A.11 Frequency Distributions: Acid Crystalline, 95% Mod AASHTO (Moist regions)

unpredictable and variable properties. The histogram – similar to the entire group – had a positively skewed distribution, but the histogram is far flatter due to the restricted range of CBR scores achieved (Figure A.11d).

A.1.4 High Silica Materials

Descriptive statistics analyses of the 93 samples indicate that, in general, the high silica group has lower mean Atterberg Limits. This can be ascribed to the fact that high silica rock materials are usually more inert with regard to producing clayey materials. In fact, in many instances any fine materials (e.g. clay or silt) in the sample are from colluvial materials sampled with the rock material. Chert gravel, for instance, often gets its strength from the inert rock gravel, whilst its finer matrix component comes from overlying colluvium or residual materials. The Atterberg Limits also had considerably reduced standard deviations and notable improved coefficients of variation (Table A.3).

Histograms for the Atterberg Limits conform to those of the entire group, except that values are reduced according to the parameter ranges recorded during testing. The influence of non-plastic materials is also notable, but expected. The linear shrinkage, linear shrinkage product and shrinkage product indicate that the high silica group indeed has a reduced activity potential. All three parameters showed a much lower mean – particularly the linear shrinkage product and shrinkage product – as well as reduced standard deviations. The coefficients of variation, on the other hand, do not show any significant improvement. The linear shrinkage histogram complies with that of the entire group, even though recorded values are considerably lower. Simultaneously the linear shrinkage product and shrinkage product also conform to the distribution of the group, but are less peaked, as illustrated in Figure A.12a and Figure A.12b respectively. This is also ascribed to the reduced range of values recorded for the rock group, which in turn can be ascribed to its more inert nature.

The mean grading modulus was calculated to be 1,49, signifying that in general the high silica materials are coarser than the entire group. The standard deviation did not

Table A.3 Descriptive Statistics Summary: High Silica (Moist region, 95% Mod AASHTO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
High Silica : 95% Mod AASHTO									
Mean	20,8	7,9	12,9	3,7	130,6	211,2	1,49	16,3	26,3
Standard Deviation	9,48	5,56	5,06	2,61	145,53	206,02	0,61	11,85	21,52
Coefficient of Variation	0,46	0,70	0,39	0,71	1,11	0,98	0,41	0,73	0,82
Minimum	0	0	0	0	0	0	0,44	0	1
Maximum	52	29	23	13	813	1118	2,48	41	105
n	93	93	93	93	93	93	93	93	93

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

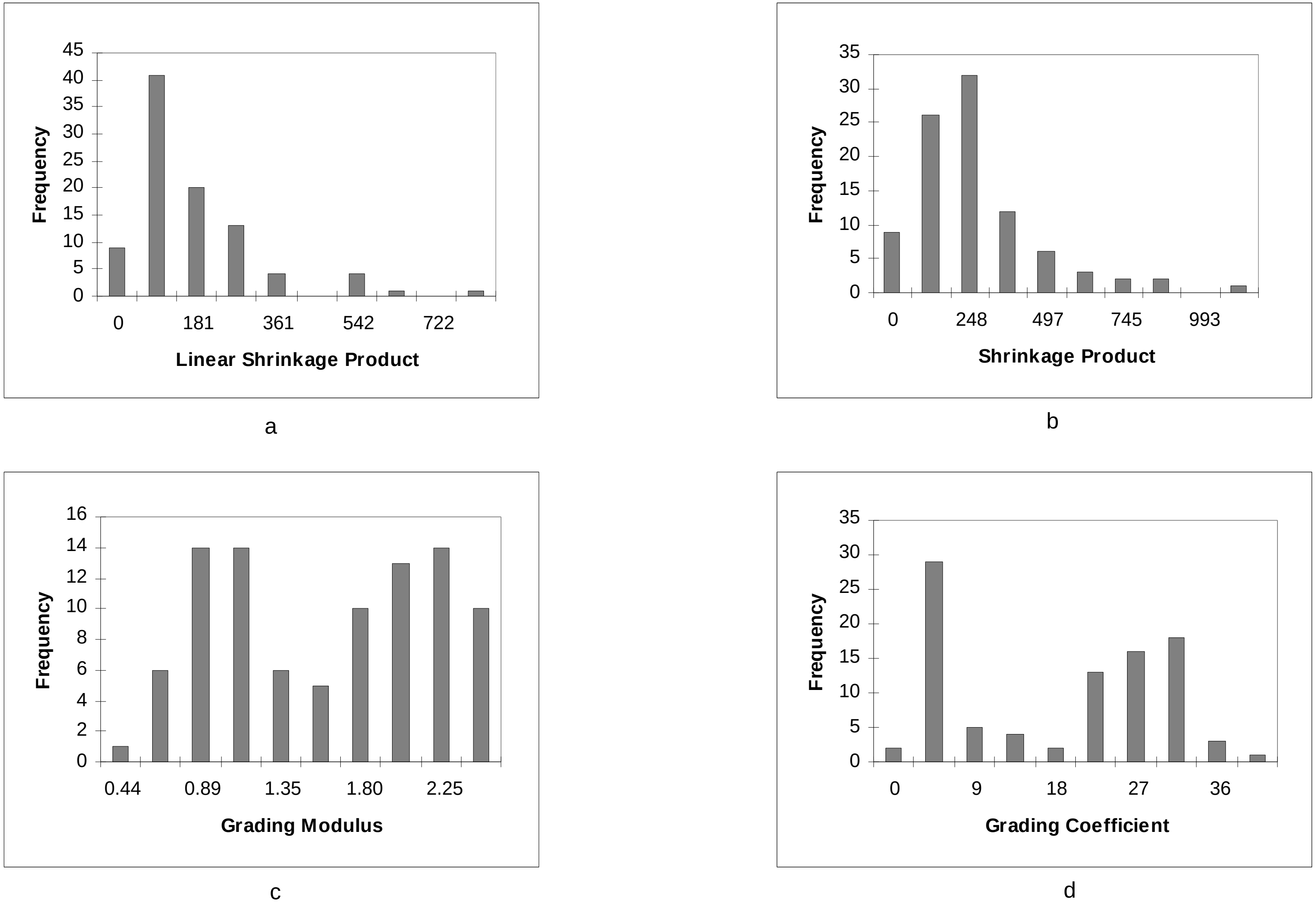


Figure A.12 Frequency Distributions: High Silica, 95% Mod AASHTO (Moist regions) improve significantly. The grading coefficient revealed a slightly larger standard deviation and coefficient of variation suggesting little refinement from the group. As with most of the other parameters of the group, the grading modulus and gradient coefficient's histograms conform in shape to those of the entire group, but with reduced values and peaks. The grading coefficient histogram also had a smaller second peak in its bimodal distribution, compared with the entire group. The two histograms are illustrated in Figure A.12c and Figure A.12d.

The general assumption that high silica materials are ideal for road construction is supported by the fact that the material group produced a mean CBR of 26,3%, as opposed to the entire group's mean CBR of 19,6%. The standard deviation is notably larger than that of the entire group, but the recorded CBR values span nearly the same range. The coefficient of variation improved slightly, but not enough to be of significance.

A.1.5 Arenaceous Materials

The descriptive statistics – as determined from 26 samples of arenaceous material – revealed interesting results. The Atterberg Limits of this group had mean values roughly half that of the entire group. The means recorded for the liquid limit, plasticity index, plastic limit and additionally the linear shrinkage, were 13,2%, 4,4%, 8,8% and 2,1%, respectively. Of the four parameters, the liquid limit, plasticity index and linear shrinkage also showed a marked improvement in standard deviation, though the coefficients of variation indicate that the improvements are not necessarily ascribed to material characteristics, as the coefficients of variation were mostly higher than that of the group for the same parameter. Furthermore, histograms of the Atterberg Limits were of limited use, due to the fact that only 26 samples were analysed. This was deemed insufficient and – combined with the bias resulting from non-plastic materials – delivered very general results. It would be expected, though, that the histogram for the Atterberg Limits would generally be positively skewed, tending towards lower values. The linear shrinkage histogram – illustrated in Figure A.13a – shows a positively skewed graph that is again ascribed to the tendency of the material to be non-plastic. For all practical purposes, the first bar of the histogram

(0,0) may be ignored to remove the bias produced by non-plastic materials, though the abundance of non-plastic samples does convey a lot about the material group (a separate model will be developed to directly address non-plastic materials). The positively skewed shape can then be clearly observed. A comparison between the entire group and the material group is illustrated in Table A.4.

Considering the reduced mean linear shrinkage of the group, a reduced mean linear shrinkage product and shrinkage product are not entirely unexpected; however the recorded mean values for the two parameters were 49,08 and 97,96 respectively. This comes to roughly a quarter and a third of the entire group's mean values for the same parameters. As with the linear shrinkage, positively skewed histograms were produced by the linear shrinkage product (Figure A.13b) and shrinkage product (Figure A.13c). This reiterates the tendency of the material toward a non-plastic nature.

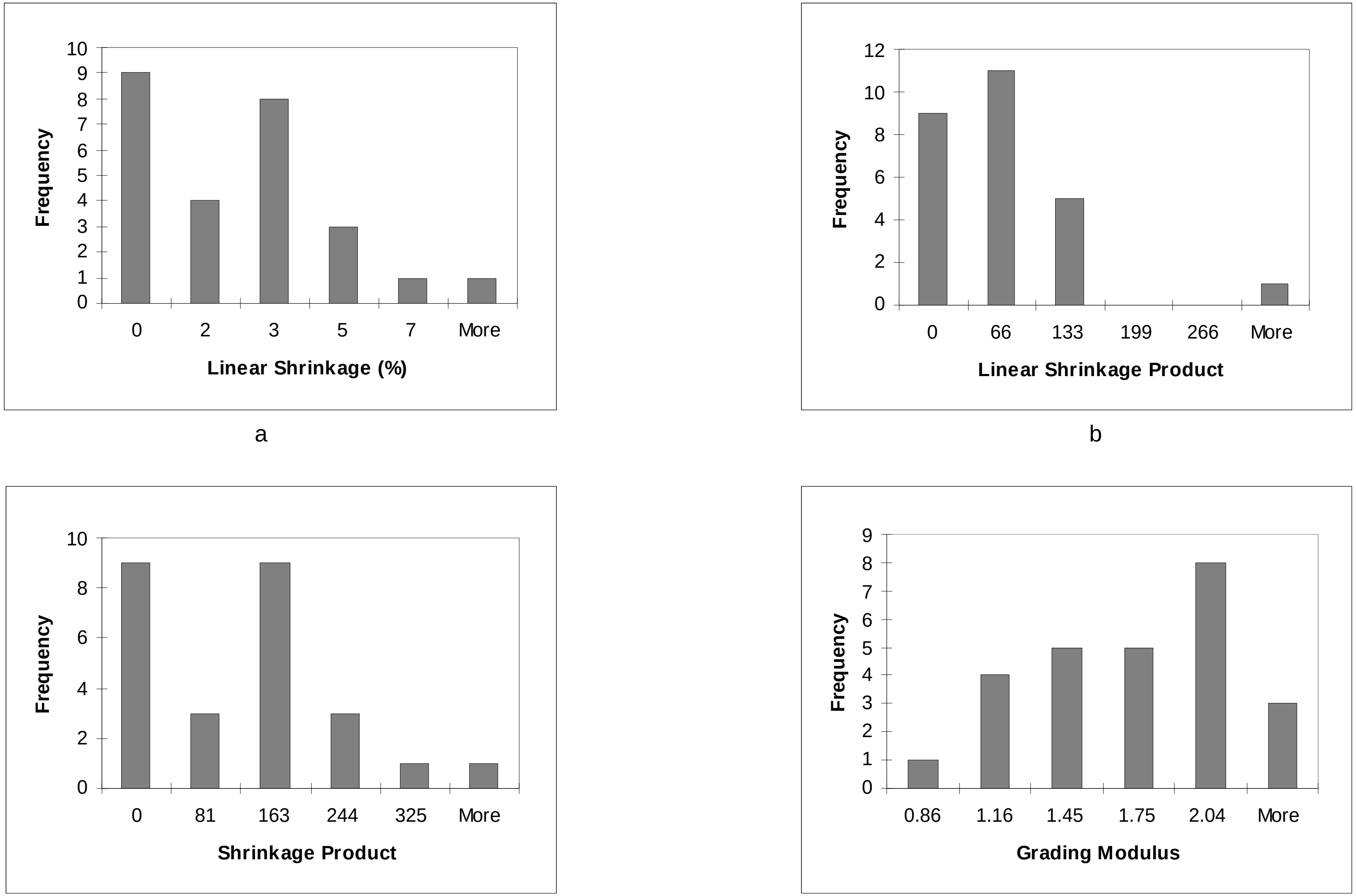
Analysis of the grading properties revealed that the arenaceous group tended to be coarser than the entire group of data analysed. A mean grading modulus of 1,59 was calculated, compared with the entire group's 1,43. A significantly reduced standard deviation was also noted, but more importantly the coefficient of variation was only 0,24. Simultaneously, the grading coefficient also showed refinement to a higher mean, reduced standard deviation and also an improved coefficient of variation. Though the grading coefficient produced a variable histogram, the grading modulus showed a clear negative skewness, suggesting that the material tends towards a coarser distribution (Figure A.13d). This appears to hold true, considering a minimum grading modulus of 0,86 for the group.

Lastly, the mean CBR of the arenaceous group was 24,9%, some 5% higher than that of the entire group. The standard deviation and coefficient of variation of this parameter also showed a marked improvement that serves as evidence of less variable material properties.

Table A.4 Descriptive Statistics Summary: Arenaceous (Moist r[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,7	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,50	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Arenaceous : 95% Mod AASHTO									
Mean	13,2	4,3	8,8	2,1	49,1	98,0	1,59	19,1	24,9
Standard Deviation	10,34	4,52	6,34	2,04	66,84	98,92	0,39	7,70	11,64
Coefficient of Variation	0,79	1,04	0,72	0,99	1,36	1,01	0,24	0,40	0,47
Minimum	0	0	0	0	0	0	0,86	7	2
Maximum	40	19	21	8	332	407	2,34	34	45
n	26	26	26	26	26	26	26	26	26

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



a

b

c

d

Figure A.13 Frequency Distribution: Arenaceous, 95% Mod AASHTO (Moist regions)

A.1.6 Argillaceous Materials

A total of 73 samples of argillaceous material was analysed and descriptive statistics revealed that the Atterberg Limits did not vary significantly from the entire group, both with regard to mean values and standard deviation. The liquid limit and plasticity index did, however, show slightly improved coefficients of variation, whilst the plastic limit had a slightly higher coefficient of variation. The liquid limit, plasticity index and plastic limit have positively skewed histograms which are difficult to interpret, due to the fact that all three histograms are somewhat deformed by a number of non-plastic samples which result in a peak at zero. The three respective histograms are illustrated in Figure A.14a-c. Of interest is that, once disregarding the bias of non-plastic materials, none of the three parameters have exceptionally high Atterberg Limits. One would expect that shale, for example, could have elevated Atterberg Limits due to the larger constituent of fine particles in the sedimentary composition. Critically, one must remember the initial bias discussed earlier – that of field selection. Considering shale as an example, a highly weathered shale material is likely to have elevated Atterberg Limits, excessive fines and most likely, poor CBR scores. However, in-field judgement would lead to such a material not being sampled. Instead, only materials that are deemed potential construction material will be sampled. A summary of the descriptive statistics is illustrated in Table A.5.

The linear shrinkage, linear shrinkage product and shrinkage product confirm the selective sampling discussed above. The mean linear shrinkage, linear shrinkage product and shrinkage product are all notably lower than that of the entire group. Also, the latter two parameters had a reduced standard deviation compared with the entire group, whilst the former had a slightly higher standard deviation. None of the three parameters showed a significant improvement in its coefficient of variation either. The histograms for the linear shrinkage product and shrinkage product each show a clear positively skewed distribution (Figure A.14d-e), emphasising the bias in sampling.

Perhaps the best illustration of selective sampling can be obtained from the grading modulus. A mean grading modulus of 1,62 was calculated. Compared with the entire

Table A.5 Descriptive Statistics Summary: Argillaceous (Moist [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Argillaceous : 95% Mod AASHTO									
Mean	25,5	9,5	16,0	4,7	172,9	229,1	1,62	20,2	17,1
Standard Deviation	12,09	6,24	7,96	2,86	211,74	221,00	0,64	8,45	12,54
Coefficient of Variation	0,47	0,66	0,50	0,61	1,22	0,96	0,40	0,42	0,73
Minimum	0	0	0	0	0	0	0,17	0	2
Maximum	57	34	44	15	1104	1170	2,64	30	90
n	73	73	73	73	73	73	73	73	73

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

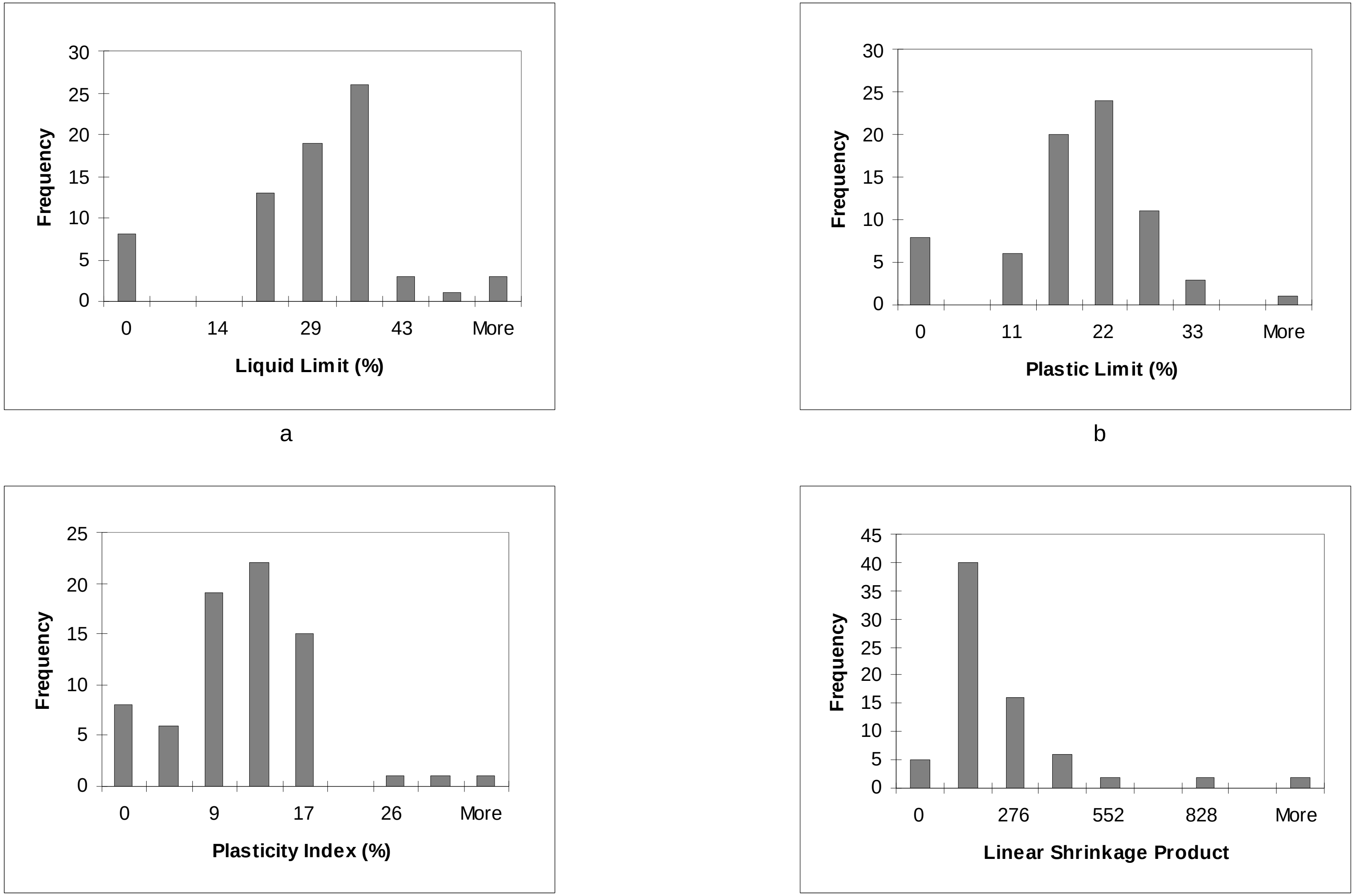


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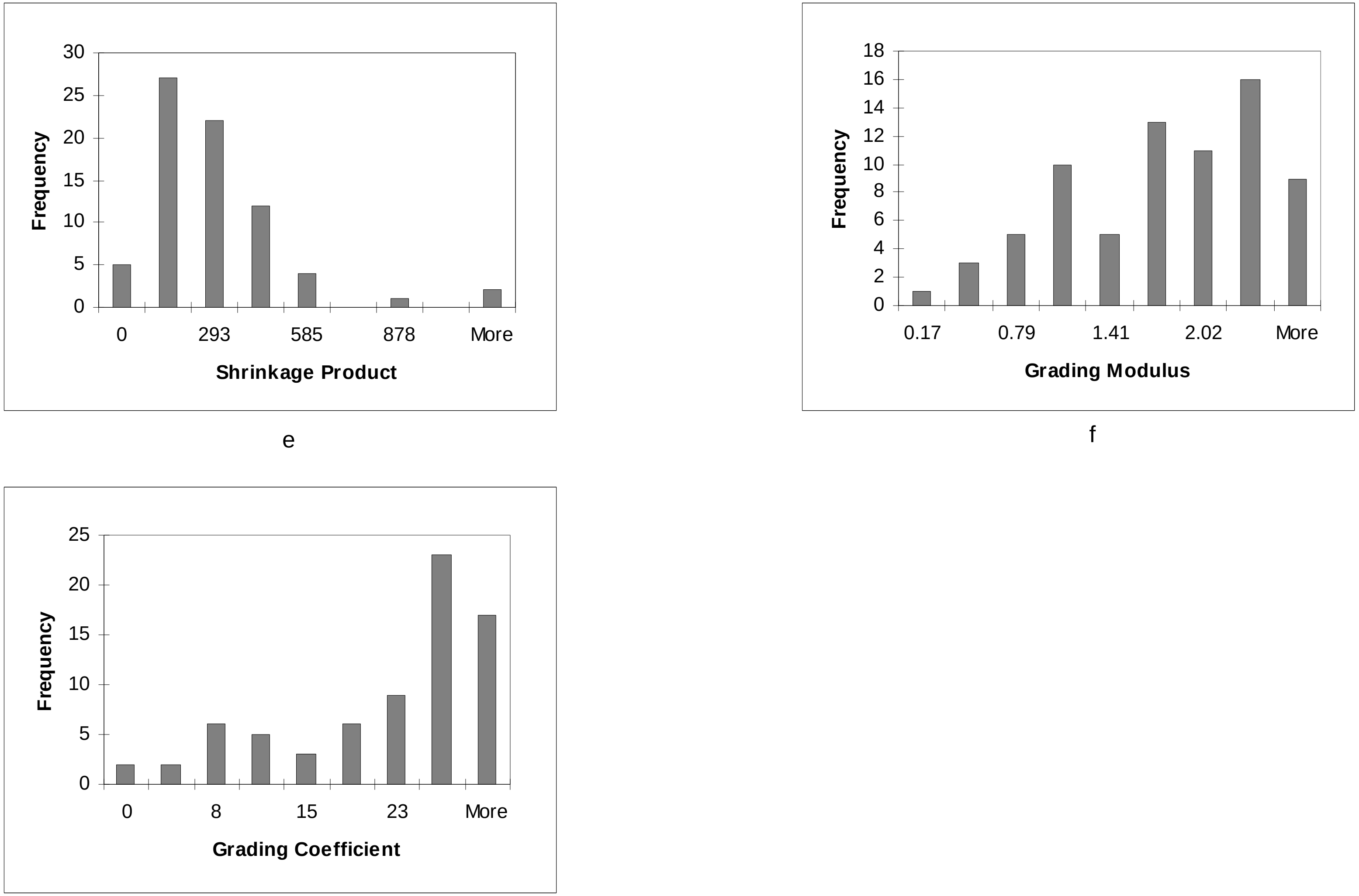
Figure A.14 Frequency Distribution: Argillaceous, 95% Mod AASHTO (Moist regions)



e

f

g

Figure A.14 Frequency Distribution: Argillaceous, 95% Mod AASHTO (Moist regions) continued group's mean grading modulus of 1,43 the argillaceous material appears coarser overall. It must also be noted that the finest argillaceous material sampled had a grading modulus of 0,17 – this proves that there are indeed such fine materials included in the sample population. The fact that the mean grading modulus – and to a lesser extent the grading coefficient –is higher than the entire group's grading modulus, indicates that coarser materials were sampled for CBR testing, as opposed to highly weathered, silty, clayey materials. Considering the variability of the material particle sizes, the standard deviation of the grading modulus and grading coefficient will therefore be of limited significance. Despite this fact, both these parameters showed improved coefficients of correlation compared with the group, which in turns suggests refinement. That being stated, both the grading modulus and grading coefficient had negatively skewed histograms (Figure A.14 f-g). This emphasises that coarser materials were sampled for CBR testing, as opposed to fine – and probably more highly weathered – materials.

Despite the suspected selective sampling of argillaceous materials, a mean CBR of 17,1% was achieved, as opposed to the mean CBR of 19,6% of the entire group. Descriptive statistics did indicate a lower standard deviation and a slightly improved coefficient of variation, though overall it appears as though the argillaceous materials are generally weaker than the majority of materials tested.

A.1.7 Calcrete Materials

The variable nature of calcrete – and other pedogenic deposits – often makes for unpredictable material behaviour. Nineteen calcrete samples analysed in this section emphasised the variability of calcrete, though the population of samples is not large enough to draw worthwhile conclusions (Table A.6). The limited number of samples is scribed to the fact that calcretes mostly occur in dry areas; however, their presence in moist areas brings to mind the effect of climate change and its influence on pedogenic material in particular.

Every parameter analysed – except the grading modulus and grading coefficient – showed both higher mean values and variability compared with the entire dataset. The

Table A.6 Descriptive Statistics Summary: Calcrete (Moist regi[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Calcrete : 95% Mod AASHTO									
Mean	29,6	15,6	14,1	6,4	353,8	465,9	1,30	16,2	23,4
Standard Deviation	28,29	18,21	11,49	7,22	539,75	619,06	0,57	8,92	24,58
Coefficient of Variation	0,95	1,17	0,82	1,13	1,53	1,33	0,44	0,55	1,05
Minimum	0	0	0	0	0	0	0,22	0	1
Maximum	81	51	40	20	1590	1777	2,35	28	69
n	19	19	19	19	19	19	19	19	19

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

standard deviation of nearly all the parameters was found to be roughly twice that of the entire group and in addition, coefficients of variation were increased. With the exception of the plastic limit, the Atterberg Limits had notably larger means, whilst the linear shrinkage product and shrinkage product had much higher mean values than the entire group. Histograms for the Atterberg Limits and shrinkage products proved erratic, with little or no recognisable distribution pattern.

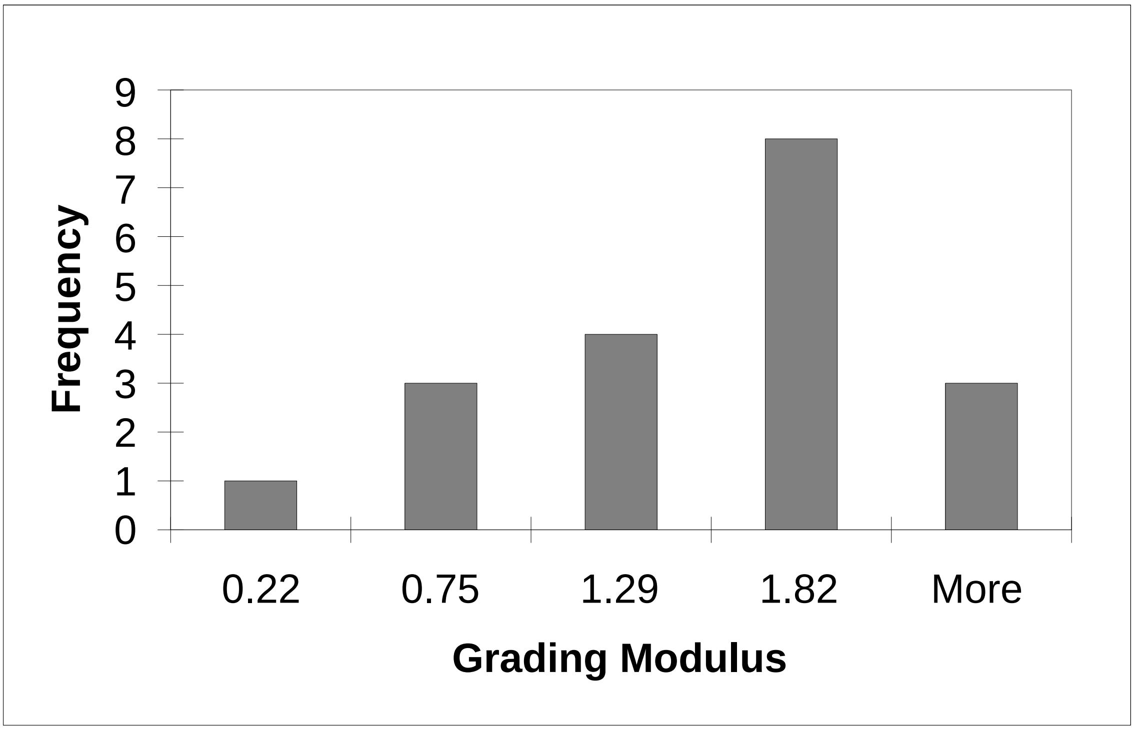
The grading modulus and grading coefficient were the only parameters with reduced standard deviations, compared with the entire group, though even this reduction was limited. Simultaneously, whilst the grading modulus and the entire group had a similar coefficient of variation, the grading coefficient of the calcrete group was slightly better than that of the entire group. Both parameters produced a negatively skewed histogram, perhaps clearer illustrated in Figure A.15a and Figure A.15b, respectively.

Disregarding the variability of the calcrete materials, a higher mean CBR was achieved than that of the entire group; however the standard deviation was found to be far greater. To illustrate the variability of the data, the mean CBR was 23,4%, but the standard deviation was 24,6. This variability along with only a small number of calcrete samples limits the applicability and significance of the histogram produced.

A.1.8 Ferricrete Materials

Some 108 ferricrete samples were analysed from moist areas. The analysis delivered unexpected results – as illustrated in Table A.7. Considering that ferricrete is a pedogenic material that may be hosted in any material, one would expect its properties to depend on the material properties of the host material(s). The descriptive statistics indicate that ferricrete very closely resembles the entire group's characteristics, but with slightly depressed Atterberg Limits and shrinkage characteristics.

The Atterberg Limits all had slightly lower means than the entire group, with smaller standard deviations as well as improved (reduced) coefficients of variation. The



a

b

Figure A.15 Frequency Distributions: Calcrete, 95% Mod AASHTO (Moist regions)

Table A.7 Descriptive Statistics Summary: Ferricrete (Moist re[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Ferricrete : 95% Mod AASHTO									
Mean	24,7	10,9	13,8	5,0	188,8	306,5	1,35	19,7	17,0
Standard Deviation	11,04	6,68	5,15	3,14	202,69	250,32	0,49	10,75	19,09
Coefficient of Variation	0,45	0,61	0,37	0,62	1,07	0,82	0,36	0,55	1,12
Minimum	0	0	0	0	0	0	0,34	2	1
Maximum	60	40	21	18	1482	1665	2,38	46	110
n	108	108	108	108	108	108	108	108	108

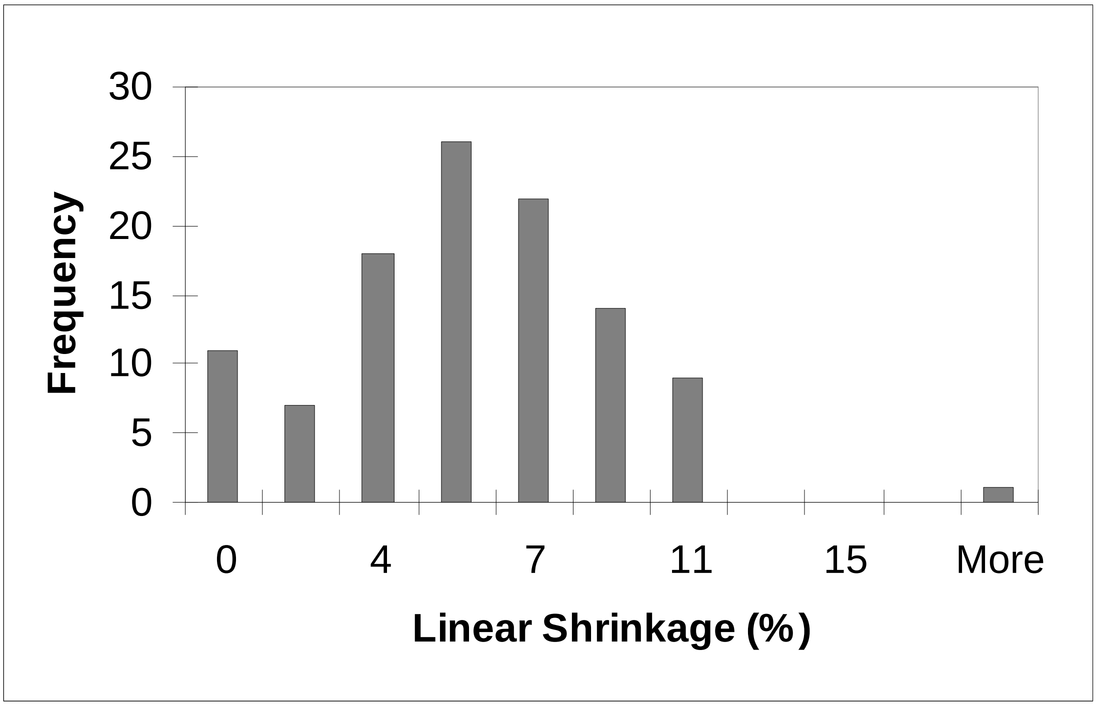
LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Atterberg Limits also had histograms conforming to that of the entire group, though they were not as peeked.

The shrinkage characteristics also showed little difference in the means. The linear shrinkage product showed the largest reduction, with a mean of 188,8 compared with 205,5 of the entire group. The linear shrinkage, linear shrinkage product and shrinkage product had reduced standard deviations compared with the entire group. The linear shrinkage product and shrinkage product had standard deviations of 202,7 and 250,3 compared with the entire group's respective standard deviations of 272,5 and 326,1. Though this might seem notably large, the scale of the two parameters must be borne in mind, as both are products of two parameters. Of interest is the fact that histograms for the linear shrinkage (Figure A.16a) and shrinkage product (Figure A.16b) seem to conform to that of the entire group, but are far less peaked. This emphasises that the ferricrete is – in very general terms – less active with regard to shrinkage than the entire group.

Analysis of the grading modulus and grading coefficient showed contradictory results. Whilst the grading modulus showed a reduction in the mean, the grading coefficient showed a small – yet notable – increase in mean. Both parameters had a reduced standard deviation compared with the entire group. The significant difference between the two parameters lies in the coefficients of variation. Whilst both parameters showed an improvement, i.e. a reduction, in the coefficient of variation, the grading modulus had a coefficient of variation of 0,36 compared with the grading coefficient's coefficient of variation of 0,55. It is therefore anticipated that the grading modulus would correlate better with further analyses.

Finally, the mean CBR for the ferricrete group was 17,0% - some 2,6% less than that of the entire group. The standard deviation of the ferricrete group was also slightly larger than that of the entire group. At the same time the coefficient of variation was larger than that of the entire group. All the points mentioned suggest that, as expected, ferricrete is a variable material, most likely due to the fact that much of its character is derived from its host material. The results also suggest that ferricrete



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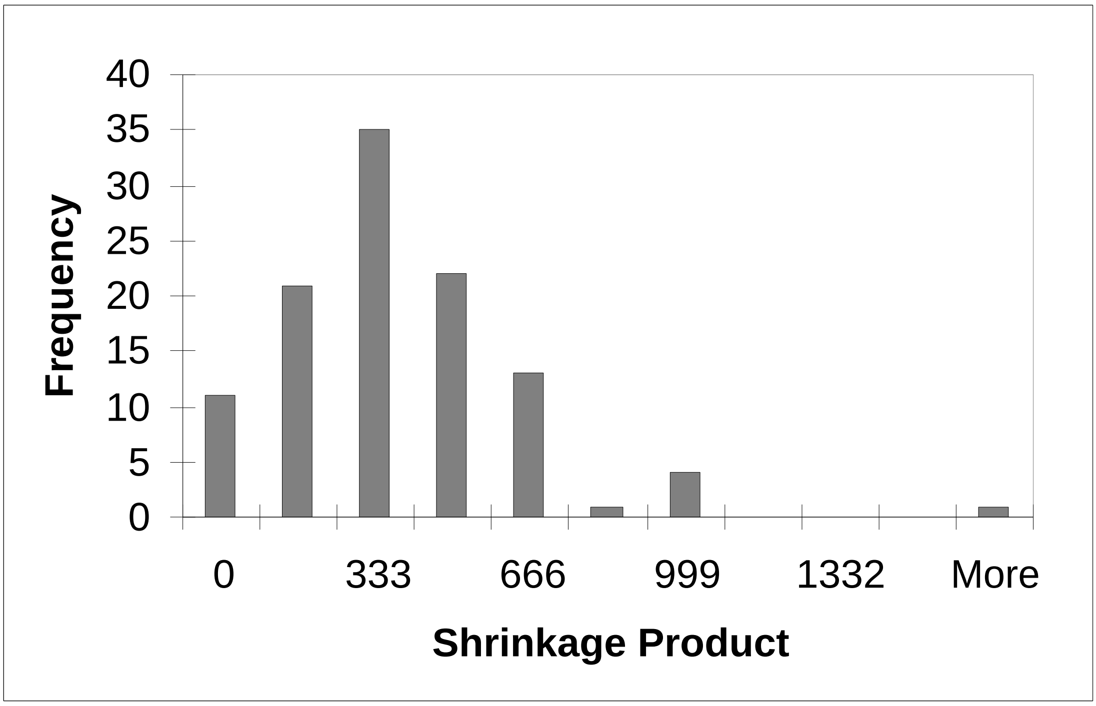

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Figure A.16 Frequency Distributions: Ferricrete, 95% Mod AASHTO (Moist regions) is not as favourable a construction material as often described in industry, despite the past evidence of good performance.

A.1.8 Colluvium

The final group of the 95% Mod AASHTO density compaction that was analysed, was that of colluvial materials in which 95 samples were included. It is logical that one would expect the largest variation in material properties from this group – even compared with pedogenic materials – as transported materials may be from a wide variety of origins (Table A.8).

Not surprisingly the colluvial materials had both a higher mean liquid limit and – consequently – a higher mean plasticity index compared with the entire group. Both parameters also had a larger standard deviation than the entire group and neither had a significantly improved coefficient of variation than its counterpart in the entire group. In contrast with the liquid limit and plasticity index, the plastic limit had only a slightly higher mean (compared with the entire group) and also a slightly improved coefficient of variation. As with the remaining Atterberg Limits, though, a larger standard deviation was recorded for the plastic limit compared with the entire group.

A good indication of the colluvial materials' properties is revealed by the linear shrinkage, linear shrinkage product and shrinkage product. All three parameters showed a large increase in mean values. Respective means of the three parameters were 6,3%, 346,6 and 497,7. Comparing these values with their overall group counterparts – 5,3%, 205,5 and 307,3 respectively – it is apparent that the colluvial materials seem to be more moisture sensitive. Despite having larger standard deviations, though, all three parameters showed lower coefficients of variation; however the reduced coefficients still suggest high variability within the data.

Analysis of the grading modulus and grading coefficient revealed that, in general, colluvial materials tend to be finer than the other materials tested. Respective means of the grading modulus and grading coefficient were 0,87 and 6,9. The entire group had respective means of 1,43 and 17,7. The standard deviation for both parameters

Table A.8 Descriptive Statistics Summary: Colluvium (Moist region, [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	26,5	11,1	15,3	5,3	205,6	307,3	1,43	17,68	19,6
Standard Deviation	13,93	8,74	6,76	3,97	272,49	326,14	0,62	11,10	17,10
Coefficient of Variation	0,53	0,78	0,44	0,75	1,33	1,06	0,43	0,63	0,87
Minimum	0	0	0	0	0	0	0,17	0	0
Maximum	88	57	44	30	1823	2083	2,64	46	110
n	574	574	574	574	574	574	574	574	574
Colluvium : 95% Mod AASHTO									
Mean	29,6	13,8	15,8	6,3	346,64	497,7	0,87	6,9	13,3
Standard Deviation	16,72	10,68	7,27	4,48	370,21	425,39	0,42	7,97	12,31
Coefficient of Variation	0,56	0,77	0,46	0,71	1,07	0,85	0,48	1,15	0,93
Minimum	0	0	0	0	0	0	0,20	0	0
Maximum	88	57	38	22	1823	2083	1,97	35	73
n	95	95	95	95	95	95	95	95	95

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

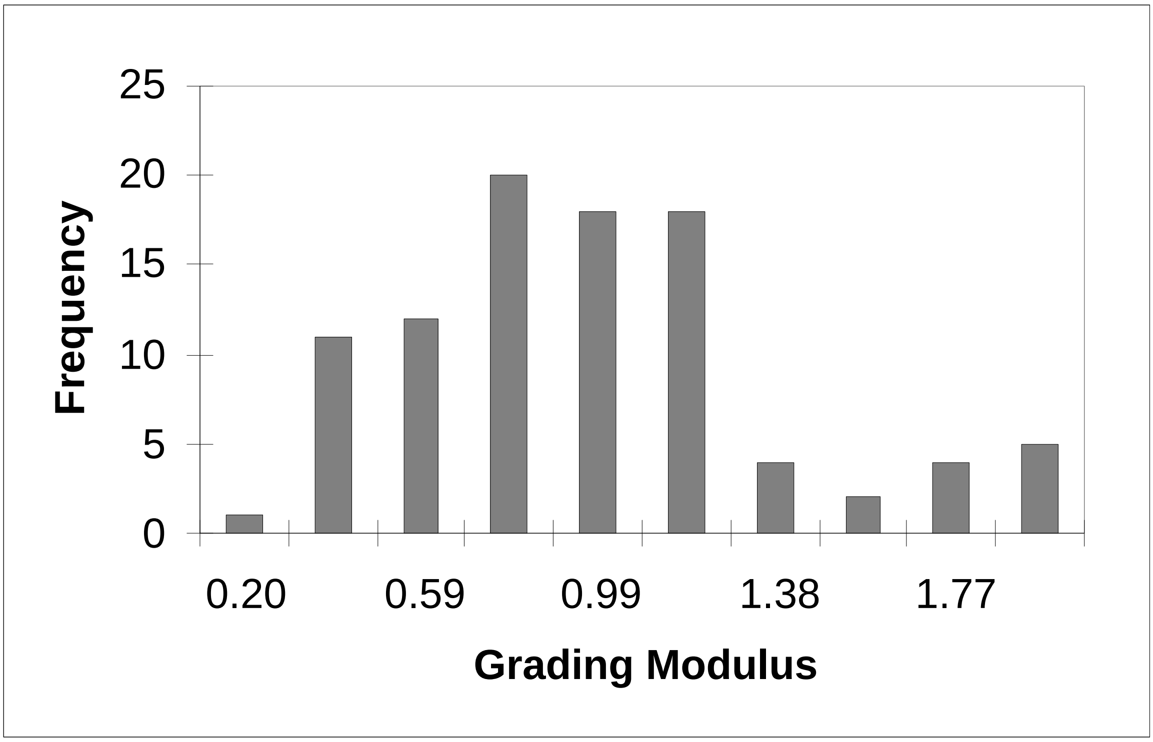
were found to be less than that of the entire group, which suggests that colluvial materials sampled are not as variable with regard to (particularly coarser) particle size distribution. It is interesting to note that whilst the grading modulus had a slightly improved coefficient of variation relative to the entire group, the grading coefficient had a much larger coefficient. As with the ferricrete, it is expected that the grading modulus would correlate better with other material properties than the grading coefficient. Histograms of the grading modulus and grading coefficient – illustrated in Figure A.17a and Figure A.17b – indicate the tendency of the material to be finer than the entire group. The histogram peaks are also less peaked than that of the entire group, but critically the concentration at both lower grading moduli and grading coefficients is clearly illustrated.

The last parameter tested – the CBR – indicated that colluvial materials tend to produce poorer results than the cumulative group tested. A mean CBR of 13,3% was revealed, compared with a mean CBR of 19,6% of the entire group. Whilst the standard deviation showed notable improvement from the entire group, the coefficient of variation was slightly higher. This would suggest that the colluvial material is highly variable, which is not surprising considering the composition thereof.

A.1.9 Non-Plastic Materials

After considering the difference in the properties of non-plastic materials from those of other materials (of any material type), it was deemed wise to do a separate analysis of only non-plastic materials. In this instance, “non-plastic” materials are materials for which a plasticity index of 0% is recorded.

Analyses of Atterberg Limits and shrinkage parameters was deemed senseless for the non-plastic materials, as both sets of parameters will be severely incapacitated due to the non-plastic nature of the materials. The 62 samples analysed revealed that the non-plastic materials are slightly coarser than the entire group, with slight reduction in both the standard deviation and coefficient of variation. The striking difference between the non-plastic materials and the entire group, however, came from the CBR values. A mean CBR of 33,8% was calculated for non-plastic materials compared



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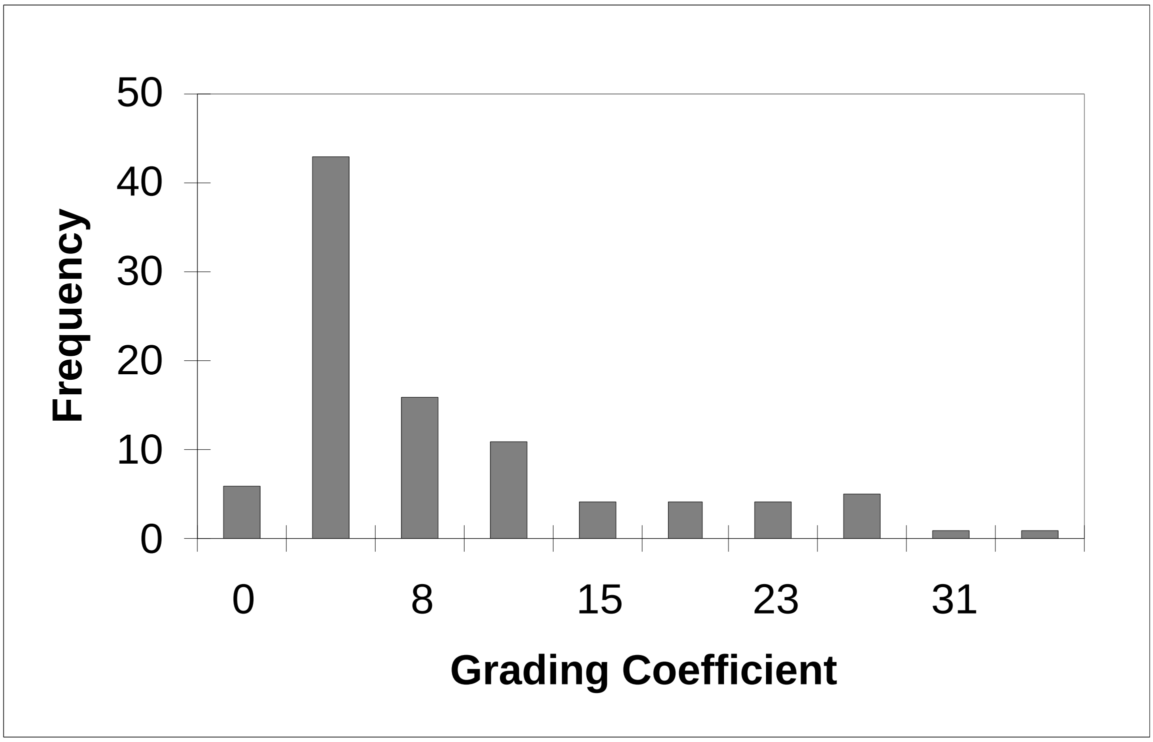

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Figure A.17 Frequency Distribution: Colluvium, 95% Mod AASHTO (Moist regions) with a mean of 19,6% of the entire group. The notably larger standard deviation and slightly reduced coefficient of variation confirms a spread of data, as with the entire group.

A.2 Descriptive Statistics: Moist Areas: 98% Mod AASHTO

A.2.1 All Groups

A number of small differences were noted between materials of the 95% Mod AASHTO density and the 98% Mod AASHTO density; however these differences were not significant and can not be related to the density measure of the material (i.e. the slight variability is not dependant on the material compaction, e.g. variations in the liquid limit). A summary of the descriptive statistics is included in Table A.9. From the summary the following was observed:

- *Liquid Limit:* A mean liquid limit of 25,8% was calculated for the entire dataset, which consisted of 1016 samples. A standard deviation of 13,69 was recorded and so too a coefficient of variation of 0,53. The parameter values ranged between 0% (non-plastic) and 88%, which indicates a large spread of sample properties, as is to be expected. A histogram for the liquid limit – illustrated in Figure A.18 – shows a positively skewed distribution, with an additional peak at zero which is ascribed to non-plastic materials.
- *Plastic Limit:* Similar to the liquid limit and plasticity index, the plastic limit had a mean slightly lower than that of its 95% Mod AASHTO counterpart. A marginally larger range was noted for the 98% Mod AASHTO group, ranging from 0% to 66%. A standard deviation of 6,95 was calculated and the coefficient of variation was established to be 0,47; hence the plastic limit has the best normalised correlation of the three Atterberg Limits. Though the histogram of the plastic limit was positively skewed, it appeared to have much higher peak values than either the liquid limit or plasticity index, suggesting that the recorded values are more clustered than in the other two parameters (Figure A.19).

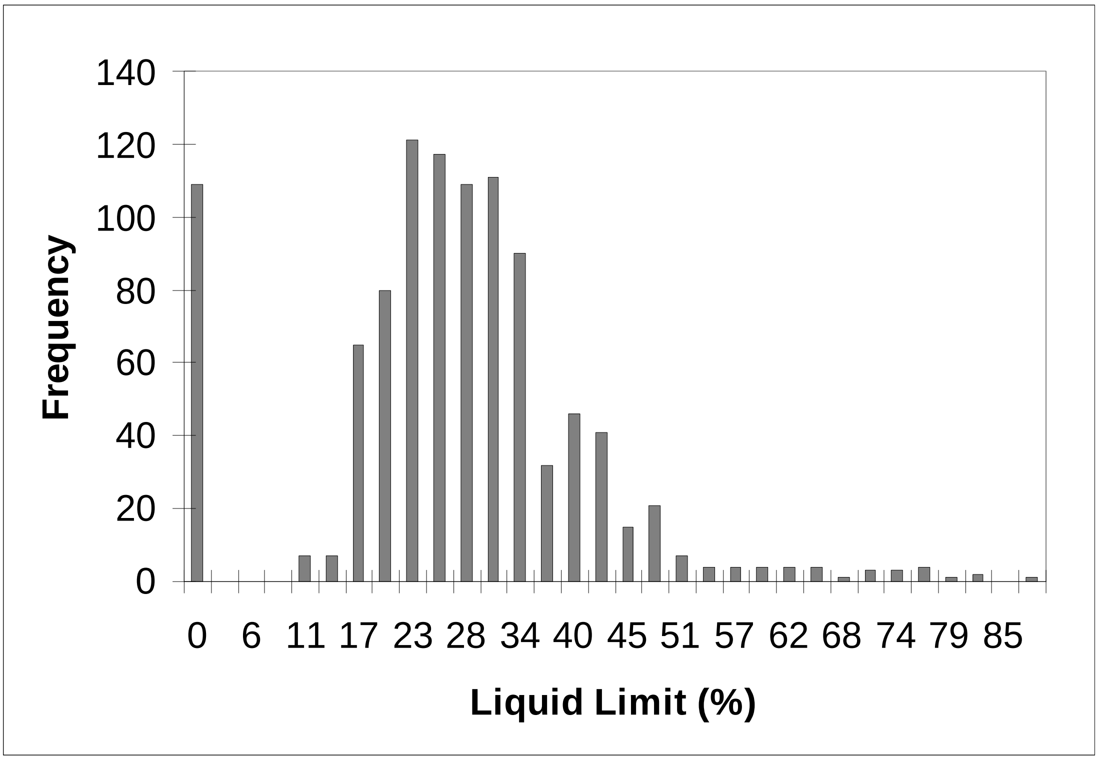

Figure A.18 Frequency Distribution of Liquid Limit (All groups, 98% Mod AASHTO)

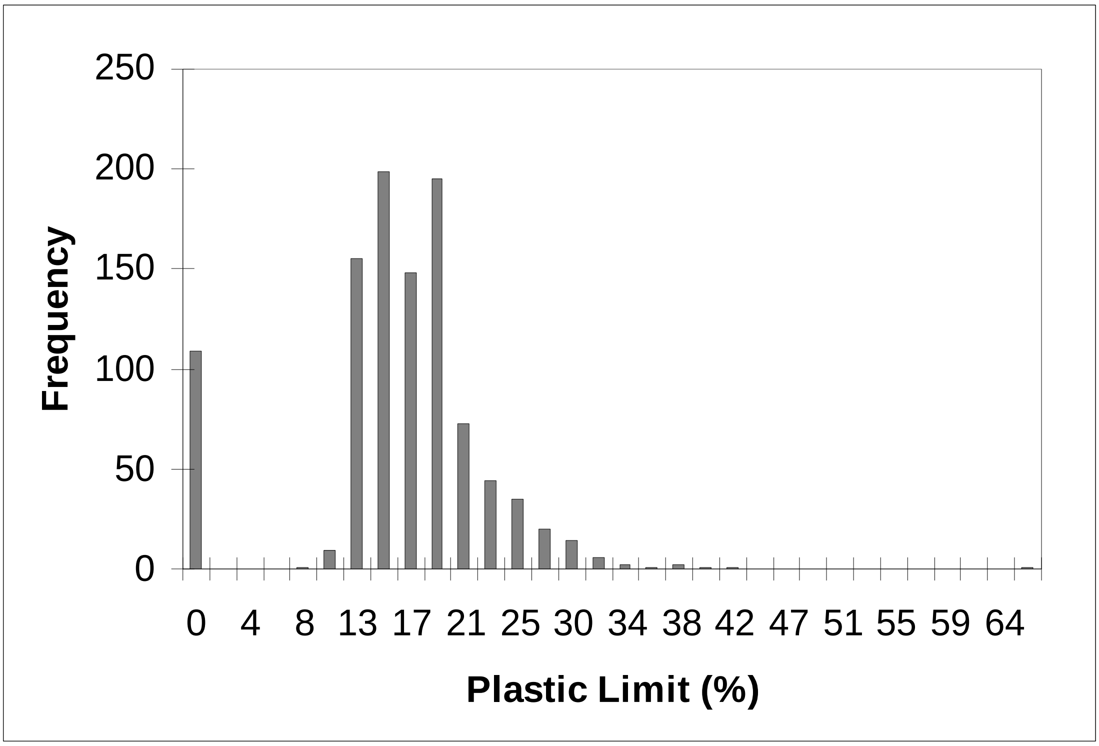

Figure A.19 Frequency Distribution of Plastic Limit (All groups, 98% Mod AASHTO)

- *Plasticity Index:* Plasticity indices ranged from 0% (non-plastic) to 57%, representing materials with no affinity for volume changes to material with a very high affinity. The mean was calculated as 10,9% with a standard deviation of 8,33 and a coefficient of variation of 0,77. This indicates that despite normalisation, results analysed were still highly variable. The plasticity index resembled the liquid limit's distribution, with a positively skewed distribution and an additional peak at 0%, representing non-plastic materials (Figure A.20). It must once more be borne in mind that the plasticity index is subject to a double error, as it is derived from both the liquid limit and the plastic limit.
- *Linear Shrinkage:* The linear shrinkage properties correlated well with the 95% Mod AASHTO values discussed. A mean linear shrinkage of 5,1% was recorded, whilst the standard deviation and coefficient of variation were calculated to be 3,80 and 0,74 respectively. The recorded values ranged from 0% to 30%, indicating again that both inert materials and materials with an affinity for volume changes were analysed. A positively skewed histogram - Figure A.21 – illustrates that samples with elevated linear shrinkages (higher than thirteen) are the exception to lower linear shrinkages.

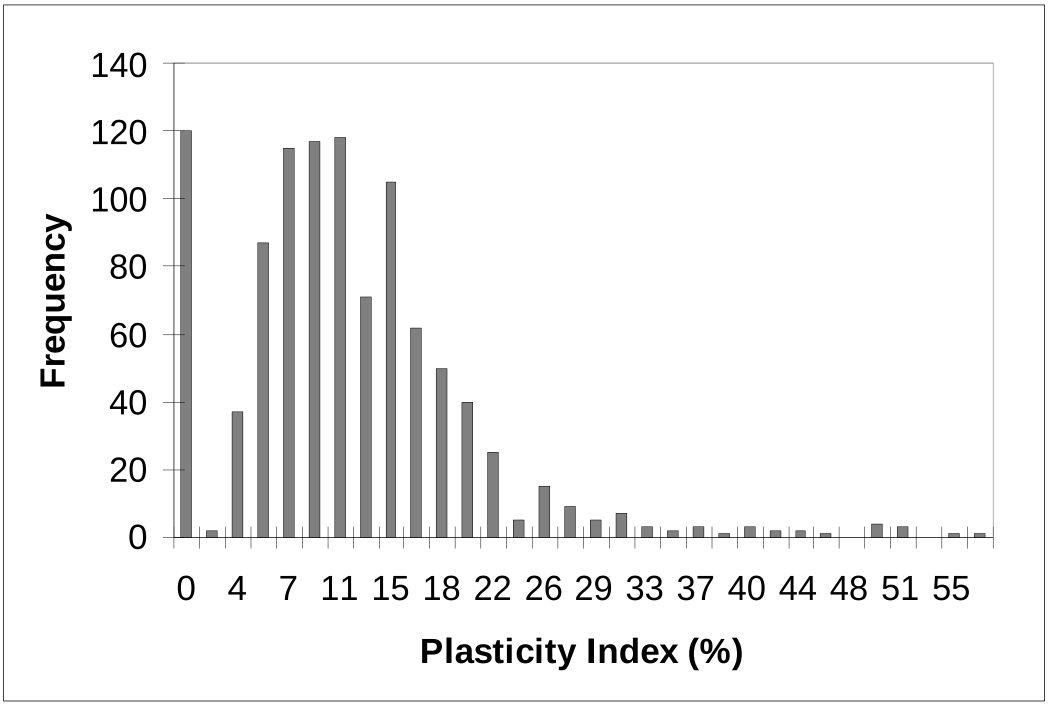

Figure A.20 Frequency Distribution of Plasticity Index (All groups, 98% Mod AASHTO)

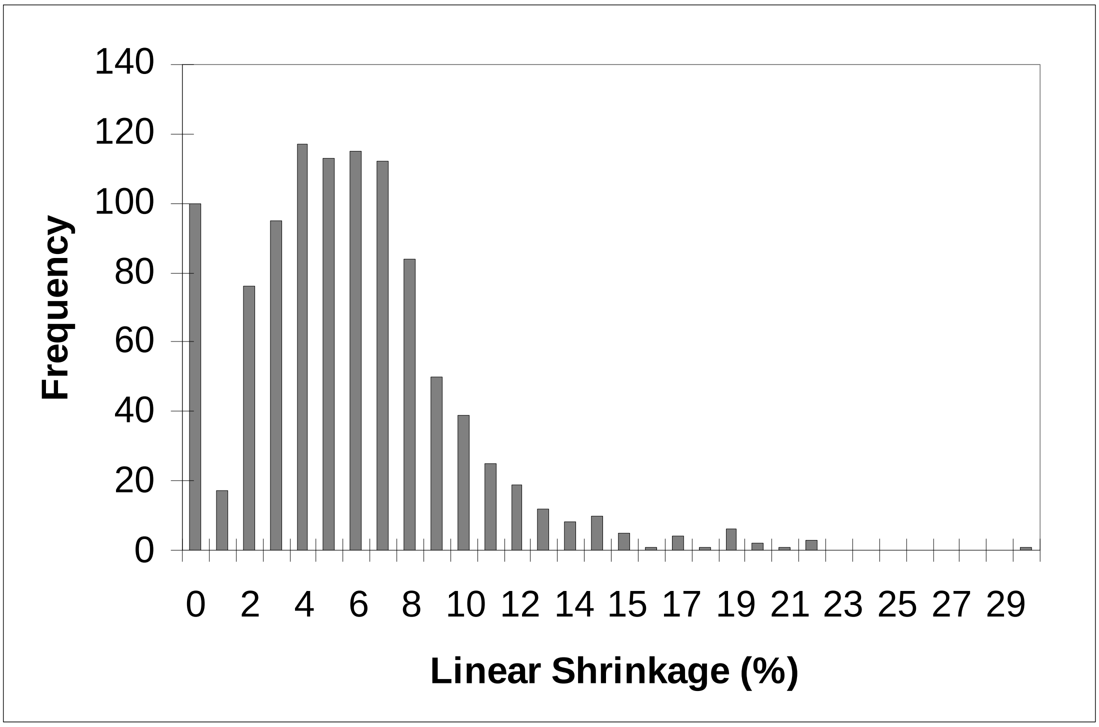

Figure A.21 Frequency Distribution of Linear Shrinkage (All groups, 98% Mod AASHTO)

- *Linear Shrinkage Product:* The linear shrinkage product emphasised how well properties of the 95% Mod AASHTO group and 98% Mod AASHTO group correlate. A mean of 205,5 was recorded for the 95% Mod AASHTO group, and 208,6 for the 98% Mod AASHTO group. Considering that the parameter is a mathematical product (of the linear shrinkage and P075), the correlation is largely significant. A standard deviation of 258,01 was recorded and so too a coefficient of variation of 1,24. The coefficient of variation – as with the 95% Mod AASHTO group – emphasises the variability of the materials analysed as far as this parameter is concerned. The range recorded spanned from zero to 1823. The parameter's histogram (Figure A.22) revealed a very well defined, positively skewed shape indicating that despite the large range, the majority of the samples had proportionally low scores. This is confirmed by the parameter's mean.

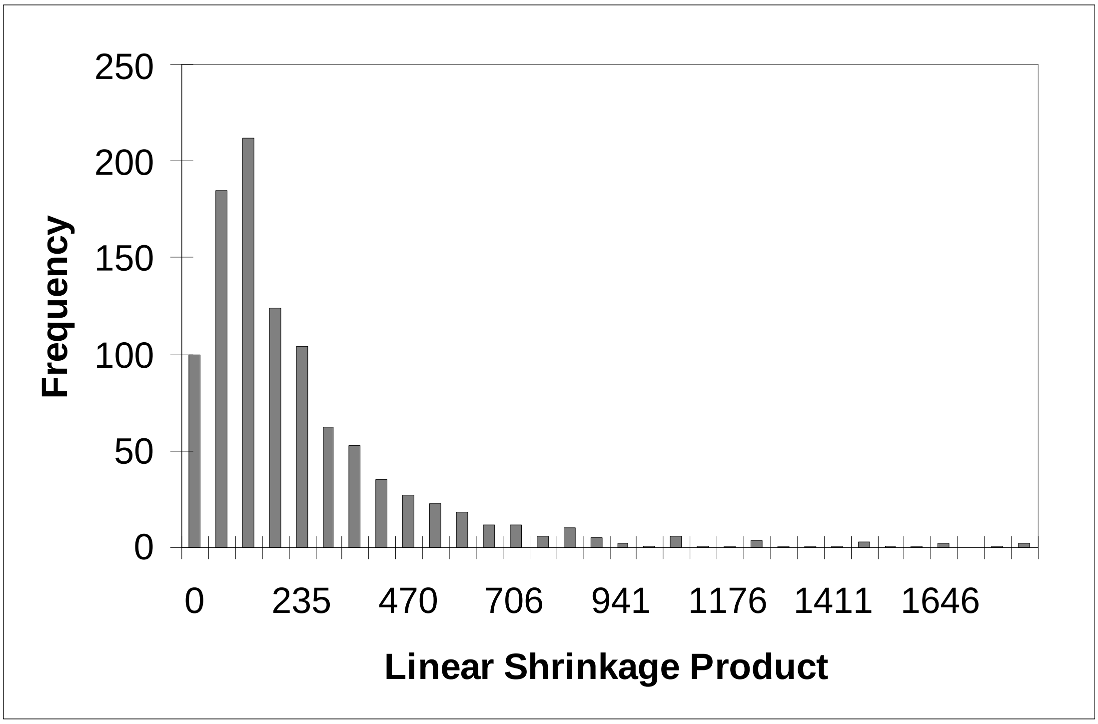

Figure A.22 Frequency Distribution of Linear Shrinkage Product (All groups, 98% Mod AASHTO, moist regions)

- *Shrinkage Product:* As with the linear shrinkage product, the shrinkage product complied well with its 95% Mod AASHTO counterpart. A mean of 315,7 was calculated, ranging from zero to 2083. A standard deviation of 316,88 was recorded, whilst 1,00 was recorded as the coefficient of variation. This implies poor property correlation within the group; considered that a coefficient of variation of 1,00 means that the standard deviation is equal to the mean. The shrinkage product also has a histogram with similar properties to the linear shrinkage product, i.e. a well-developed, clear, positively skewed shape emphasising the relatively low mean compared with the range recorded (Figure A.23).
- *Grading Modulus:* One of only two parameters which showed notable deviation from the 95% Mod AASHTO group, was the grading modulus. A mean grading modulus of 1,34 was calculated, compared with a mean of 1,43 for the 95% Mod AASHTO group. It is anticipated, though, that the finer nature of the 98% Mod AASHTO group can not be practically related to the compactive effort and is therefore considered to have resulted from sampling differences.

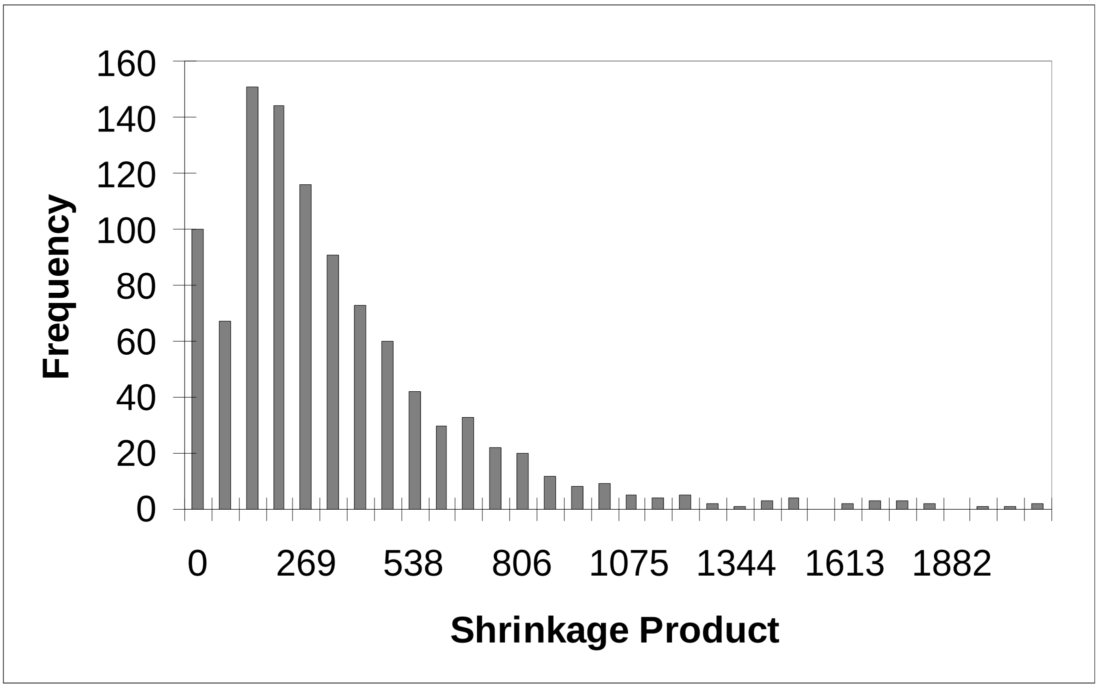

Figure A.23 Frequency Distribution of Shrinkage Product (All groups, 98% Mod AASHTO, moist regions)

It must also be emphasised that 574 samples were analysed for the 95% Mod AASHTO group, whereas 1016 samples were analysed for the 98% Mod AASHTO group; hence the latter is likely to be more representative. The grading moduli ranged from 0,10 to 2,68 with a standard deviation of 0,59. The coefficient of variation was 0,44, making it the parameter with the best normalised correlation (the same was noted for the 95% Mod AASHTO group). Figure A.24 illustrates the parameter's histogram, which illustrates a large size distribution. The histogram was found to be erratic, as one clear peak is clear (GM=1,02); however the remainder of the histogram may be interpreted either as a very flat positive distribution or a poorly developed bimodal distribution. Either interpretation emphasises the erratic make-up of samples analysed.

- *Grading Coefficient:* As with the grading modulus, the grading coefficient indicated a fine material make-up. A mean of 16,0 was calculated (compared with 17,7 of the 95% Mod AASHTO group), with a standard deviation of 11,22 and coefficient of variation of 0,70. The parameter therefore showed poorer correlation after normalisation than the grading modulus. The parameter values ranged from zero to 45. Of importance is the grading coefficient's histogram which clearly indicates a bimodal distribution, suggesting that the grading modulus also has a bimodal distribution, rather than a poorly developed, positively skewed distribution (Figure A.25). The first peak of the grading coefficient's histogram is more pronounced than the second and is most likely associated with finer materials such as colluvium. The second peak, however, includes coarser materials and is therefore probably associated (literally) with gravel materials.

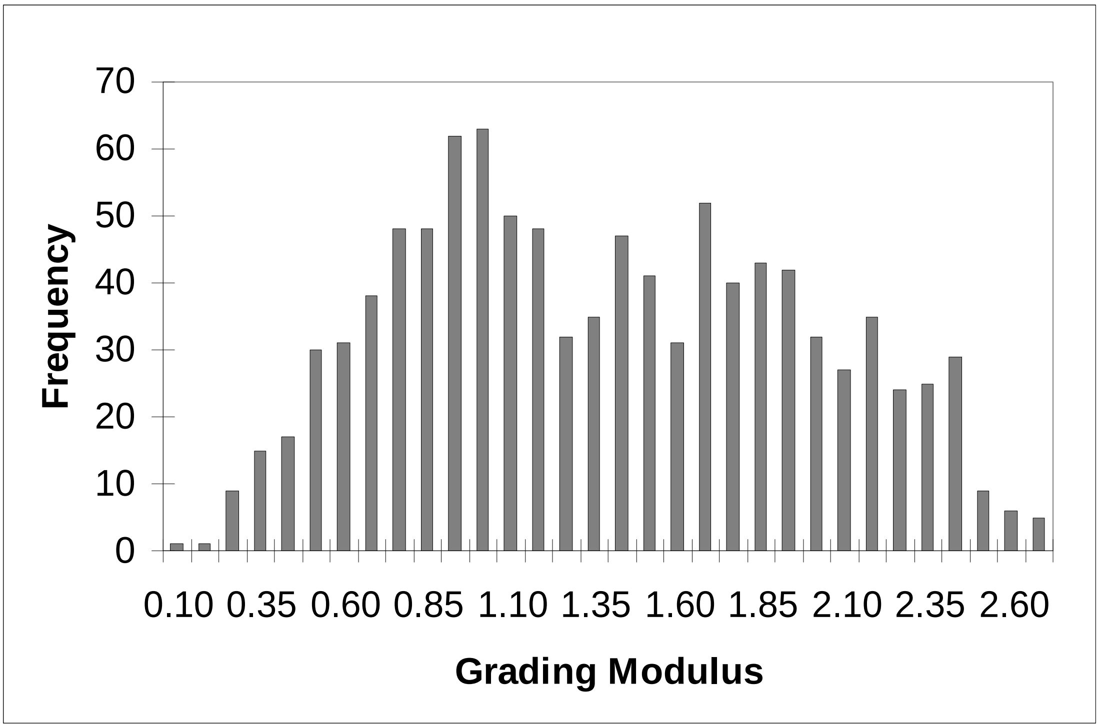

Figure A.24 Frequency Distribution of Grading Modulus (All groups, 98% Mod AASHTO, moist regions)

- *CBR at 98% Mod AASHTO (NSCBR):* It is interesting to note that there is not a significant increase in the mean CBR at 98% Mod AASHTO compaction (21,2%), compared with the 95% Mod AASHTO compaction (19,6%). One would have anticipated a much larger increase in the mean CBR than that calculated. However, a larger range was recorded for the 98% Mod AASHTO group, spanning from 1% to 150%. The standard deviation was recorded as 22,37, whilst the coefficient of variation was calculated to be 1,06. This complies with the variability of the materials tested. A clear, positively skewed histogram is illustrated in Figure A.26. An interesting point is that during data collection, a considerable number of samples delivered lower CBR scores at 98% Mod AASHTO compaction, than at 95% Mod

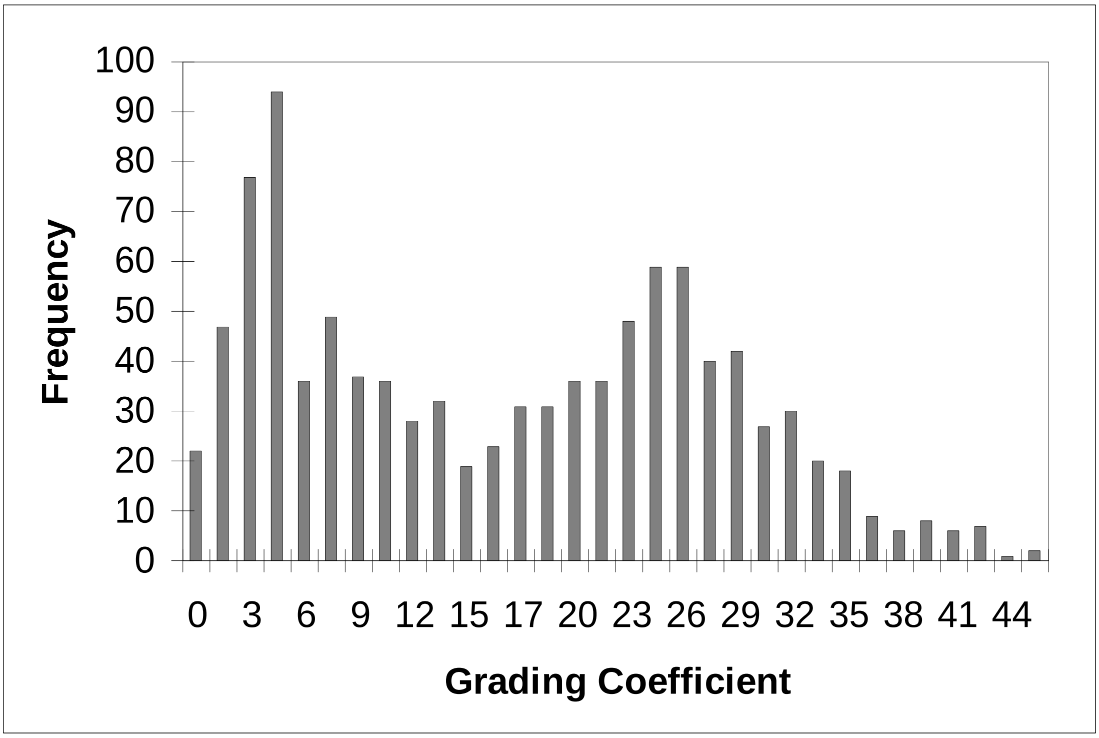

Figure A.25 Frequency Distribution of Grading Coefficient (All groups, 98% Mod AASHTO, moist regions)

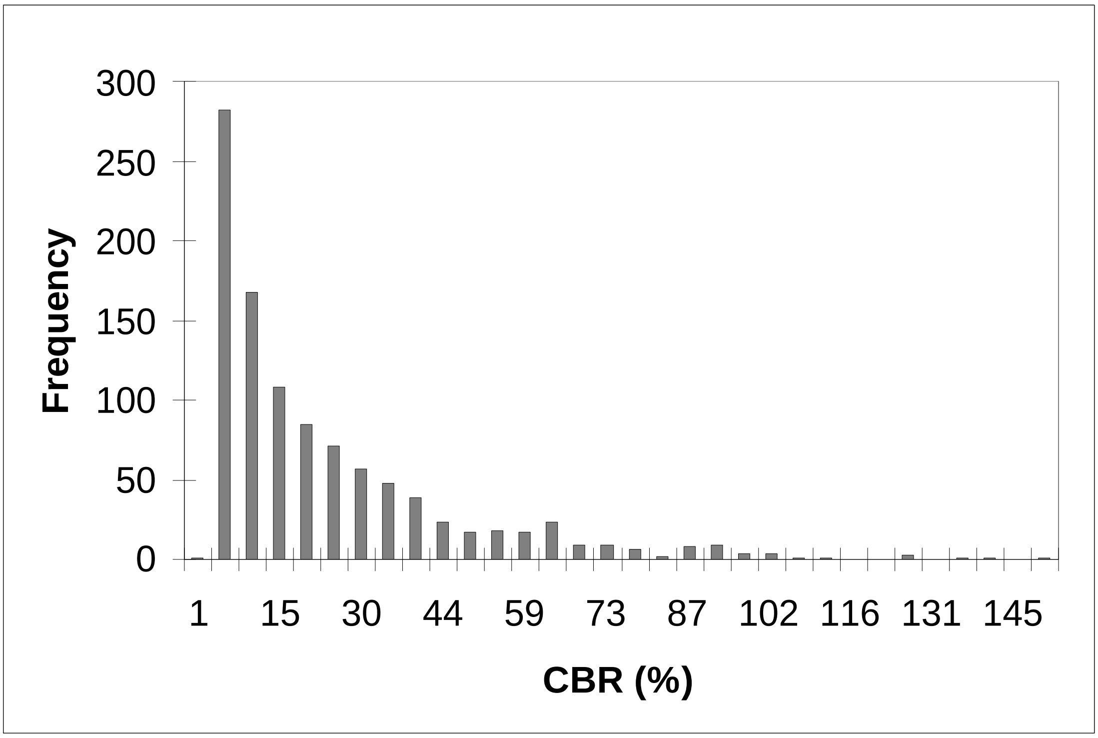

Figure A.26 Frequency Distribution of CBR (All groups, 98% Mod AASHTO, moist regions)

AASHTO compaction. A discussion with Dr Paige-Green (2007, personal communication, CSIR, Pretoria) revealed a number of possible reasons, including the possible re-use (or recompaction) of sample material or that some materials may tend to endure the compactive effort of 95% compaction but not 98% compaction, resulting in breakage at the compactive effort and consequently, poorer performance under CBR testing.

A.2.2 Basic Crystalline Materials

As with the 95% Mod AASHTO group, the basic crystalline group also produced elevated Atterberg Limits relative to the entire group. The liquid limit, in particular, showed a markedly higher mean than the entire dataset. Whilst the liquid limit had a standard deviation nearly compliant with the entire group, both the plasticity index and plastic limit had larger standard deviations. Simultaneously, all three parameters showed a slight improvement (reduction) in coefficient of variation. Histograms for both liquid limit and plasticity index conform to the positively skewed distribution of the entire group, but appear to be more clearly defined (Figure A.27a-b).

The analysis of 154 samples revealed that – as with the 95% Mod AASHTO group – the basic crystalline group had elevated means for the linear shrinkage, linear shrinkage product and shrinkage product. Larger standard deviations compared with the entire group also emphasises the basic crystalline group's affinity to activity in terms of volume changes and whilst the linear shrinkage showed a slightly improved coefficient of variation, none of the three parameters revealed any meaningful improvement after normalisation. The comparison between the basic crystalline group and all the groups is illustrated in Table A.9.

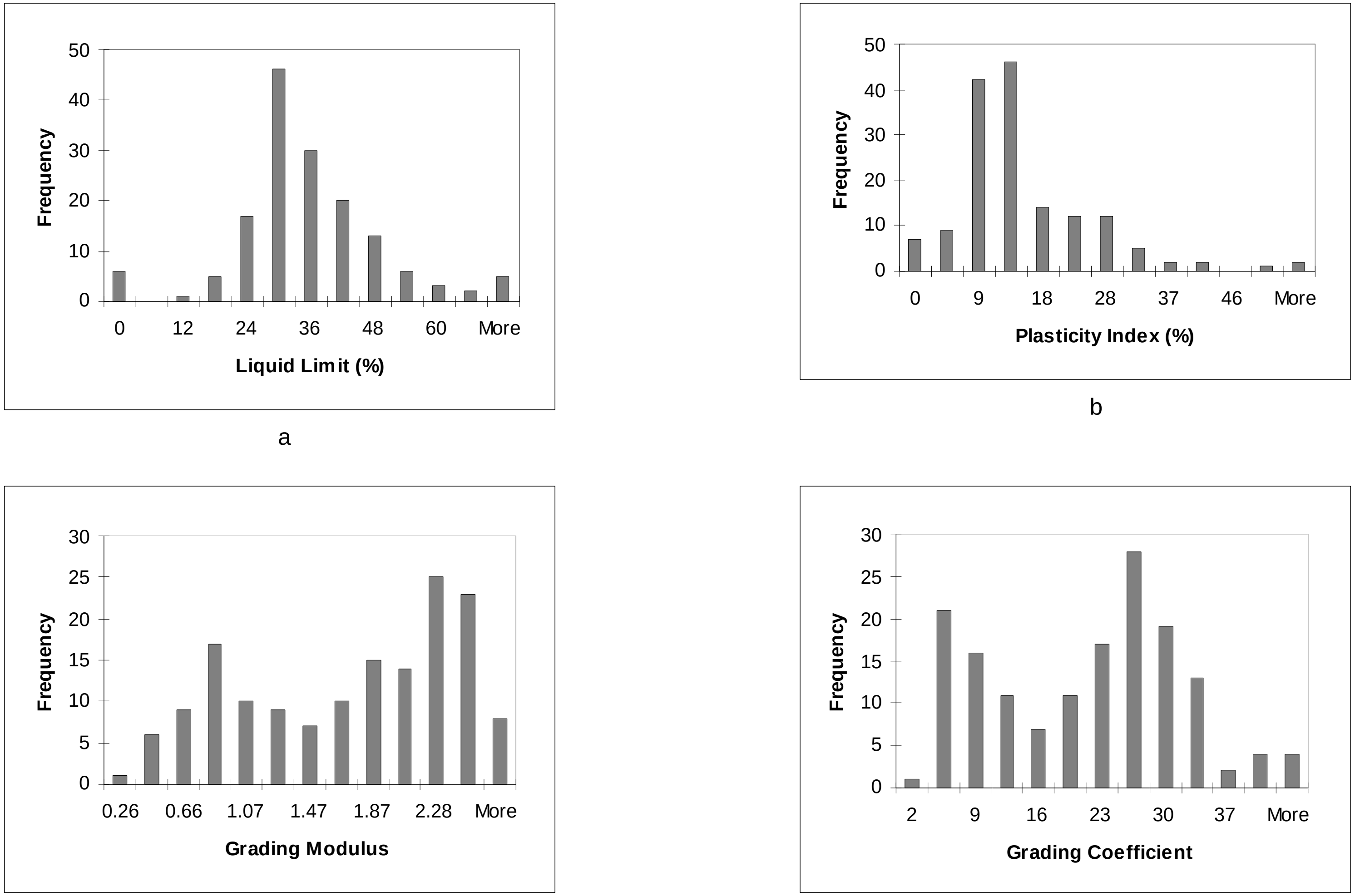

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Figure A.27 Frequency Distributions: Basic Crystalline, 98% Mod AASHTO (Moist regions)

The grading modulus and grading coefficient had slightly conflicting results. Though both parameters indicated coarser materials than the entire group, the grading modulus had a larger standard deviation than the entire group, whilst the grading coefficient had a reduced standard deviation. This is not directly comparable, though, as different grading sizes and methods are used to calculate the two parameters. Both parameters, though, showed improvement after normalisation, but the resulting coefficients of variation still indicate variable data. Both parameters also delivered bimodal histograms (Figure A.27c-d). In both histograms, the second, coarser peak is notable larger than the first which would suggest that the material tends to be coarser; however the presence of the first peak can not be dismissed as insignificant.

The final parameter analysed – the CBR – revealed that the basic crystalline group has a slightly better mean CBR (24,6%) compared with the entire group's 21,2%. The basic crystalline group proved more variable, though, as a slightly larger standard deviation was calculated. Simultaneously, the coefficient of variation improved slightly but still indicates very variable results.

A.2.3 Acid Crystalline Materials

In the 100 samples analysed for the acid crystalline group, improvement was noted in the accuracy of the Atterberg Limits (refer to Table A.10). The liquid limit, plasticity index and plastic limits showed reduced standard deviations and improved coefficients of variation. It was also noted that all three parameters had a much reduced maximum value, compared with the entire group – roughly half the maximum value of the entire group. In terms of mean values, though, no large differences prevailed. The largest difference was the mean of the liquid limit, which proved to be slightly higher than that of the entire group. Also of interest, are the respective histograms for the liquid limit, plasticity index and plastic limit, as illustrated in Figure A.28a-c. Disregarding the initial bar that results from non-plastic materials, a seemingly normal distribution is found for all three parameters. This deviates from the distributions of the entire group compacted to 98% Mod AASHTO density.

Table A.9 Descriptive Statistics Summary: Basic Crystalline (M[illegible]ITO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
				All Groups : 98% Mod AASHTO					
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
				Basic Crystalline : 98% Mod AASHTO					
Mean	32,8	13,5	19,3	6,6	231,0	334,2	1,6	19,3	24,6
Standard Deviation	13,53	9,62	7,07	4,31	313,18	380,39	0,68	10,50	24,03
Coefficient of Variation	0,41	0,71	0,37	0,66	1,36	1,14	0,41	0,54	0,98
Minimum	0	0	0	0	0	0	0,26	2	1
Maximum	72	55	66	21	1722	1953	2,68	44	138
n	154	154	154	154	154	154	154	154	154

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Table A.10 Descriptive Statistics Summary: Acid Crystalline (M[illegible]HTO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Acid Crystalline : 98% Mod AASHTO									
Mean	27,0	10,9	16,1	5,0	169,7	271,7	1,46	19,6	20,9
Standard Deviation	9,98	5,66	5,85	2,67	154,21	197,47	0,46	10,43	18,75
Coefficient of Variation	0,37	0,52	0,36	0,53	0,91	0,73	0,32	0,53	0,90
Minimum	0	0	0	0	0	0	0,38	3	1
Maximum	49	25	33	12	866	1065	2,35	42	92
n	100	100	100	100	100	100	100	100	100

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

As with the Atterberg Limits discussed above, the linear shrinkage, linear shrinkage product and shrinkage product also showed a notable refinement from the entire group, though the data was still highly variable. Though the mean linear shrinkage did not show significant variation from the group, both the linear shrinkage product and the shrinkage product had considerably reduced mean and maximum values, compared with the entire group. This complies with the more "inert" nature of the acid crystalline group with regard to properties of volume changes.

Both the grading modulus and grading coefficient conveyed that in general, the basic crystalline group was slightly coarser than the entire group, with both parameters having higher means. At the same time both parameters also had reduced standard deviation and coefficients of variation, indicating a refinement from the mixed materials.

CBR scores conformed (roughly) to the entire group. The mean CBR can be accepted to be equal to the entire dataset's mean CBR. Neither the standard deviation nor the coefficient of variation showed much improvement. This emphasises once more the variability of the CBR scores achieved, even after normalisation.

A.2.4 High Silica Materials

Properties of the high silica group analysed complied well with its 95% Mod AASHTO counterpart. The 162 samples analysed showed similar trends and tendencies in nearly every respect (Table A.11). Atterberg Limits had reduced means compared with the entire group, whilst also showing smaller standard deviations. The liquid limit and plasticity index showed a slight improvement in coefficient of variation, whilst the plastic limit remainder virtually unchanged. The improvements in coefficient of variation of the liquid limit and plasticity index are of little significance, though, as the results still indicate variable tendencies. Histograms – illustrated in Figure A.29 – indicate that the plasticity index has a poorly defined, positively skewed distribution. Simultaneously the plastic limit has a very peaked, positively skewed distribution. Both histograms would suggest that the Atterberg Limits are not strongly associated with the high silica group.

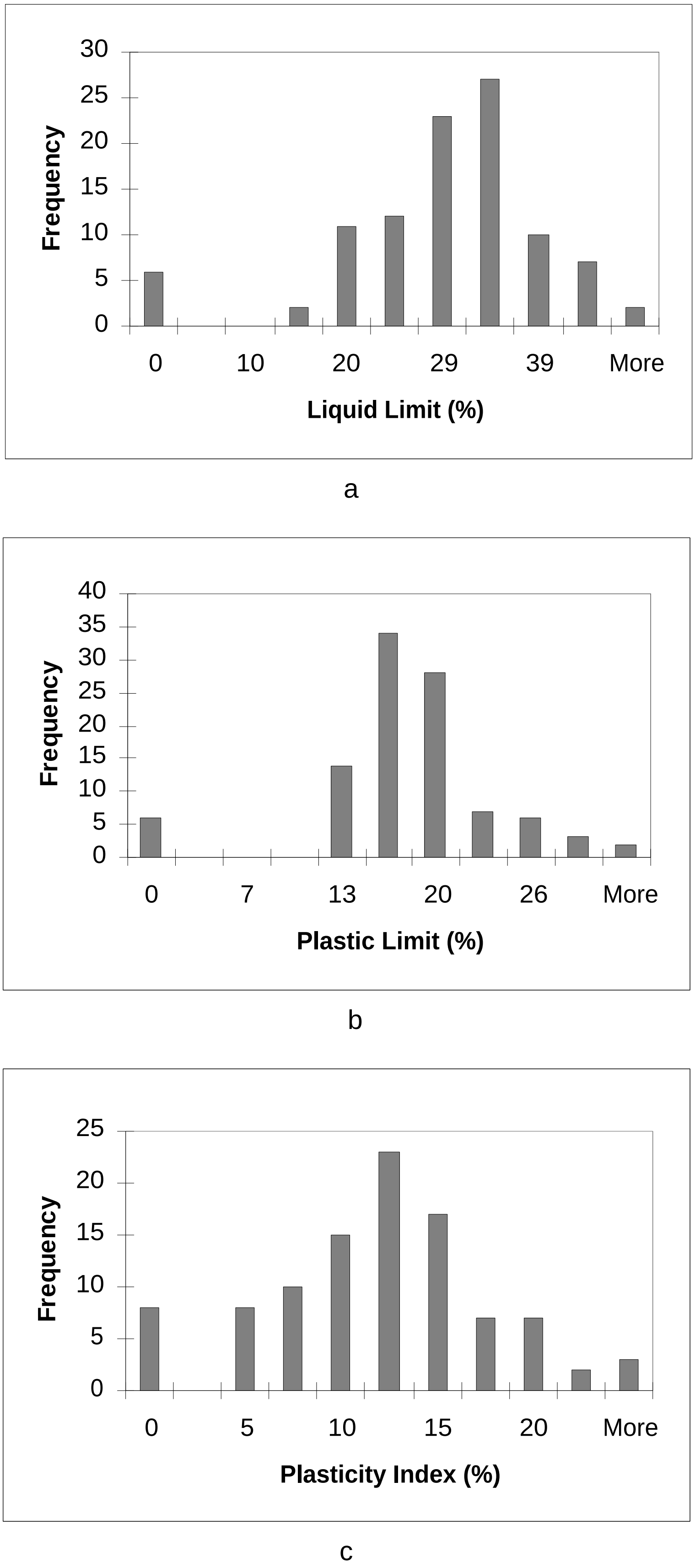

Figure A.28 Frequency Distributions: Acid Crystalline, 98% Mod AASHTO (Moist regions)

Table A.11 Descriptive Statistics Summary: High Silica (Moist [illegible])

	LL	**PI**	**PL**	**LS/BLS**	**LSP**	**SP**	**GM**	**GC**	**CBR**
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
High Silica : 98% Mod AASHTO									
Mean	20,7	8,0	12,7	3,8	139,9	225,8	1,37	14,2	27,7
Standard Deviation	10,35	5,80	5,96	2,77	150,88	211,62	0,60	11,62	31,14
Coefficient of Variation	0,50	0,73	0,47	0,74	1,08	0,94	0,43	0,82	1,12
Minimum	0	0	0	0	0	0	0,31	0	2
Maximum	54	30	41	13	798	1131	2,57	41	150
n	162	162	162	162	162	162	162	162	162

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

The more "inert" nature of high silica materials is also again prevalent in the 98% Mod AASHTO group. The linear shrinkage, linear shrinkage product and shrinkage product had means considerably lower than that of the entire group whilst simultaneously having much reduced standard deviations. It is interesting to note that despite the much reduced standard deviation, there was little – if any – improvement after normalisation. Coefficients of variation for the three parameters remained nearly unchanged from that of the entire group.

The grading modulus and grading coefficient once again delivered slightly contradicting results. Whilst the grading modulus indicates a mean slightly higher than that of the entire group, the grading coefficient indicates a slightly lower mean. This can be ascribed once more to the fact that different grading parameters are used to calculate the grading modulus and grading coefficient. Neither parameters showed any improvement in standard deviation, but whilst the coefficient of variation of the grading modulus showed little improvement, the grading coefficient showed a further lapse after normalisation. Histograms for the two parameters (Figure A.29c-d) indicate two peaks each. The first peaked in both instances is roughly that of a coarse sand, whilst the second may correspond with a coarse gravel.

In compliance with the 95% Mod AASHTO group, the 98% Mod AASHTO high silica group also had a larger mean CBR of 27,7% compared with 21,2% of the entire group. A larger standard deviation was calculated and so too an increased coefficient of variation. A maximum CBR of 150% was noted in this group, which is also the highest CBR score achieved in the entire group compacted to 98% Mod AASHTO.

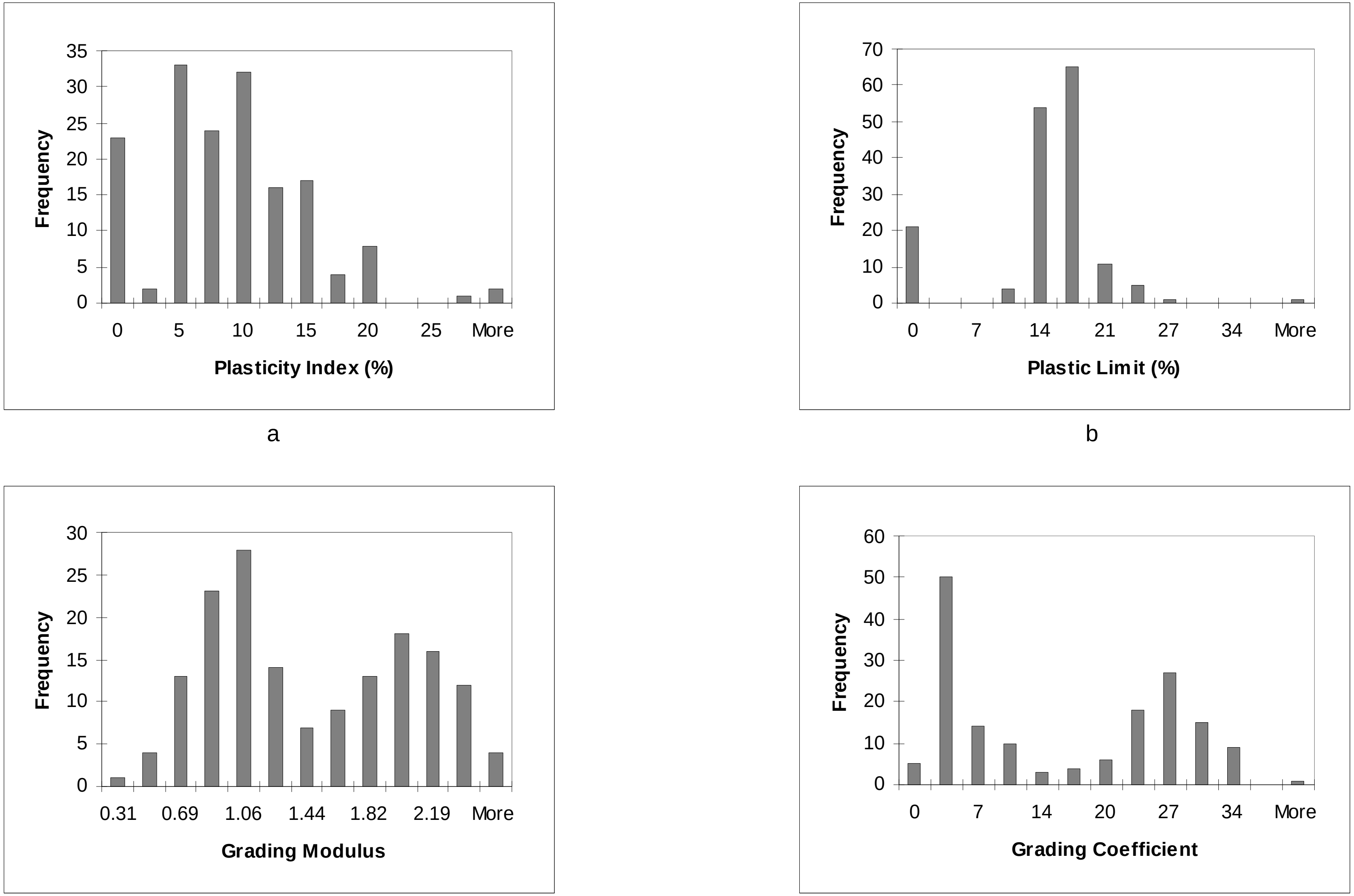

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Figure A.29 Frequency Distribution: High Silica, 98% Mod AASHTO (Moist regions)

A.2.5 Arenaceous Materials

Only 53 samples of arenaceous material were analysed (compacted to 98% Mod AASHTO). Despite the reduced number of samples analysed, the samples originated from various regions of South Africa and the characteristics revealed were well manifested. The arenaceous materials displayed a depression in Atterberg Limits, even more than the high silica group (refer to Table A.12). The means of the liquid limit, plasticity index and plastic limit were 13,2%, 4,2% and 9,0% respectively. This is in sharp contrast to the entire group's respective means of 25,8%, 10,9% and 14,9%. Both the liquid limit and plasticity index also had reduced standard deviations – the plasticity index in particular almost has half the entire group's standard deviation. That being stated, it was unexpected that all three parameters' coefficients of variation were much larger than that of the entire group. This seemingly indicates that normalisation of the parameters' data resulted in more variable results. Histograms for the liquid limit and plasticity index (Figure A.30a-b) illustrate clearly that a large number of the samples were non-plastic, resulting in a dominant bar at zero on the X-axes. If one disregards this bar, a positively skewed distribution can be noted in both histograms, suggesting that the material group tends toward lower liquid limits and plasticity indices.

As is to be expected, the linear shrinkage, linear shrinkage product and shrinkage product had means far lower than those of the entire group. The nature of the material was discussed in section A.1.5 and the same applies here. As with the Atterberg Limits, the three shrinkage-related parameters showed markedly reduced standard deviations; however the coefficients of variation were found to be larger than those of the group. A histogram of the shrinkage product best displays the characteristics related to volume change in this material group. The distribution is similar to that of the liquid limit and plasticity index (Figure A.30c) and emphasises the material group's tendency toward non plastic materials and material with a low plasticity index. Such materials can broadly be associated with inactive materials.

Table A.12 Descriptive Statistics Summary: Arenaceous (Moist [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Arenaceous : 98% Mod AASHTO									
Mean	13,2	4,2	9,0	2,1	53,4	108,8	1,53	17,1	31,2
Standard Deviation	10,67	4,29	6,96	2,49	71,8	128,42	0,36	7,35	20,82
Coefficient of Variation	0,81	1,02	0,77	1,17	1,34	1,18	0,24	0,43	0,67
Minimum	0	0	0	0	0	0	0,77	5	2
Maximum	40	19	23	13	332	663	2,34	34	83
n	53	53	53	53	53	53	53	53	53

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

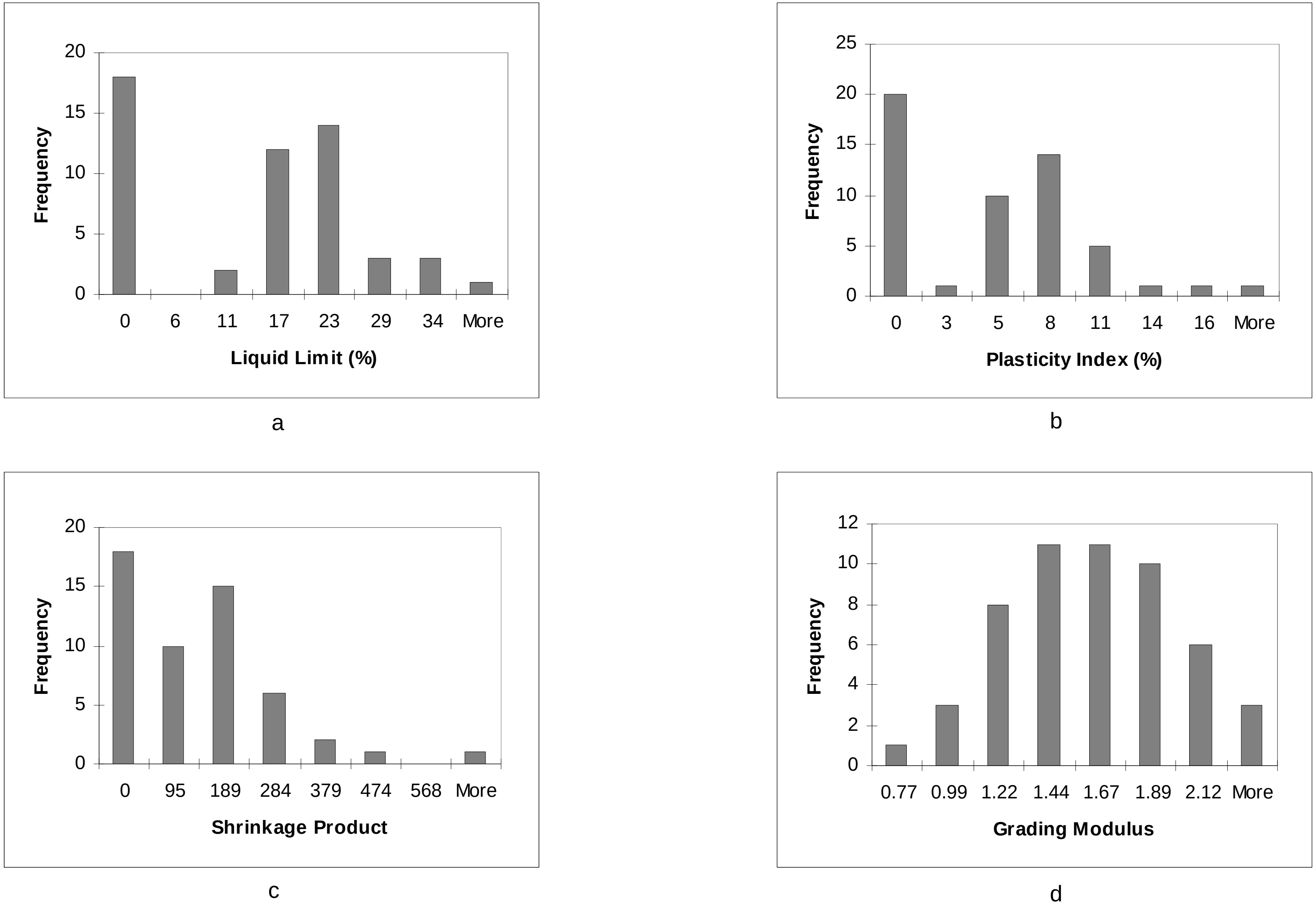

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Figure A.30 Frequency Distributions: Arenaceous, 98% Mod AASHTO (Moist regions)

Analysis of the grading modulus and grading coefficient revealed that the arenaceous materials are generally coarser than the entire group. Both parameters also had drastically reduced standard deviations, rightfully suggesting that grading is very significant as far as the material characteristics are concerned. However, the most striking descriptor of the parameters is the coefficient of variation. The grading modulus had a coefficient of variation of only 0,24 whilst the grading coefficient had a coefficient of variation of 0,43. The former is one of the best coefficients of variation encountered thus far, suggesting that it will be pivotal in formulating an empirical prediction model. The predictability using the grading modulus will also be aided by the normal distribution (Figure A.30d) of the histogram. The single peak is clear and is easily discernable when comparing the plot against the histogram for the entire group.

Finally, the mean CBR calculated for this group showed a large improvement compared with the entire group. A mean CBR of 31,2% was recorded, compared with 21,2% of the entire group. The standard deviation and coefficient of variation – though of limited use here – indicates some refinement upon normalisation, but not enough to indicate significantly improved data accuracy.

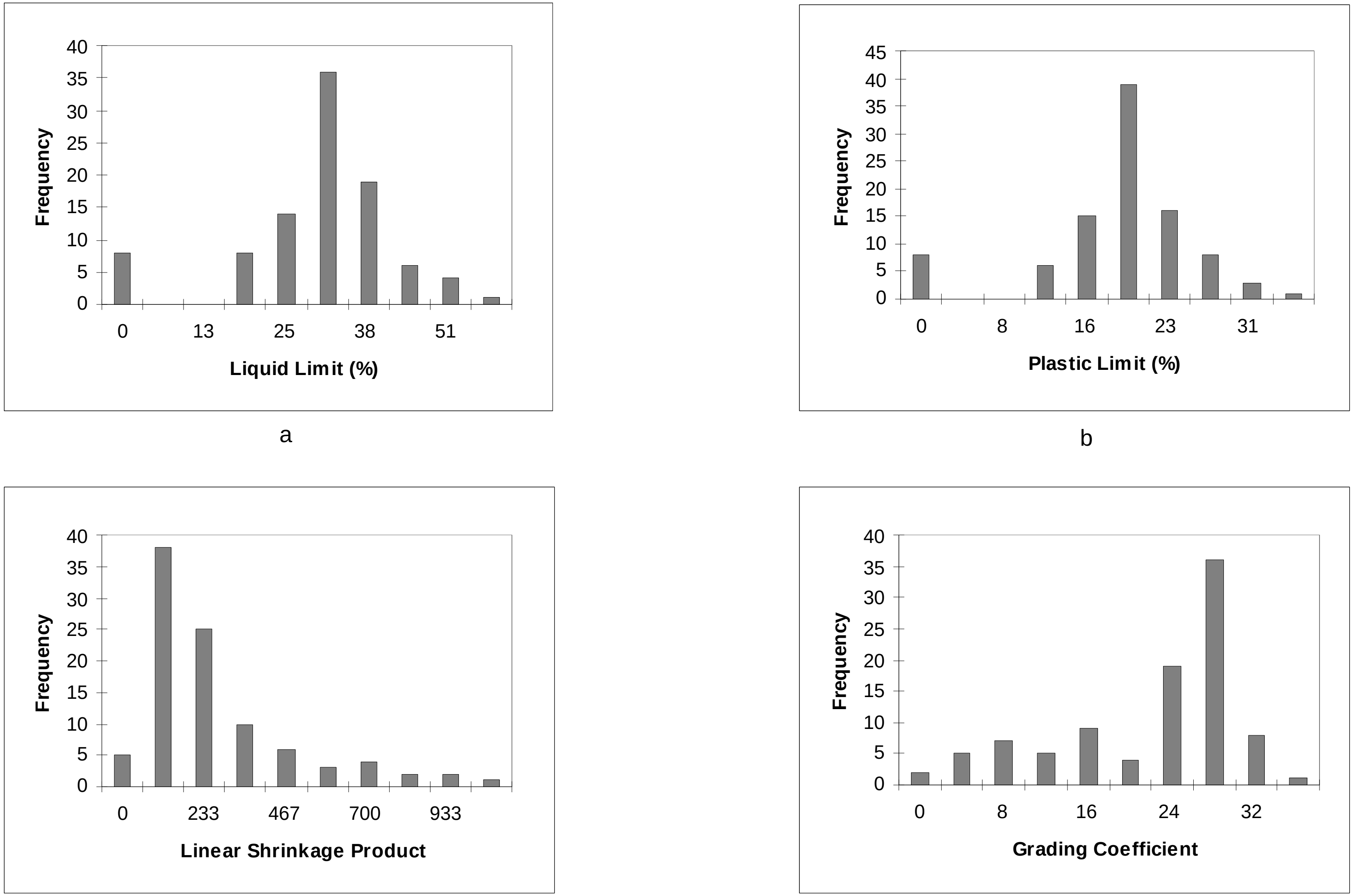
A.2.6 Argillaceous Materials

Some 96 samples of argillaceous material were analysed. The results indicated Atterberg Limits with mean values similar to the entire group (Table A.13). The liquid limit and plastic limit had means slightly larger than the group, but all three parameters showed a slight reduction in standard deviation and coefficient of variation. Both the liquid limit and plastic limit revealed histograms that may be interpreted as either a near-normal distribution or a positively skewed distribution with a short tail (Figure A.31a-b). However, one thing that is clear from both histograms is that there are far less non-plastic samples in the sample population relative to other material groups.

Table A.13 Descriptive Statistics Summary: Argillaceous (Mois[illegible] [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Argillaceous : 98% Mod AASHTO									
Mean	27,4	10,8	16,6	5,6	211,7	289,5	1,56	20,0	22,6
Standard Deviation	11,09	6,34	6,80	3,86	217,39	259,61	0,64	8,56	19,74
Coefficient of Variation	0,40	0,59	0,41	0,69	1,03	0,90	0,41	0,43	0,87
Minimum	0	0	0	0	0	0	0,18	0	2
Maximum	57	34	35	30	1050	1184	2,64	36	105
n	96	96	96	96	96	96	96	96	96

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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d

Figure A.31 Frequency Distributions: Argillaceous, 98% Mod AASHTO (Moist regions)

The linear shrinkage was found to have a slightly higher mean than the entire group, with its standard deviation increasing very slightly whilst simultaneously, the coefficient of variation showed a small decrease. The linear shrinkage product, in turn, had a mean roughly conforming to the entire group, though both the standard deviation and coefficient of variation showed small, yet notable, improvement. The mean calculated for the shrinkage product was notably smaller than that of the entire group, with reduction in both the standard deviation and the coefficient of variation. The reductions, however, are too small to be of significance as far as accuracy goes. The linear shrinkage product's histogram (Figure A.31c) illustrates the group's tendency lower values clearly with a positively skewed distribution. Logically one would expect a tendency toward more "active" materials for argillaceous materials, but as discussed previously, a sampling bias is anticipated.

Both the grading modulus and the grading coefficient indicate materials coarser than the entire group. This was also the case for the 95% Mod AASHTO group and is surprising as one may expect argillaceous materials to deliver sample that are finer than the majority of materials. However, it must be anticipated that the CBR sample target is mainly gravel and as such finer materials are most likely deliberately not sampled. Whilst the grading coefficient showed a reduction in standard deviation from the group, the grading modulus showed an increase. At the same time the grading modulus showed only a slight improvement in coefficient of variation, whilst the grading coefficient revealed a marked reduction. The tendency to sample coarser material is clearly illustrated in the grading coefficient's histogram (Figure A.31d) by a well-developed, positively skewed distribution.

The CBR mean calculated for the argillaceous group was 22,6% with a standard deviation of 19,74. This indicates that the argillaceous group produces slightly improved CBR scores compared with the entire group and that the standard deviation is roughly the same, if not slightly reduced. Though the coefficient of variation improved from the entire group's 1,06 to 0,87 the coefficient is still large and indicates variability in the data, despite normalisation.

A.2.7 Calcrete Materials

Calcrete materials compacted to 98% Mod AASHTO density had a tendency toward high variability, similar to its 95% Mod AASHTO counterpart. The comparative descriptive statistics are illustrated in Table A.14. Atterberg Limits proved elevated compared with the entire group, with the liquid limit and plasticity index's means standing out, in particular. As explained previously, calcretes – as all pedogenic materials – are hosted in materials of various origins. The variation in host materials is responsible for the variable properties observed. The reduced number of samples (27) can be ascribed to the climate, as calcretes are not commonly associated with moist areas.

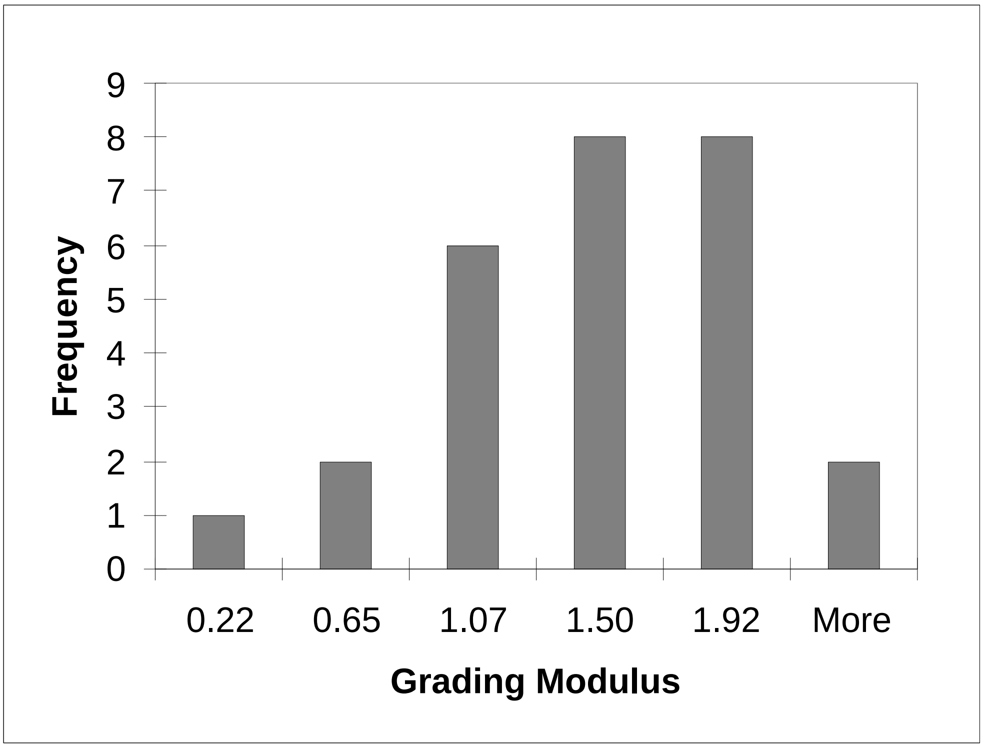
Interestingly the calcrete group appeared to be more susceptible to volume changes than the entire group. The linear shrinkage, linear shrinkage product and shrinkage product all had means far greater than that of the entire group. Simultaneously the standard deviation of all three parameters also far exceeded those of the entire group. Though both the linear shrinkage product and shrinkage product showed a small improvement in their respective coefficients of variation, the improvement in the linear shrinkage's coefficient of variation was more pronounced. Even the latter improvement, though, indicate highly variable data.

As with some of the other groups, the grading modulus and grading coefficient delivered conflicting results. Whilst the grading modulus had a mean slightly lower than the group, the grading coefficient had a small increase in mean compared with the entire group. Both parameters, however, did show significant reduction in standard deviation, whilst the grading coefficient had a notably improved coefficient of variation. Figure A.32a-b illustrates a clear negatively skewed distribution for the grading modulus and a poorly developed, negatively skewed distribution for the grading coefficient. It must be borne in mind that the peaks of both parameters do not tend toward very coarse materials, suggesting that the grading modulus may reflect the group's grading properties more accurately than the grading coefficient.

Table A.14 Descriptive Statistics Summary: Calcrete (Moist reg[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Calcrete : 98% Mod AASHTO									
Mean	31,2	15,6	15,6	6,6	327,9	464,5	1,27	16,3	24,1
Standard Deviation	23,99	15,41	10,08	6,23	458,07	526,40	0,52	8,66	30,46
Coefficient of Variation	0,77	0,99	0,64	0,95	1,40	1,13	0,41	0,53	1,26
Minimum	0	0	0	0	0	0	0,22	0	1
Maximum	81	51	40	20	1590	1777	2,35	28	98
n	27	27	27	27	27	27	27	27	27

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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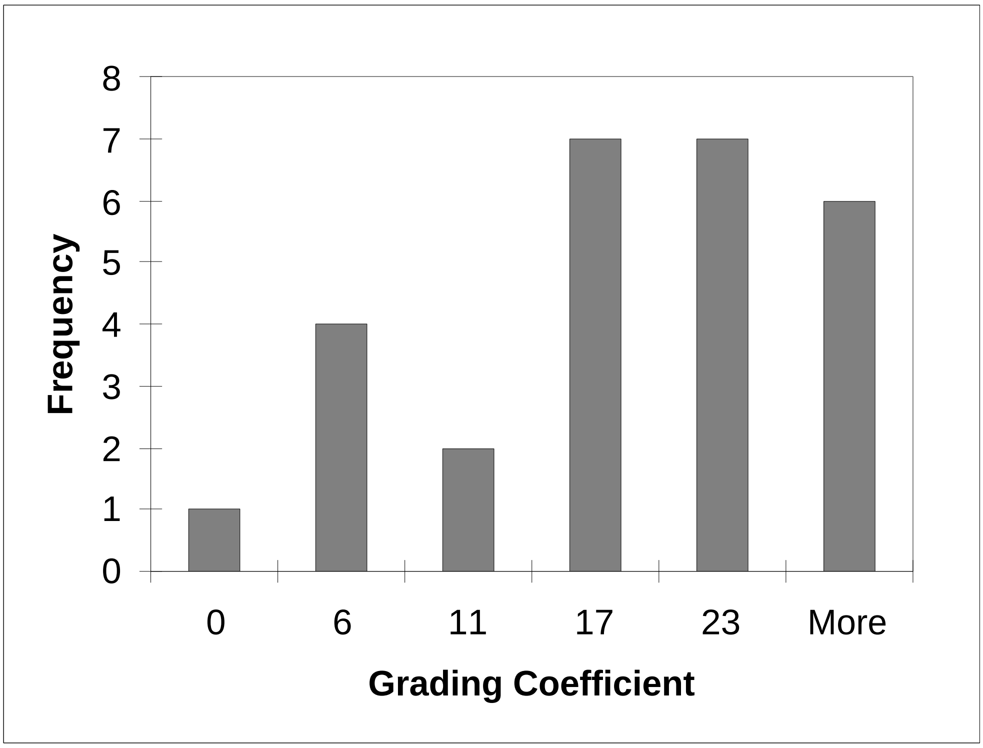

b

Figure A.32 Frequency Distributions: Calcrete, 98% Mod AASHTO (Moist regions)

Despite the calcrete's seemingly larger affinity to swell and react, the mean CBR of the group was larger than the entire group's, scoring a mean CBR of 24,1% compared with 21,2% of the entire group. A standard deviation of 30,46 was recorded though, and considering the small number of samples producing the result, it is not surprising to find the elevated coefficient of variation which is even larger than that of the entire group.

A.2.8 Ferricrete Materials

A comprehensive 258 samples of ferricrete were analysed for 98% Mod AASHTO compaction. The analysis revealed that the liquid limit, plasticity index and plastic limit all had means lower than those of the entire group (Table A.15). At the same time, all three parameters had slightly reduced standard deviations, as well as slightly improved coefficients of variation. The latter still indicates variability despite refinement from the group.

As with the Atterberg Limits discussed above, the linear shrinkage, linear shrinkage product and shrinkage product had slightly, yet notably, reduced means compared with that of the entire group, indicating that in general, ferricrete has a lower affinity to swell or react compared with the norm. Standard deviations and coefficients of variation were also reduced compared with the entire group, but both properties still indicate a large spread of data. Figure A.33 illustrates that whilst the linear shrinkage has an erratic (possibly poorly developed positive) distribution, the linear shrinkage product's histogram has a well-developed, positively skewed distribution, emphasising its tendency to lower activity.

The occurrence of contradicting grading parameters is continued in the ferricrete group, with the grading modulus indicating a slightly reduced mean compared with the entire group, and the grading modulus indicating a slight elevation. The grading modulus, though, revealed a notably reduced standard deviation and improvement (i.e. reduction) in coefficient of variation, whilst the grading coefficient's standard deviation did not vary notably from the entire group and did not show much improvement in coefficient of variation.

Table A.15 Descriptive Statistics Summary: Ferricrete (Moist r[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Ferricrete : 98% Mod AASHTO									
Mean	23,2	10,0	13,3	4,6	177,8	292,3	1,28	18,0	16,1
Standard Deviation	11,01	6,38	5,49	2,97	172,64	231,34	0,48	11,75	16,88
Coefficient of Variation	0,47	0,64	0,41	0,64	0,97	0,79	0,37	0,65	1,05
Minimum	0	0	0	0	0	0	0,29	0	2
Maximum	62	35	27	14	1144	1344	2,38	45	125
n	258	258	258	258	258	258	258	258	258

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

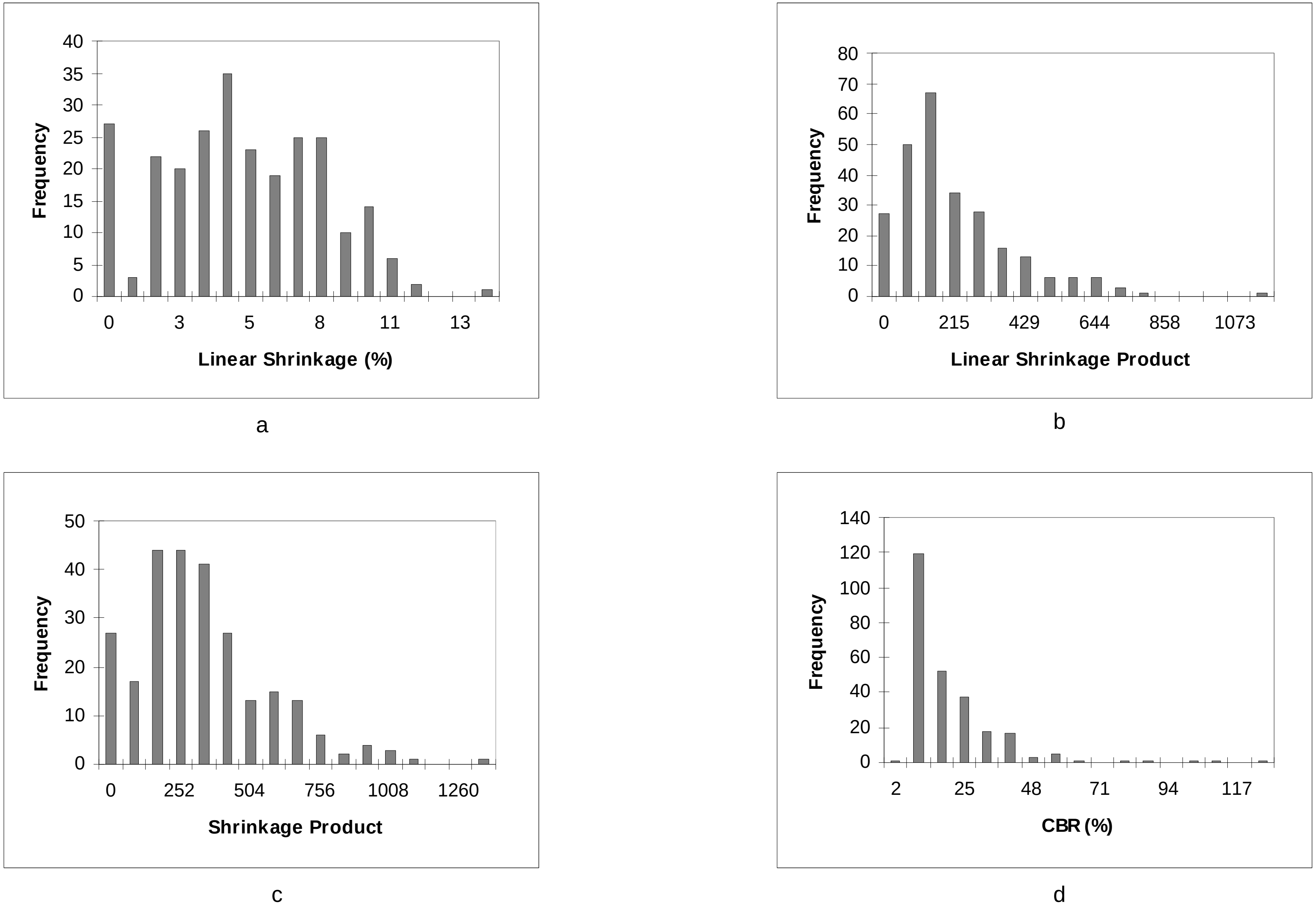

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Figure A.33 Frequency Distributions: Ferricrete, 98% Mod AASHTO (Moist regions)

A significantly lower mean CBR was calculated for the ferricrete group, confirming the statement made concerning the favourability of the material for CBR testing in section A.1.8. The CBR's histogram (Figure A.33d) also shows a clearly positively skewed distribution, which indicates a strong concentration of results at the lower range of the CBR scores. Though the standard deviation of the group was reduced by a substantial amount, the coefficient of variation still indicates that the CBR contains variable data. This is ideal for the research at hand, as it indicates a large spread of CBR properties.

A.2.9 Colluvium

A total of 154 samples of colluvial materials were analysed. Elevated means were calculated for the Atterberg Limits, particularly for the liquid limit and plasticity index (Table A.16). Also, larger standard deviations were noted particularly – again – for the liquid limit and plasticity index; however whilst the plasticity index and plastic limits showed little variation from the entire group's coefficient of variation, the liquid limit showed a slight deterioration.

Shrinkage parameters proved volatile, compared with the entire group. The linear shrinkage, linear shrinkage product and shrinkage product all had largely elevated means compared with the group. Both the linear shrinkage product and shrinkage product had the entire group's maximum values – 1823 and 2083 respectively. All three parameters also had larger standard deviations than the entire group, whilst coefficients of variation indicate highly variable data, even after normalisation. Figure A.34a emphasises the colluvium's elevated potential to swell and shrink, with a histogram clearly illustrating a significant tendency for materials to have high linear shrinkage values when comparing the group to most of the remaining material groups, bar the basic crystalline group.

Table A.16 Descriptive Statistics Summary: Colluvium (Moist [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 98% Mod AASHTO									
Mean	25,8	10,9	14,9	5,1	208,6	315,7	1,34	16,0	21,2
Standard Deviation	13,69	8,33	6,95	3,80	258,01	316,88	0,59	11,22	22,37
Coefficient of Variation	0,53	0,77	0,47	0,74	1,24	1,00	0,44	0,70	1,06
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,68	45	150
n	1016	1016	1016	1016	1016	1016	1016	1016	1016
Colluvium : 98% Mod AASHTO									
Mean	29,6	14,1	15,5	6,4	365,5	520,7	0,82	5,6	15,2
Standard Deviation	16,89	10,75	7,19	4,58	373,25	429,14	0,38	6,94	16,74
Coefficient of Variation	0,57	0,76	0,46	0,71	1,02	0,82	0,46	1,23	1,10
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	38	22	1823	2083	1,97	35	91
n	154	154	154	154	154	154	154	154	154

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

Both grading parameters – the grading modulus and grading coefficient – indicate much finer materials in the colluvial group than in the entire group. The parameters had drastically reduced means. Surprisingly – considering the nature and origin of colluvial materials – both parameters indicated a smaller standard deviation. It was expected that the colluvial group would be more variable in terms of grading than the entire group. Despite the reduced standard deviation, both the grading modulus and grading coefficient showed an increase in coefficient of variation, the former showing only a slight increase and the latter almost doubling. The tendency for colluvial materials to have a finer composure is clearly illustrated in Figure A.34b-c with both the grading modulus and grading coefficient’s histograms showing positively skewed distributions, though the grading modulus’ distribution is not clearly defined.

As anticipated, the colluvial group produced a mean CBR lower than that of the entire group. A mean CBR of 15,2% was calculated, with a standard deviation of 16,74. The standard deviation and large coefficient of variation confirm a variety of data, but the descriptive statistics indicate the generally limited potential of colluvium.

A.2.10 Non-Plastic Materials

120 non-plastic materials were included in the 98% Mod AASHTO group. The non-plastic materials had a mean CBR of 36,2% which is – like its 95% Mod AASHTO counterpart – much larger than the entire group. Though the CBR had a larger standard deviation, the coefficient of variation was reduced, but still very large. The grading modulus and grading coefficient had contradicting means, the former being slightly larger than the entire group, and the latter slightly smaller. Both parameters had a reduced standard deviation, but whilst the grading modulus showed an improvement in coefficient of variation, the grading coefficient showed a slight deterioration.

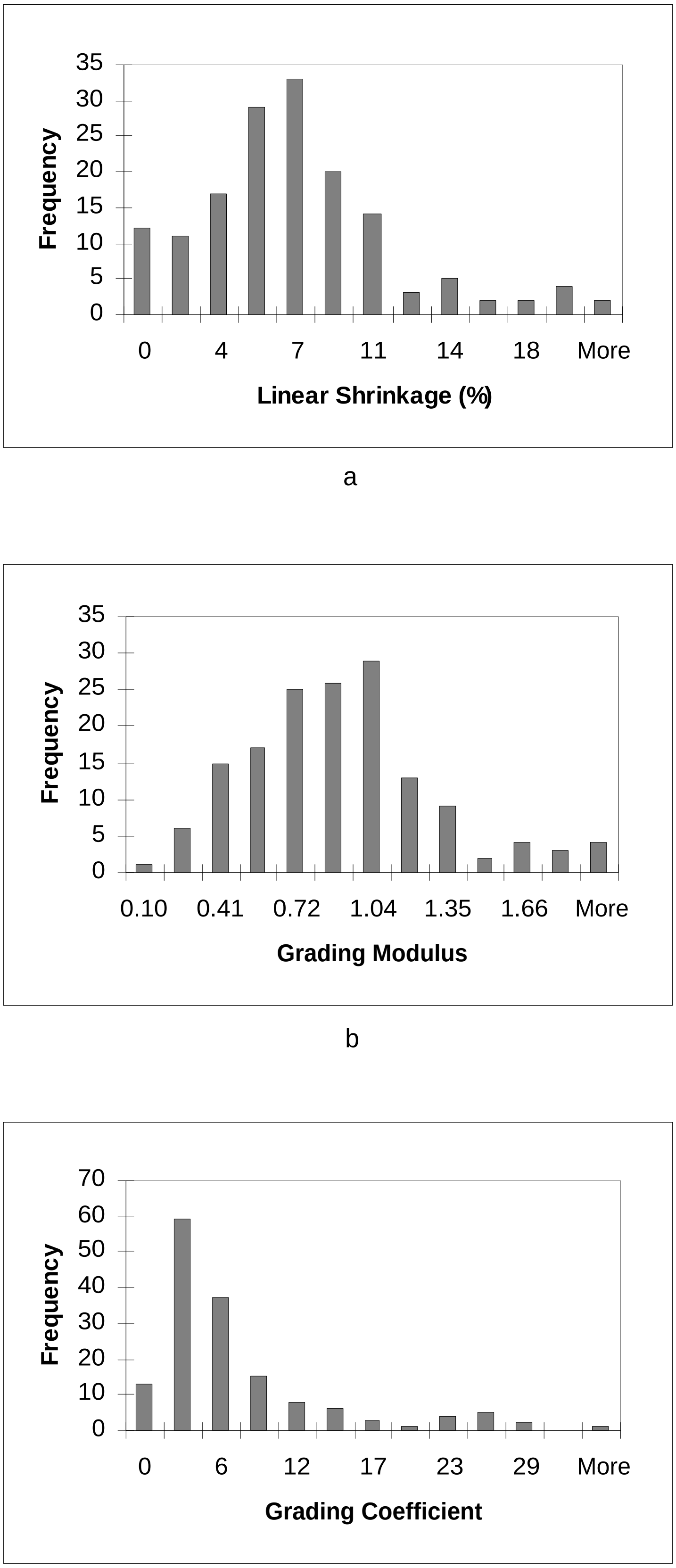

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Figure A.34 Frequency Distributions: Colluvium, 98% Mod AASHTO (Moist regions)

A.3 Descriptive Statistics: Moist Areas: 100% Mod AASHTO

A.3.1 All Groups

The group of materials compacted to Mod AASHTO density comprised some 1179 samples of mixed materials. After comparing the descriptive statistical analysis and histograms of the group with that of its 95% Mod AASHTO and 98% Mod AASHTO counterparts, it was found that the group conformed very well to both and hence a full discussion of each parameter will not be given. A summary of the descriptive statistics is conveyed in Table A.17.

The only parameter showing a difference – and expectantly so – was the CBR, which shall be discussed in short. As one would expect, the mean CBR was found to be significantly higher than that op the previous groups analysed. The 100% Mod AASHTO group had a mean CBR of 32,1%, compared with 21,2% and 19,6% for the 98% and 95% Mod AASHTO density groups. The 100% Mod AASHTO group also had a significantly larger standard deviation that the other groups and a much larger maximum CBR. The coefficient of variation still indicates, though, that the data is highly variable.

A.3.2 Basic Crystalline Materials

As encountered before with less dense compactions, the basic crystalline group had elevated means compared with the entire group means (Table A.17). The liquid limit and plastic limit, in particular, had significantly elevated means, but neither parameter showed much deviation in standard deviation from the entire group, whilst the plasticity index showed a small increase. All three parameters had improved coefficients of variation, indicating that normalisation of the data to the group results in improved data correlation. A total of 178 samples were analysed.

Table A.17 Descriptive Statistics Summary: Basic Crystalline ([illegible] SHTO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Basic Crystalline : 100% Mod AASHTO									
Mean	33,0	13,9	19,1	6,7	246,9	355,5	1,60	18,9	34,0
Standard Deviation	13,47	9,42	7,00	4,25	321,40	390,59	0,69	10,62	33,33
Coefficient of Variation	0,41	0,68	0,37	0,63	1,30	1,10	0,43	0,56	0,98
Minimum	0	0	0	0	0	0	0,26	1	2
Maximum	72	55	66	21	1722	1953	2,68	44	181
n	178	178	178	178	178	178	178	178	178

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

In terms of the shrinkage parameters, results indicate that the basic crystalline group is (again) more susceptible to volume changes. The mean linear shrinkage of the group was considerably larger than that of the entire group and whilst the standard deviation increased, a slightly reduced coefficient of variation was calculated. The linear shrinkage product and shrinkage product both also had increased means compared with the entire group; however the means were not as drastically elevated as was expected. As with the linear shrinkage, both parameters also had larger standard deviations, but their coefficients of variation showed little, if any, improvement. The shrinkage product's histogram (Figure A.35a) showed an interesting distribution. The graph had a positive distribution, but had two dominant peaks.

Grading parameters revealed that the basic crystalline group – as before – tends to be coarser than the entire group with both the grading modulus and grading coefficient having notably increased means compared with the entire group. Of interest is that whilst the grading modulus has a higher standard deviation, the grading coefficient has a slightly reduced standard deviation. Simultaneously the grading modulus shows little change in coefficient of variation, whilst the grading coefficient shows a considerable improvement. The two coefficients of variation still suggest variability within the group, but this is anticipated due to the nature of chemical weathering of basic crystalline materials. Both the grading modulus and grading coefficient showed a bimodal distribution (Figure A.35b-c) with the second peak – resembling coarser material – being larger than the first. This suggests that as noted before, a bias most likely prevails due to selective sampling of coarser materials (gravel) as opposed to highly weathered, finer materials (clay).

Analysis of the CBR scores revealed that the basic crystalline group, compacted to 100% Mod AASHTO density, has a mean CBR of 34,0%. This is two percentage points higher than that of the entire group. The group also has a slightly larger standard deviation, but considering the range of CBR values (2% to 181%), this is not surprising.

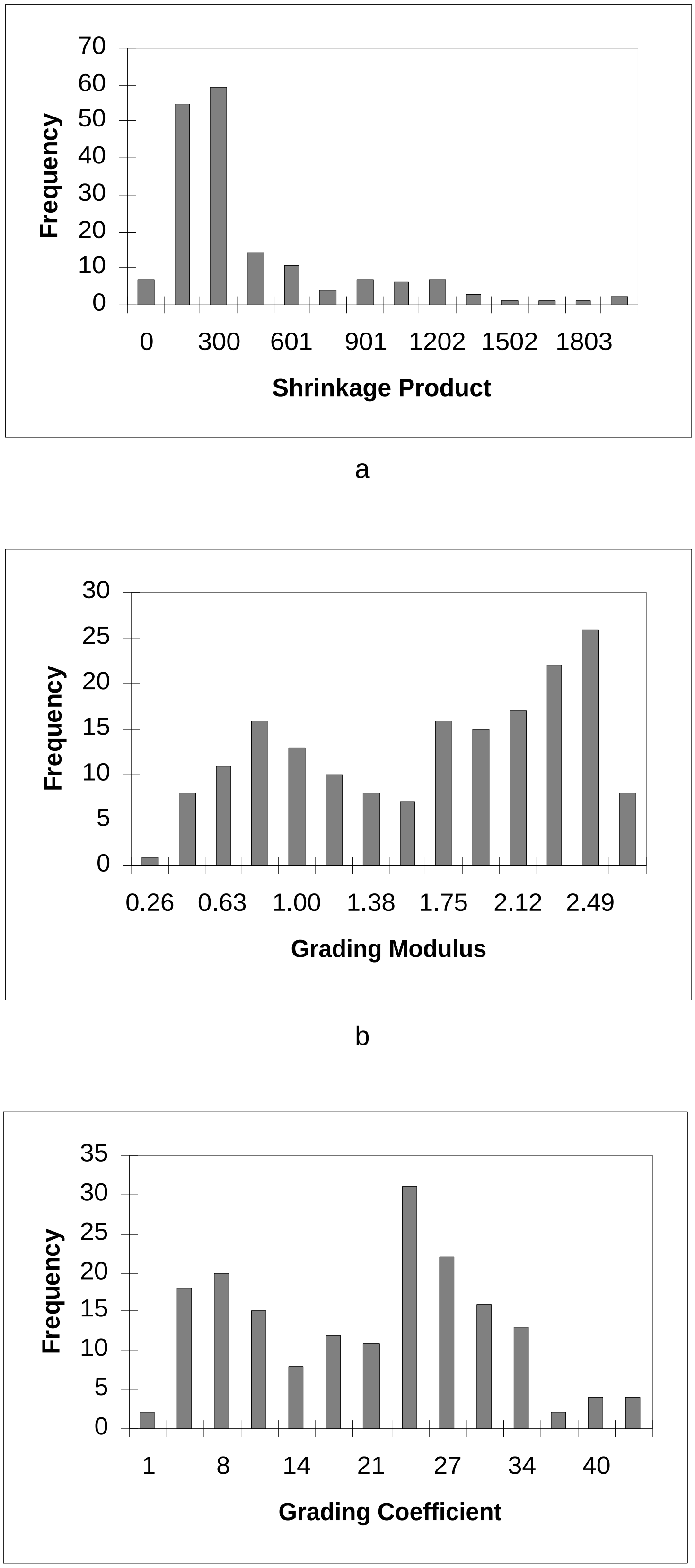

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Figure A.35 Frequency Distributions: Basic Crystalline, 100% Mod AASHTO (Moist regions)

A.3.3 Acid Crystalline Materials

Analysis of 109 acid crystalline samples revealed that the group compacted to Mod AASHTO density relates well to lower density groups. As before, the acid crystalline group had a mean liquid limit and plastic limit slightly higher than the entire group, but the plasticity index showed a minute decrease (Table A.18). All three parameters showed a reduction in standard deviation, as well as notably improved coefficients of variation. Whilst the liquid limit and plastic limit had histograms compliant with the norm, the plasticity index revealed a histogram that may be interpreted as an off-set, positively skewed distribution or a normal distribution (Figure A.36a). The interpretation lies largely with the reader.

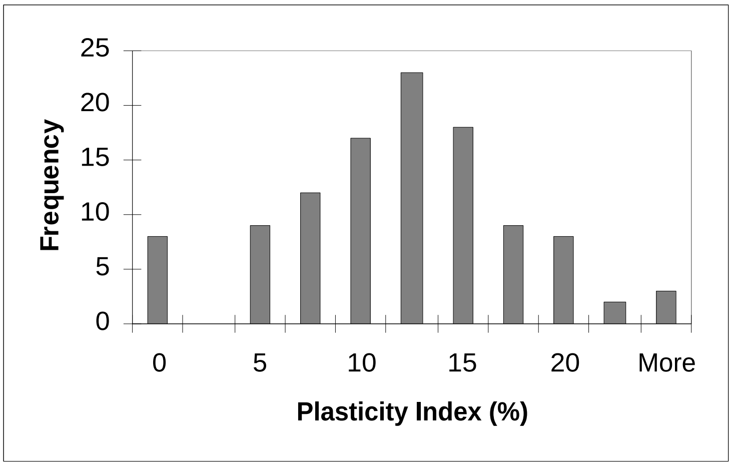
Whilst the linear shrinkage of the acid crystalline group did not deviate significantly from the entire group, the linear shrinkage product and shrinkage product both showed markedly reduced means. All three parameters had reduced standard deviations, which suggest a refinement in data, most likely ascribed to the more inert nature of the acid crystalline group, as opposed to e.g. the acid crystalline group. Whilst the linear shrinkage and shrinkage product showed significant improvements in their respective coefficients of variation, the linear shrinkage product lacked refinement. Despite the former parameters improving, the calculated coefficients of variation still indicate that the data is highly variable. The linear shrinkage histogram (Figure A.36b) delivered an unclear graph. The chart can be interpreted either as a normally distribution or negatively skewed distribution, once more depending on the reader's interpretation.

Both the 95% Mod AASHTO and 98% Mod AASHTO groups were found to be coarser on average than the respective entire groups – as indicated by the grading modulus and grading coefficient. The 100% Mod AASHTO group conformed to this trend. However, of the two parameters only the grading modulus showed a marginally reduced standard deviation, whilst both groups had reduced coefficients of variation. For the third time a histogram was generated that is difficult to interpret as either a normal distribution or a negatively (or positively) skewed distribution.

Table A.18 Descriptive Statistics Summary: Acid Crystalline (M[illegible]SHTO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Acid Crystalline : 100% Mod AASHTO									
Mean	27,0	10,9	16,1	5,1	167,1	268,7	1,48	19,8	32,2
Standard Deviation	9,78	5,62	5,68	2,70	153,28	195,61	0,47	10,15	28,99
Coefficient of Variation	0,36	0,52	0,35	0,53	0,92	0,73	0,32	0,51	0,90
Minimum	0	0	0	0	0	0	0,38	3	5
Maximum	49	25	33	12	866	1065	2,35	42	131
n	109	109	109	109	109	109	109	109	109

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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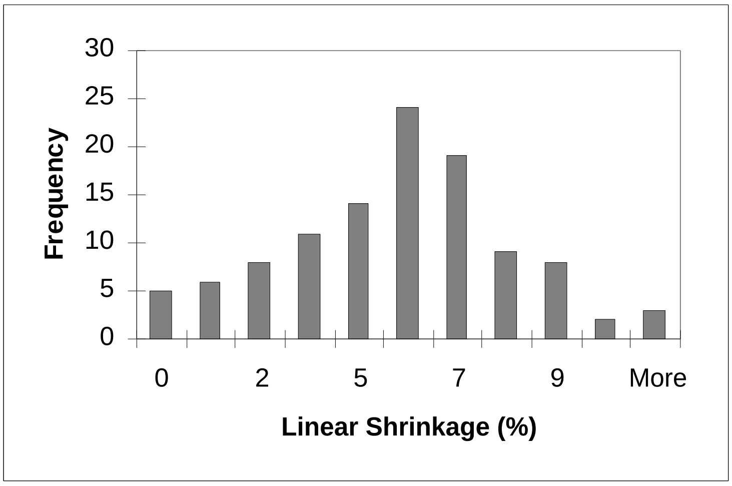

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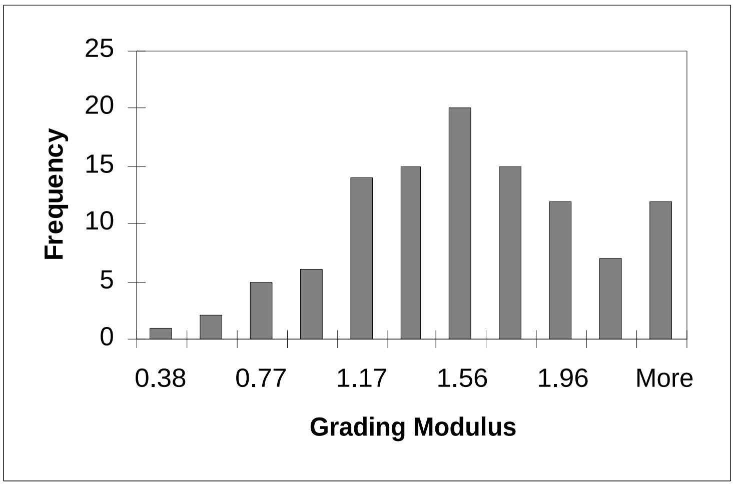

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Figure A.36 Frequency Distributions: Acid Crystalline, 100% Mod AASHTO (Moist regions)

Figure A.36c clearly illustrates the acid crystalline group's tendency to have a grading similar to that of coarse sand (as previously observed).

In terms of CBR scores achieved, the acid crystalline is level with the entire group. A mean CBR of 32,2% was calculated, compared with 32,1% of the entire group. A slightly reduced standard deviation and coefficient of variation were noted, but neither is of significant improvement.

A.3.4 High Silica Materials

The 198 samples of high silica materials analysed showed similar properties to those of the groups compacted to lower densities. In particular, the Atterberg Limits had lower means compared with the entire group and also showed reduced standard deviations. Despite the reduced standard deviations, though, no significant improvements were noted in the coefficients of variation. A comparison between the high silica group and the entire group is illustrated in Table A.19.

The linear shrinkage, linear shrinkage product and shrinkage product all showed a significantly smaller mean than that of its counterpart in the entire group. All three parameters also had a reduced standard deviation; however none showed any particular improvement in coefficient of variation. In fact, the linear shrinkage showed a very slight increase in coefficient of variation. The statistics suggests that normalisation had little effect on the variability of the material, but it did clearly illustrate that the high silica group has a lower affinity for volume changes.

As often observed in the material groups compacted to 98% Mod AASHTO density, the high silica group compacted to 100% Mod AASHTO density had contradicting result from the grading modulus and grading coefficient. Whilst the grading modulus

Table A.19 Descriptive Statistics Summary: High Silica (Moist [illegible]))

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
High Silica : 100% Mod AASHTO									
Mean	20,9	8,2	12,7	3,9	145,2	233,0	1,37	14,2	41,0
Standard Deviation	10,46	6,09	5,74	3,07	174,03	232,80	0,60	12,03	41,86
Coefficient of Variation	0,50	0,74	0,45	0,79	1,20	1,00	0,44	0,84	1,02
Minimum	0	0	0	0	0	0	0,31	0	2
Maximum	54	31	41	19	1225	1382	2,57	41	239
n	198	198	198	198	198	198	198	198	198

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

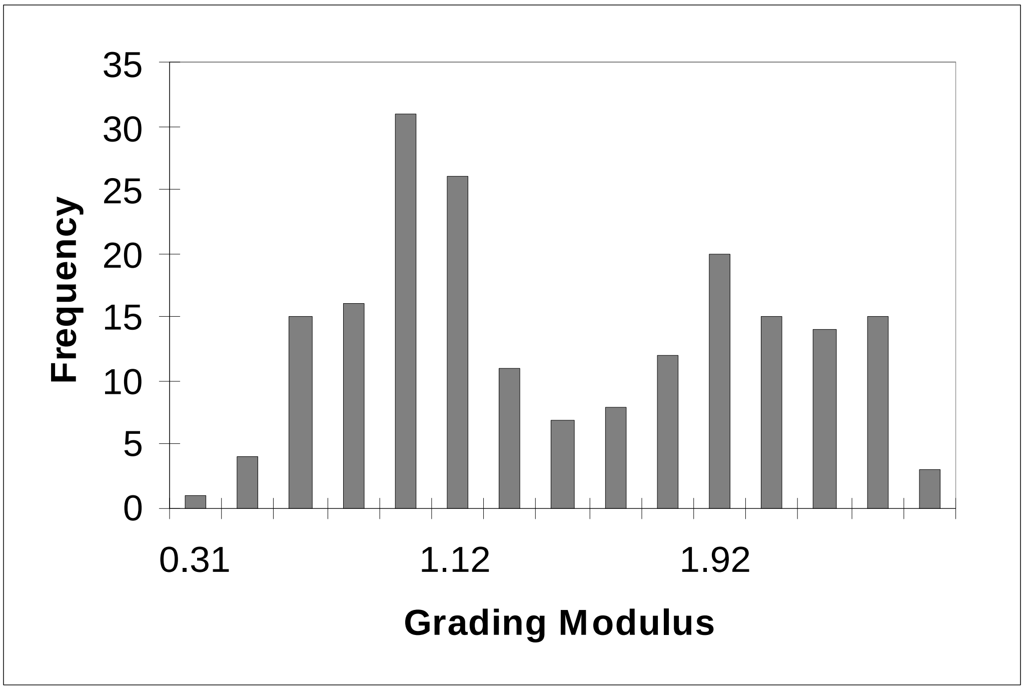
indicated a grading slightly coarser than that of the entire group, the grading coefficient indicated a slightly finer grading. At the same time, the grading modulus showed very little change from the entire group's standard deviation and coefficient of variation, but the grading coefficient showed a slight increase in both parameters. This suggests that the grading coefficient may be a less suited indicator to the high silica group than the grading modulus. Figure A.37a-b illustrates that both the grading modulus and grading coefficient had a bimodal distribution, indicating that samples may tend to be either sandy (first peaked close to zero in both cases) or gravelly (second peak, furthest away from zero).

Once again the descriptive statistics of the high silica group illustrates its favourability as construction material for road layer works, with a mean CBR of 41,0% - some nine percentage points more than the entire group's mean CBR. The CBR data did, however, also reveal a much larger standard deviation than the entire group, but the coefficient of variation showed little alteration.

A.3.5 Arenaceous Materials

A total of 59 samples belonging to the arenaceous group were analysed. As with lesser compactions, the arenaceous materials showed severely depressed Atterberg Limits compared with the entire group. The liquid limit and plasticity index stood out in this regard (Table A.20). In addition to depressed mean Atterberg Limits, the parameters also had much reduced standard deviations compared with the entire group. Despite the reduced standard deviations, all three parameters had significantly elevated coefficients of variation, compared with their respective counterparts in the entire group. The tendency of the material towards being inert with regard to shrinkage (volume changes) is therefore clearly illustrated. The group's nature is clearly observed in Figure A.38a, where it is clear that a very large number of samples are non-plastic and that elevated liquid limits are rare.

The tendency of arenaceous to be more inert with regard to volume changes – as discussed above - is further illustrated by the linear shrinkage, linear shrinkage product and shrinkage product. All three parameters achieved means that were



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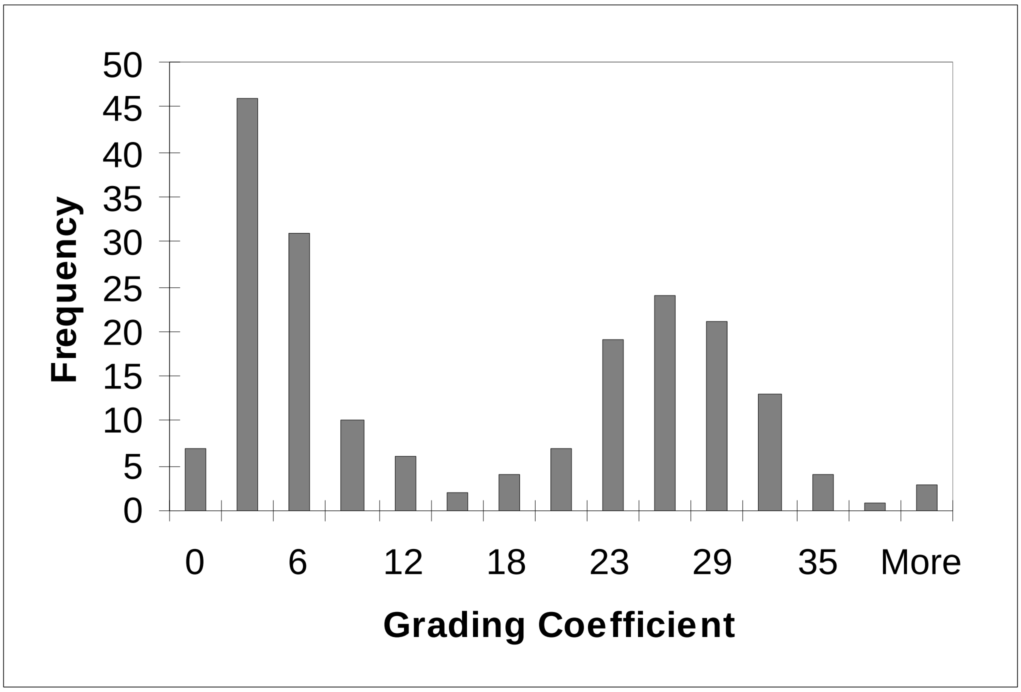

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Figure A.37 Frequency Distribution: High Silica, 100% Mod AASHTO (Moist regions)

Table A.20 Descriptive Statistics Summary: Arenaceous (Moist [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Arenaceous : 100% Mod AASHTO									
Mean	13,6	4,3	9,2	2,2	54,5	111,1	1,54	17,2	47,4
Standard Deviation	10,48	4,17	6,85	2,41	69,22	124,09	0,36	7,21	27,58
Coefficient of Variation	0,77	0,96	0,74	1,11	1,27	1,12	0,23	0,42	0,58
Minimum	0	0	0	0	0	0	0,77	5	9
Maximum	40	19	23	13	332	663	2,34	34	107
n	59	59	59	59	59	59	59	59	59

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

fractional compared to the entire group. In addition, standard deviations of all three parameters exhibited a similar reduction to the means. The limited affinity of the material group's shrinkage activity is further emphasised by the maximum values recorded for the three shrinkage parameters (Table A.20). Regardless of the large reduction in standard deviation of the parameters, the coefficients of variation indicate that normalisation resulted in little improvement in data correlation. In fact, the linear shrinkage showed a sizeable deterioration in coefficient of variation, compared with the entire group. In addition, histograms (Figure A.38b-c) of the linear shrinkage product and shrinkage product indicate clusters at low values. The influence of non-plastic materials (LSP = 0; SP = 0) is also emphasised by a dominating bar at zero on both histograms.

As encountered with other compactions, the arenaceous group tended to be coarser than the combined group (Figure A.38d). Both the grading modulus and grading coefficient had increased means and also reduced standard deviations. This suggests that the grading correlates better with the material group than the entire group. Both parameters also had reduced coefficients of variation; the grading modulus, in particular, had a coefficient of variation of 0,23 which appears promising.

A mean CBR of 47,4% was recorded for the arenaceous group. Of all the material groups analysed, this is the best mean value recorded. The standard deviation was significantly reduced compared with the entire group. It is interesting to note this refinement in standard deviation when considering that the high silica group had a mean CBR of 41,0% but a standard deviation of 41,86. Also, the arenaceous group had a coefficient of variation of 0,58 – a dramatic improvement from the entire group.

A.3.6 Argillaceous Materials

Some 106 samples of argillaceous material were analysed and compared to the entire group. Results indicate that both the liquid limit and plastic limit have larger mean values than the entire group, whilst the plasticity index remained compliant with the entire group's mean (Table A.21).

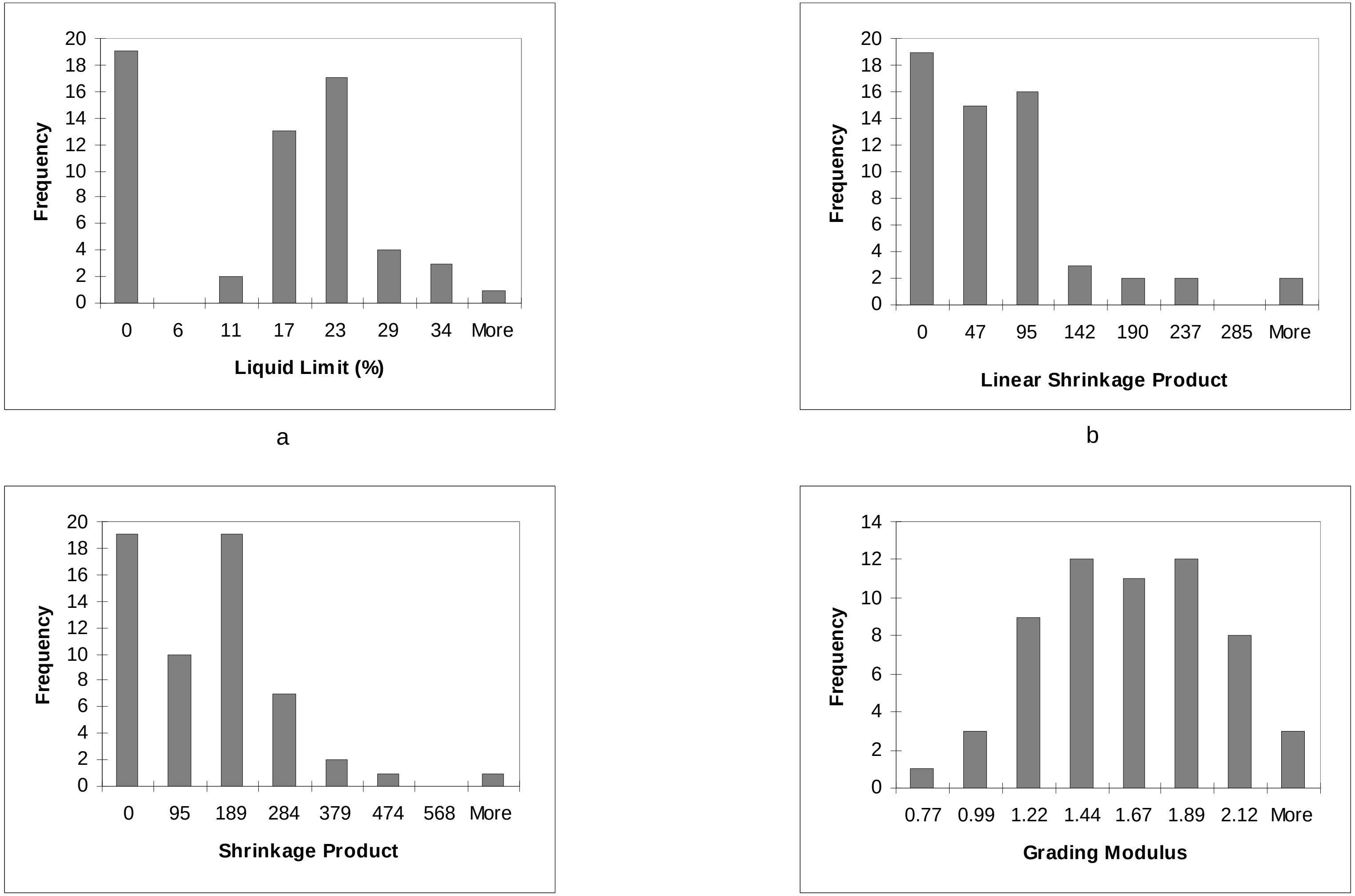

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Figure A.38 Frequency Distributions: Arenaceous, 100% Mod AASHTO (Moist regions)

Table A.21 Descriptive Statistics Summary: Argillaceous (Mois[illegible]O)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Argillaceous : 100% Mod AASHTO									
Mean	27,6	11,0	16,6	5,6	209,4	285,4	1,55	19,8	35,0
Standard Deviation	11,51	6,68	6,81	3,87	210,67	250,99	0,64	8,81	30,96
Coefficient of Variation	0,42	0,61	0,41	0,69	1,01	0,88	0,41	0,44	0,88
Minimum	0	0	0	0	0	0	0,18	0	3
Maximum	58	34	35	30	1050	1184	2,64	36	171
n	106	106	106	106	106	106	106	106	106

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

A histogram of the liquid limits recorded illustrates a peak further away from zero resulting in a slightly elevated mean (Figure A.39a). Standard deviations of the liquid limit and plasticity index showed a slight decline while the plastic limit's standard deviation remained virtually unchanged compared with the entire group. All three parameters showed a minor improvement in coefficient of variation, suggesting refinement from the entire group.

Shrinkage parameters showed a similar trend to that observed in lesser compacted groups in that neither the linear shrinkage product nor the shrinkage product showed means significantly higher than that of the entire group. On the contrary, both the linear shrinkage product and shrinkage product had means lower than those of the entire group, despite the mean linear shrinkage of the argillaceous group being marginally larger than its counterpart in the entire group. The linear shrinkage had a standard deviation slightly larger than that of the entire group, whilst its coefficient of variation indicated a slight improvement upon normalisation. The linear shrinkage product and shrinkage product, on the other hand, had reduced standard deviation and improved – though still elevated beyond significance – coefficients of variation.

Both the grading modulus and grading coefficient had elevated means relative to the entire group, indicating that the materials are generally coarser than the entire group. It must once more be emphasised that selective sampling most likely occurred during testing of argillaceous materials and hence a bias is anticipated. Nevertheless, the grading modulus' standard deviation increased slightly, whilst the grading coefficient had a reduced standard deviation relative to the entire group. Both parameters showed improvement in coefficient of variation, in particular the grading coefficient. Histograms for both parameters (Figure A.39b-c) illustrated a tendency for materials sampled to be either sandy (first peak) or more often gravelly (second peak). The grading coefficient clearly illustrates a much larger peak tending to the coarser side of the spectrum.

The mean CBR calculated was found to be marginally larger than that of the entire group, with neither the standard deviation nor the coefficient of variation showing an improvement that would indicate improved data correlation.

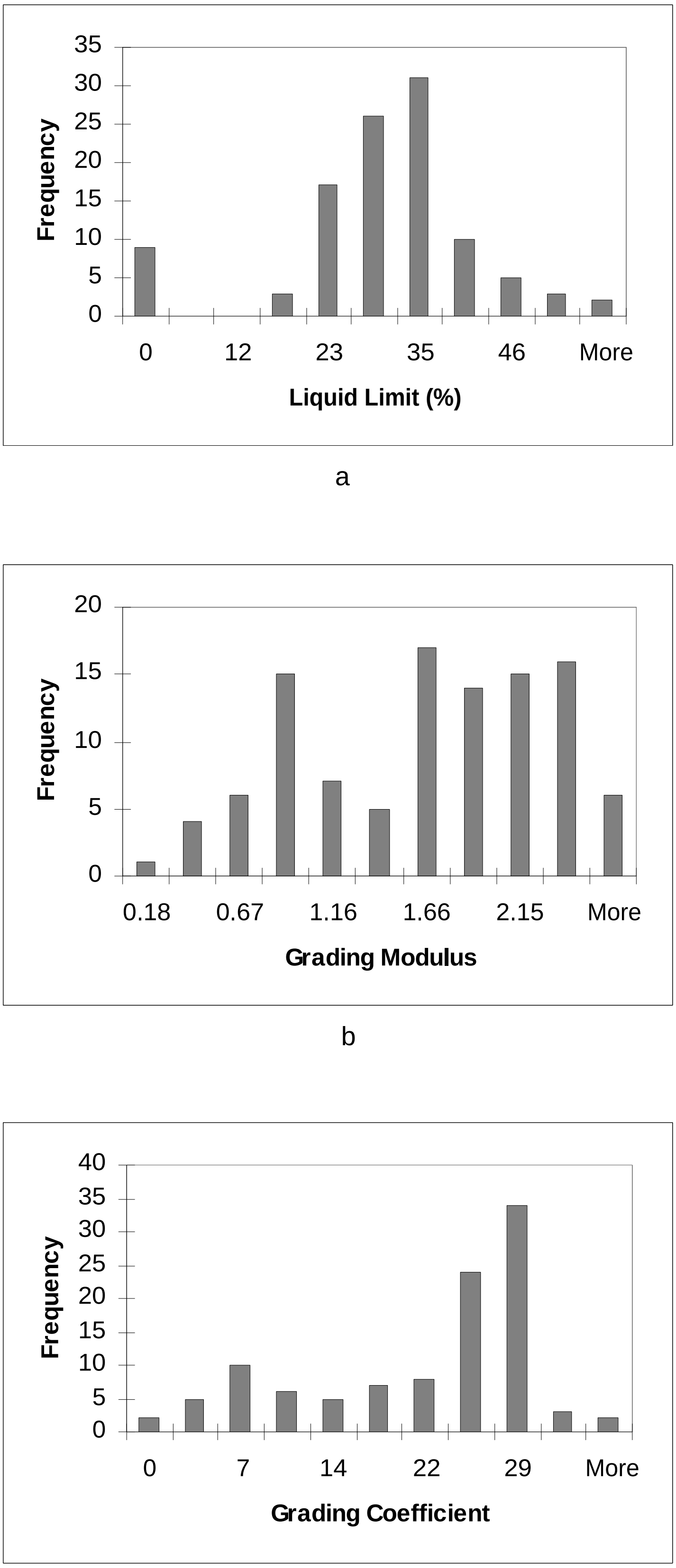

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Figure A.39 Frequency Distributions: Argillaceous, 100% Mod AASHTO (Moist regions)

A.3.7 Calcrete Materials

As with lesser compacted calcrete examined before, the sample population was somewhat limited due to the fact that calcrete is more prevalent in dry area; consequently only 34 calcrete samples were analysed. The results again indicated considerably elevated Atterberg Limits. The liquid limit, plasticity index and plastic limit each had a mean significantly higher than that of the entire group, whilst larger standard deviations were also recorded. The increased standard deviation indicates _ as before – that calcrete is susceptible to variability due to the fact that it depends largely on the properties of its host material. Normalisation of the data did not result in much improvement and coefficients of variation were indicative of highly variable properties (Table A.22). A histogram for the liquid limit (Figure A.40a) clearly illustrates the calcrete group’s tendency toward elevated values, not considering the non-plastic materials represented by the bar at zero.

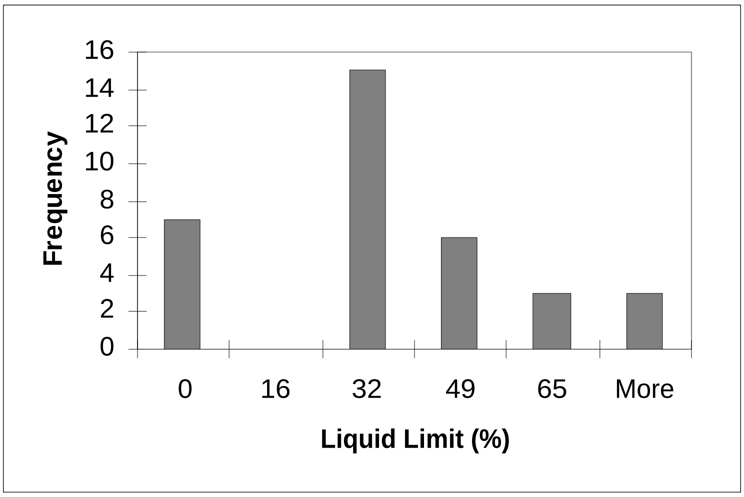
Analysis of the linear shrinkage, linear shrinkage product and shrinkage product revealed that the calcrete analysed is likely be prone to volume changes. Mean values recorded for all three parameters were much greater than those of the entire group, whilst standard deviations – particularly that of the shrinkage product – were excessive. Coefficients of variation of the three parameters also confirm the variability of the material, with the lowest coefficient of variation being that of the linear shrinkage (0,92). A histogram for the linear shrinkage (Figure A.40b) revealed a positively skewed distribution when disregarding the influence of non-plastic materials. Critical though, is the location of the graph’s peak, which serves as a good confirmation of the elevated mean linear shrinkage calculated.

The most refined properties of the calcrete group by far, are the grading modulus and grading coefficient. Both parameters indicate slightly reduced mean values compared with the entire group. The two parameters also had slightly reduced standard deviations and reduced coefficients of variation. The grading coefficient showed a particular improvement.

Table A.22 Descriptive Statistics Summary: Calcrete (Moist reg [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Calcrete : 100% Mod AASHTO									
Mean	30,0	14,7	15,2	6,3	296,0	438,1	1,26	15,6	36,4
Standard Deviation	22,16	14,12	9,44	5,78	419,62	483,13	0,51	8,87	44,37
Coefficient of Variation	0,74	0,96	0,62	0,92	1,42	1,10	0,40	0,57	1,22
Minimum	0	0	0	0	0	0	0,22	0	2
Maximum	81	51	40	20	1590	1777	2,35	28	149
n	34	34	34	34	34	34	34	34	34

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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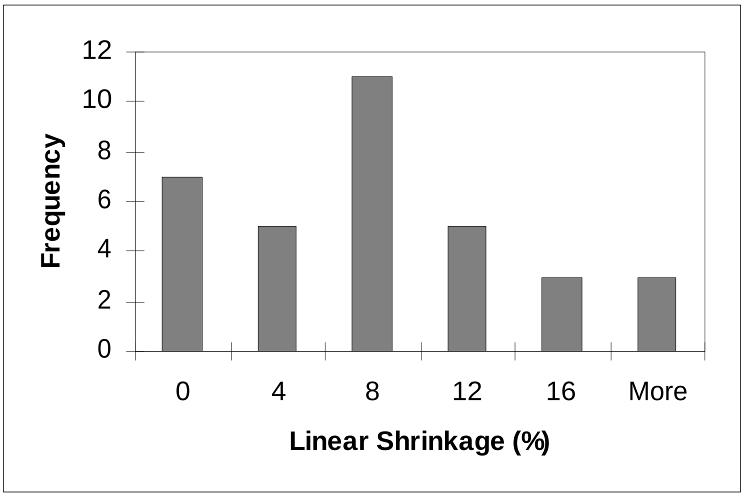

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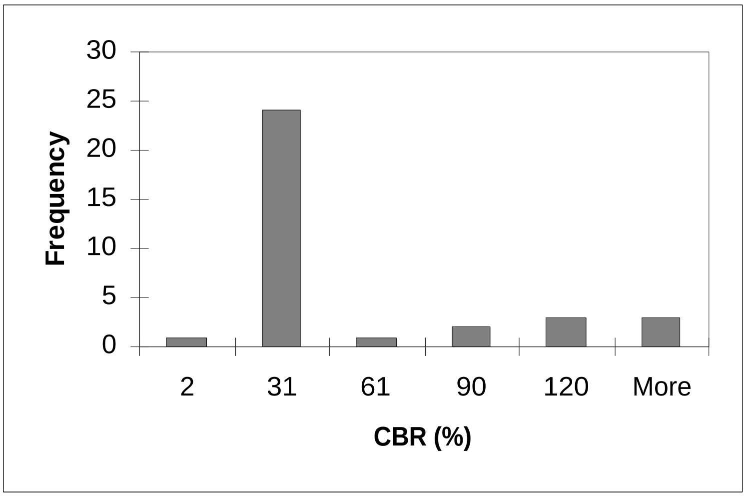

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Figure A.40 Frequency Distributions: Calcrete, 100% Mod AASHTO (Moist regions)

Despite the high variability of the calcrete, a mean CBR of 36,4% was recorded, compared with 32,1% of the entire group. However, a standard deviation of 44,37 and coefficient of variation of 1,22 emphasises that despite the impressive mean, the material is likely prove difficult with regard to predicting its behaviour. The CBR histogram (Figure A.40c) indicates that the majority of CBR scores lie between 2% and 31%, with only nine samples achieving CBR scores above this interval.

A.3.8 Ferricrete Materials

The ferricrete sample population of 300 samples upheld the trends observed in lesser compacted ferricrete groups. Atterberg Limits had lower means; however standard deviations and coefficients of variation of the liquid limit, plasticity index and plastic limit showed small reductions, signifying an improvement in data quality and refinement from the entire group (Table A.23). Histograms of the liquid limit and plastic limit illustrate that though peaks do prevail, no uniform distribution is found and that data for the two parameters are very erratically distributed (Figure A.41a-b).

Shrinkage parameters revealed that the ferricrete tends to be less susceptible to shrinkage and swelling with the linear shrinkage, linear shrinkage product and shrinkage product having reduced means. In addition, all three parameters had improved standard deviations and coefficients of variation. That being stated, the coefficients of variation calculated indicate that the parameters are still highly variable. This – as with calcrete – is to be expected, as much of the ferricrete properties depend on its host material.

The grading coefficient and grading modulus had contradictory results with the former indicating a finer material than the entire group, and the latter indicating a coarser material. Standard deviations for the grading modulus and grading coefficient also indicate a decrease and increase, respectively. However, with reference to the coefficient of variation, it is apparent that the grading modulus is far more refined than the grading coefficient, as observed before. Histograms for both parameters (Figure A.41c-d) illustrate a variable distribution, which can likely be ascribed to the variability of host materials.

Table A.23 Descriptive Statistics Summary: Ferricrete (Moist re)

	LL	**PI**	**PL**	**LS/BLS**	**LSP**	**SP**	**GM**	**GC**	**CBR**
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Ferricrete : 100% Mod AASHTO									
Mean	23,4	10,2	13,2	4,7	186,8	302,5	1,27	17,9	25,9
Standard Deviation	11,38	6,70	5,56	3,11	190,47	247,79	0,50	11,79	25,22
Coefficient of Variation	0,49	0,66	0,42	0,66	1,02	0,82	0,39	0,66	0,98
Minimum	0	0	0	0	0	0	0,29	0	3
Maximum	62	40	27	18	1482	1665	2,87	46	171
n	300	300	300	300	300	300	300	300	300

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

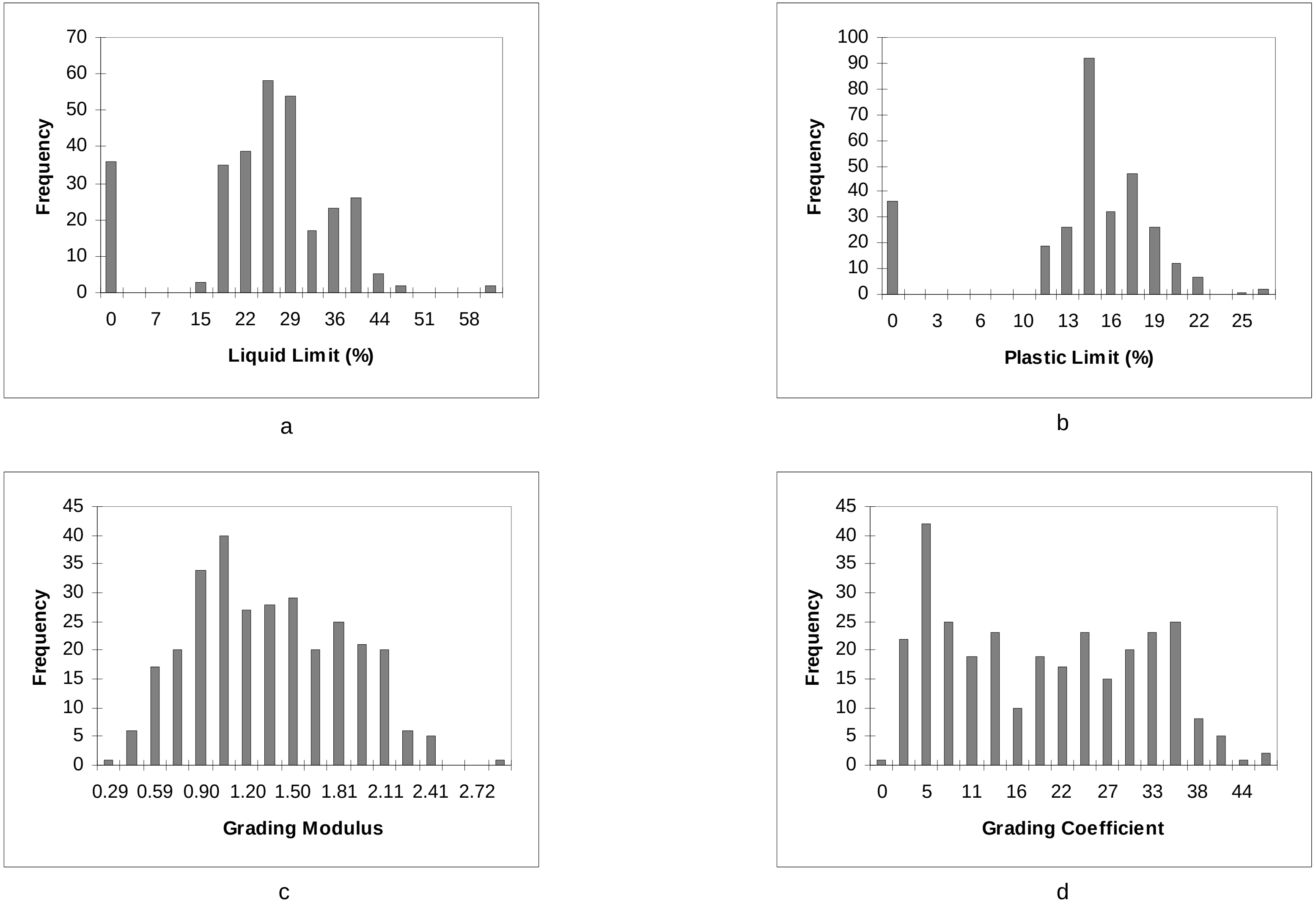

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Figure A.41 Frequency Distribution: Ferricrete, 100% Mod AASHTO (Moist regions)

The mean CBR of 25,9% is markedly lower than that of the entire group (32,1%). This confirms results encountered in lesser compacted groups that ferricrete is not truly such an ideal construction material as often perceived. Though the standard deviation did improve, the coefficient of variation remained nearly the same as that of the group, still indicating a wide spread of data.

A.3.9 Colluvium

Some 175 samples of colluvial materials were analysed in this section and results complied with the highly variable behaviour expected. The liquid limit, plasticity index and plastic limit all had elevated means relative to the entire group, as well as larger standard deviations. The increase in both these properties resulted in very little change in the parameters' coefficients of variation and hence, little improvement was noted after normalisation. Refer to Table A.24.

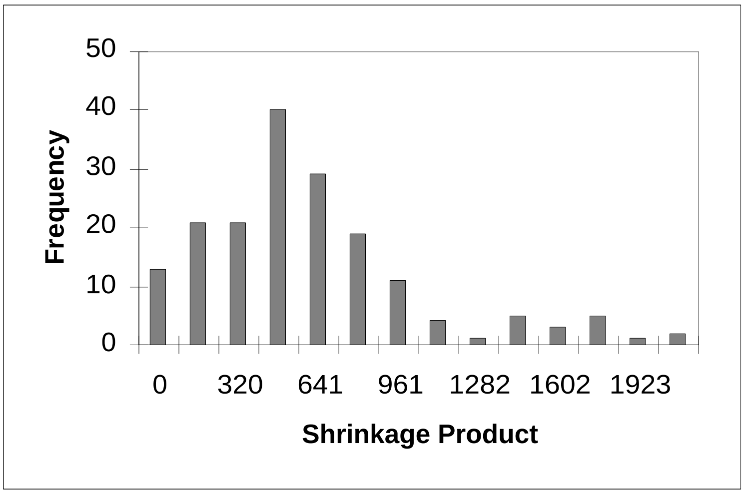
Also not surprising was the fact that colluvium held the highest values for both the linear shrinkage product and shrinkage product in the entire dataset compacted too Mod AASHTO density. These two parameters, as well as the linear shrinkage, had elevated mean values and largely increased standard deviations compared with the entire group. Consequently the coefficients of variation showed only small improvements, if any, but were still too large to suggest worthwhile refinement from the entire group. A histogram of the shrinkage product (Figure A.42a) indicates a slightly distorted, positively skewed distribution which illustrates the range of values clearly when comparing it with other material groups.

The grading modulus and grading coefficient hold true to the trend observed earlier of colluvial materials to be finer than the entire group. Both parameters had much reduced mean values, but critically showed a striking reduction in standard deviation. Whilst this resulted in little improvement of the grading modulus after normalisation, the grading coefficient revealed a drastically improved coefficient of variation, though the results still leave much to be desired in terms of refinement. Histograms for both parameters (Figure A.42b-c) show positively skewed distribution – though the

Table A.24 Descriptive Statistics Summary: Colluvium (Moist [illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 100% Mod AASHTO									
Mean	25,9	11,1	14,8	5,2	213,6	322,9	1,33	15,9	32,1
Standard Deviation	13,67	8,35	6,84	3,84	263,40	323,15	0,60	11,30	32,22
Coefficient of Variation	0,53	0,75	0,46	0,74	1,23	1,00	0,45	0,71	1,00
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	66	30	1823	2083	2,87	46	239
n	1179	1179	1179	1179	1179	1179	1179	1179	1179
Colluvium : 100% Mod AASHTO									
Mean	29,9	14,4	15,6	6,6	377,3	537,5	0,80	5,3	22,7
Standard Deviation	16,85	10,74	7,12	4,59	375,49	432,05	0,37	6,72	26,12
Coefficient of Variation	0,56	0,75	0,46	0,70	1,00	0,80	0,47	1,26	1,15
Minimum	0	0	0	0	0	0	0,10	0	1
Maximum	88	57	38	22	1823	2083	1,97	35	162
n	175	175	175	175	175	175	175	175	175

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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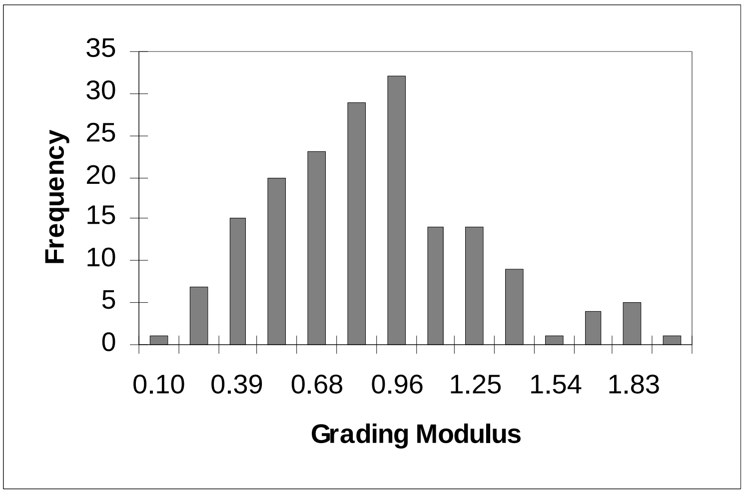

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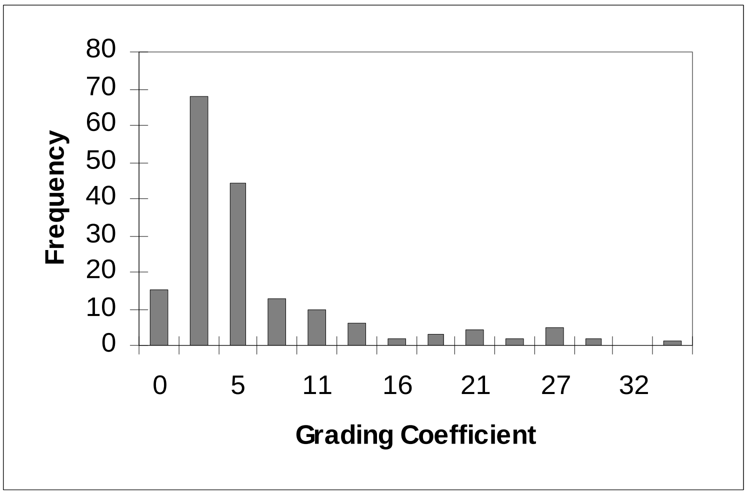

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Figure A.42 Frequency Distributions: Colluvium, 100% Mod AASHTO (Moist regions) grading modulus has a poorly formed shape – that shows a tendency of materials to be finer rather than coarse.

It is also not surprising to note that the mean CBR of the group is considerably lower than its counterpart in the entire group. A mean CBR of 22,7% was recorded, compared with 32,1% of the entire group. The standard deviation was proportionally larger than that of the entire group, resulting in an elevated coefficient of variation.

A.3.10 Non-plastic Materials

The contradiction between mean values for the grading modulus and grading coefficient was continued in non-plastic materials compacted to Mod AASHTO density, with the grading modulus having a mean of 1,37 and the grading coefficient having a mean of 12,8 (compared with respective means of 1,33 and 15,9 for the entire group). As before, both parameters showed reduction in standard deviation, whilst only the grading modulus had a reduced coefficient of variation.

The mean CBR value calculated for the non-plastic materials was much greater than that of the entire group. The mean was 53,9% compared with the entire group's mean CBR of 32,1%. 135 samples of non-plastic materials were analysed, and a standard deviation and coefficient of variation of 35,51 and 0,66 were derived, respectively.

A.4 Descriptive Statistics: Dry Areas: 95% Mod AASHTO

A.4.1 All Materials

As mentioned in the script, the dataset analysed for materials from a dry climate is significantly smaller than the dataset analysed of materials from moist areas. Consequently some 619 samples were analysed for the 95% Mod AASHTO group of mixed materials. Not all of the samples were analysed, though, as certain material groups (e.g. carbonaceous) did not contain a sufficient number of samples to allow a meaningful analysis. Also, materials such as tillite, conglomerate etc. were not analysed. The entire group compacted to 95% Mod AASHTO density revealed that though Atterberg Limits were more pronounced than expected, shrinkage parameters were generally less pronounced than those of moist areas. A short summary of the descriptive statistics can be found in Table A.25. The following was revealed by a descriptive statistical analysis:

- *Liquid Limit:* A mean liquid limit of 21,5% was calculated, along with a standard deviation of 11,66 and coefficient of variation of 0,54. This indicates variable data, as can be expected from a population of mixed materials. The 619 samples revealed a minimum liquid limit of 0% (non-plastic) and a maximum liquid limit of 73%. Figure A.43 indicates a positively skewed distribution in the parameter's frequency distribution, indicating a tendency to lower liquid limits. Also, a clear peak is visible at zero, which represents non-plastic materials.

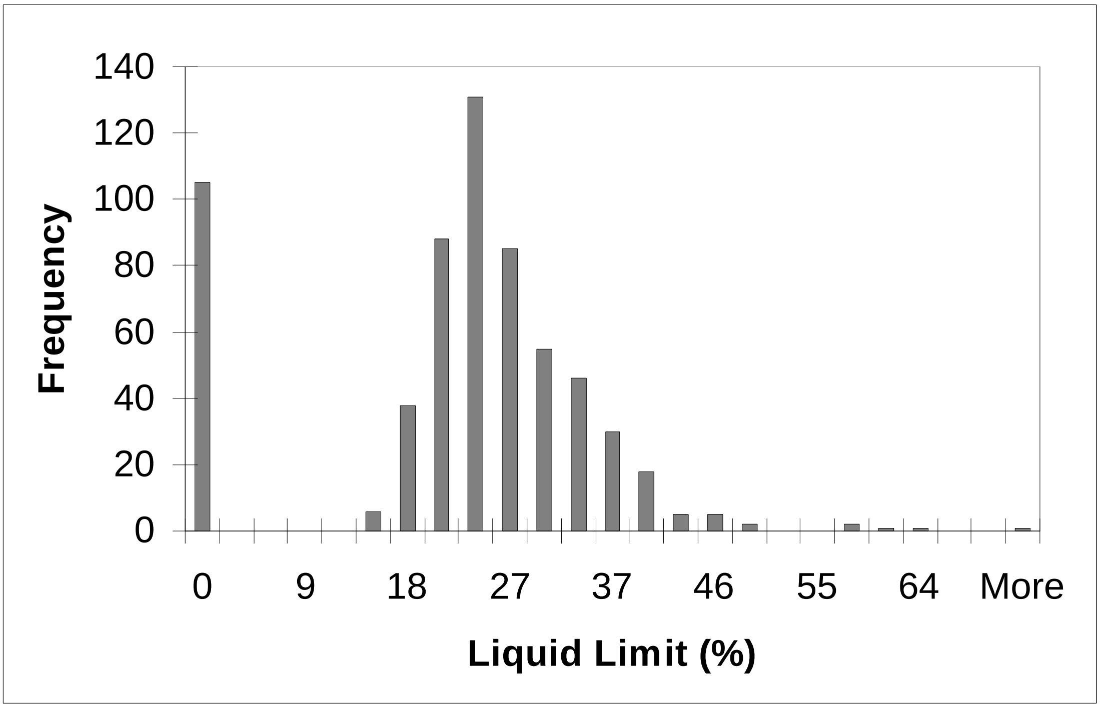


Figure A.43 Frequency Distribution of Liquid Limit (All groups, 95% Mod AASHTO, dry regions)

- *Plastic Limit:* The frequency distribution of the plastic limit (Figure A.44) closely resembles that of the liquid limit, though the parameter's mean value came to 14,4%. The standard deviation and coefficient of variation were 7,70 and 0,53 indicating similar amounts of variability in the plastic limit data. The minimum and maximum values recorded were 0% (non-plastic) and 43%, respectively.

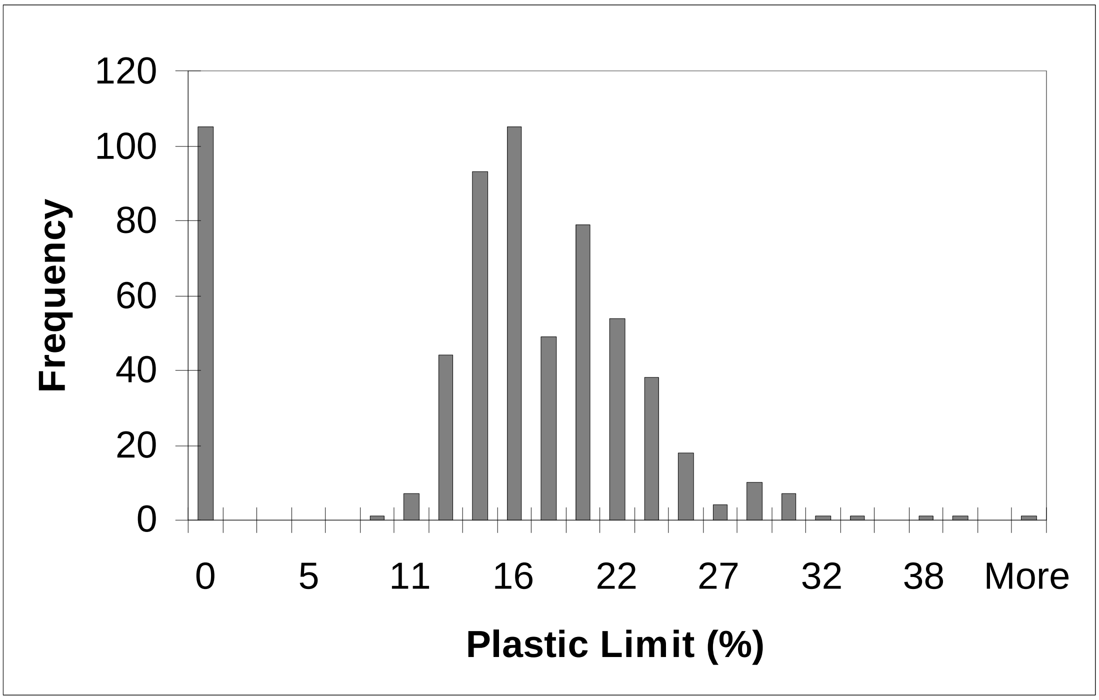


Figure A.44 Frequency Distribution of Plastic Limit (All groups, 95% Mod AASHTO, dry regions)

- *Plasticity Index:* The clearest indication of reduced Atterberg Limits is observed in the characteristics of the plasticity index. A mean plasticity index of 7,1% was found, whilst the standard deviation is 4,96 and the coefficient of variation is 0,70. The minimum and maximum plasticity indices encountered were 0% (non-plastic) and 30%, respectively. Figure A.45 illustrates a more erratically distributed histogram for the plasticity index. The graph appears to resemble a distorted, positively distribution, again with a peak representing non-plastic materials.

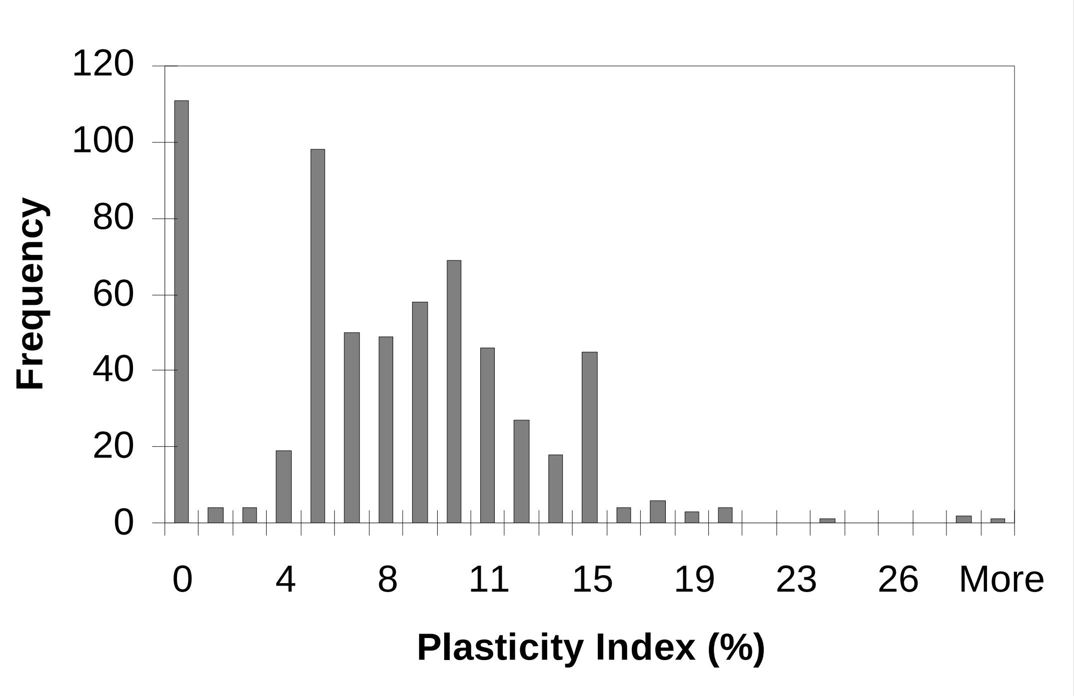


Figure A.45 Frequency Distribution of Plasticity Index (All groups, 95% Mod AASHTO, dry regions)

- *Linear Shrinkage:* The frequency distribution (Figure A.46) of the linear shrinkage indicates that the parameter tended to have lower values in the dry region. A mean of 3,5% was calculated and the standard deviation and coefficient of variation were found to be 2,21 and 0,63, respectively. Apart from a minimum linear shrinkage of 0%, a maximum linear shrinkage of 12% was calculated.
- *Linear Shrinkage Product:* It is not surprising to note that a fairly low mean of 59,4 was calculated for all materials in the dry areas. A coefficient of variation of 0,99 and standard deviation of 58,95 reveals that the variation is almost as large as the mean, though, indicating highly variable data. The parameter had values ranging from zero to 375, and a frequency distribution plot (Figure A.47) revealed a clear positive distribution, emphasising the tendency toward lower linear shrinkage products.

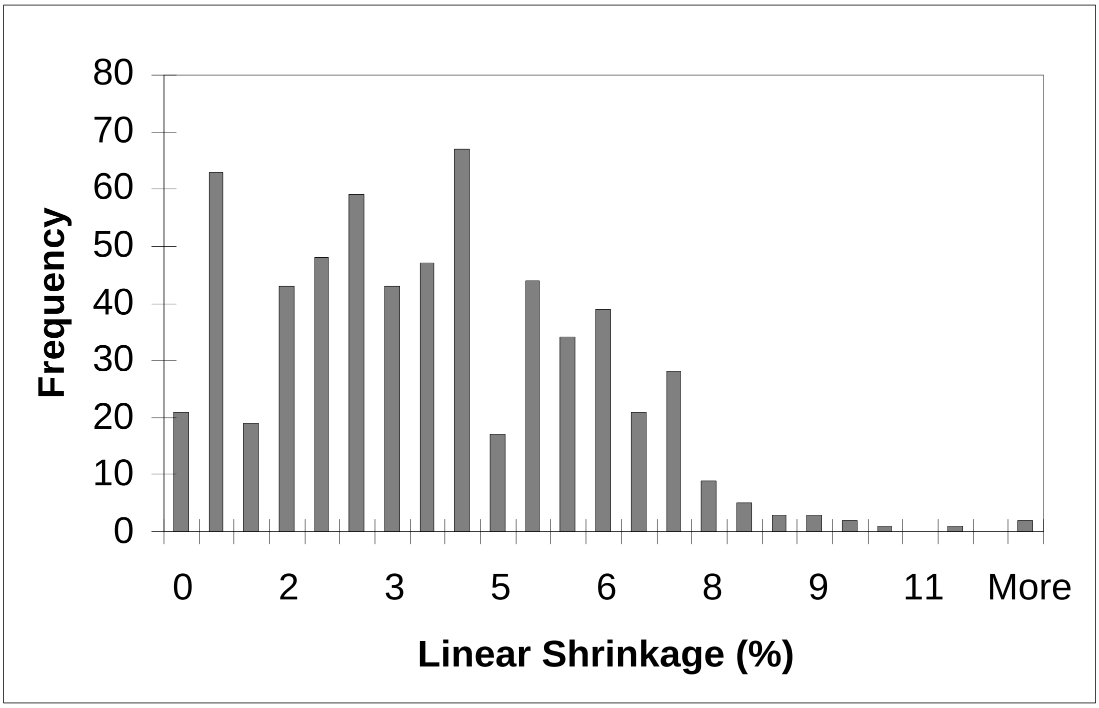


Figure A.46 Frequency Distribution of Linear Shrinkage (All groups, 95% Mod AASHTO, dry regions)

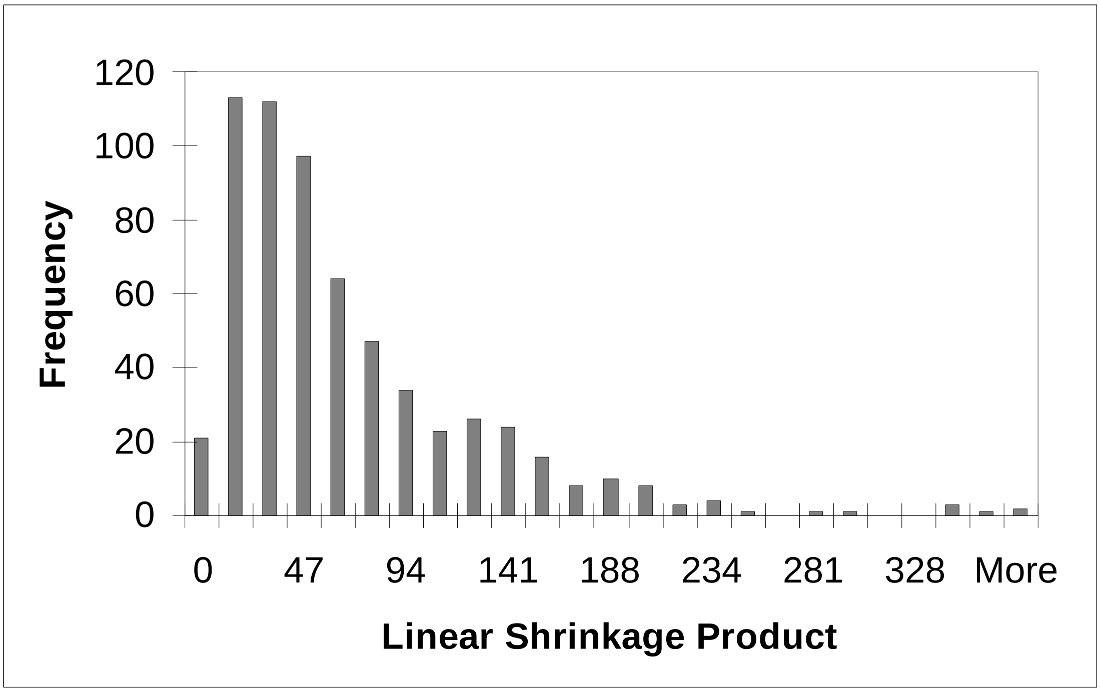


Figure A.47 Frequency Distribution of Linear Shrinkage Product (All groups, 95% Mod AASHTO, dry regions)

- *Shrinkage Product:* The shrinkage product was found to correspond to the linear shrinkage product. A mean of 119,9 was calculated, with a high variability indicated by the standard deviation (99,34) and coefficient of variation (0,83). The frequency distribution (Figure A.48) is also similar to that of the linear shrinkage product, in that a positively skewed distribution was revealed.

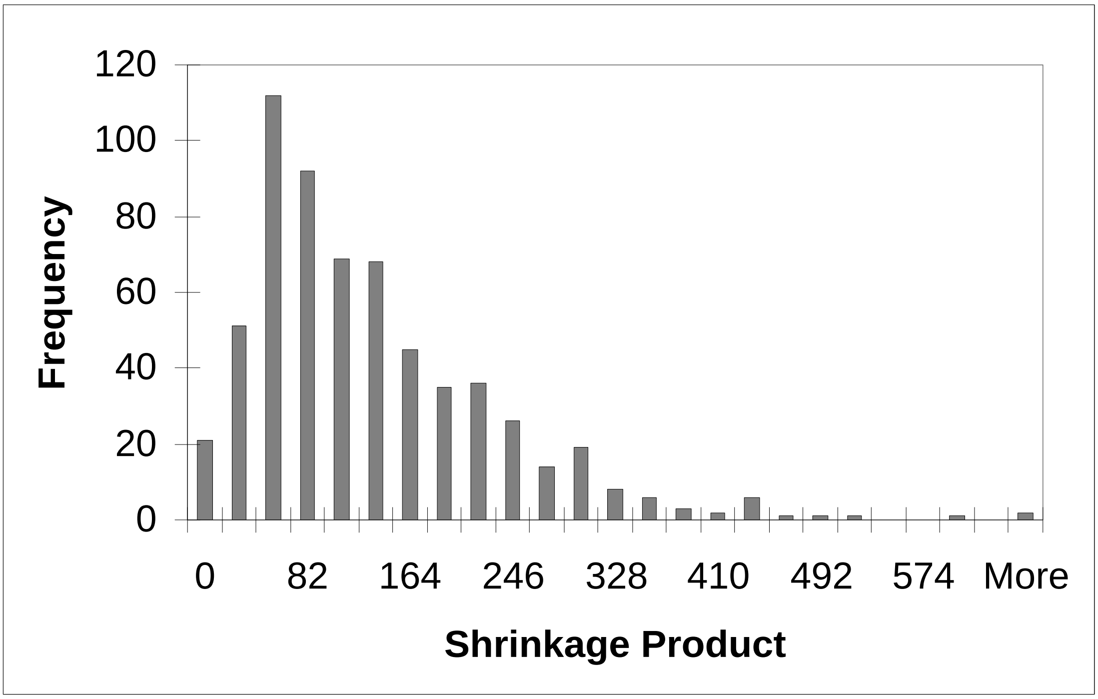


Figure A.48 Frequency Distribution of Shrinkage Product (All groups, 95% Mod AASHTO, dry regions)

- *Grading Modulus:* The grading modulus of the entire group seems more compliant with the expected image of materials in a dry region, in that the mean grading modulus is 1,95 – indicating a gravelly material. The variability of the material is still limited, as indicated by the standard deviation (0,50) and coefficient of variation (0,25). The grading moduli ranged from 0,46 to 2,87. Of particular interest is the frequency distribution of the parameter – refer to Figure A.49. Two peaks were noted, the first and larger being at 2,27 and the second, smaller peak being at 1,27. This suggests that there may be a bimodal distribution in the data.

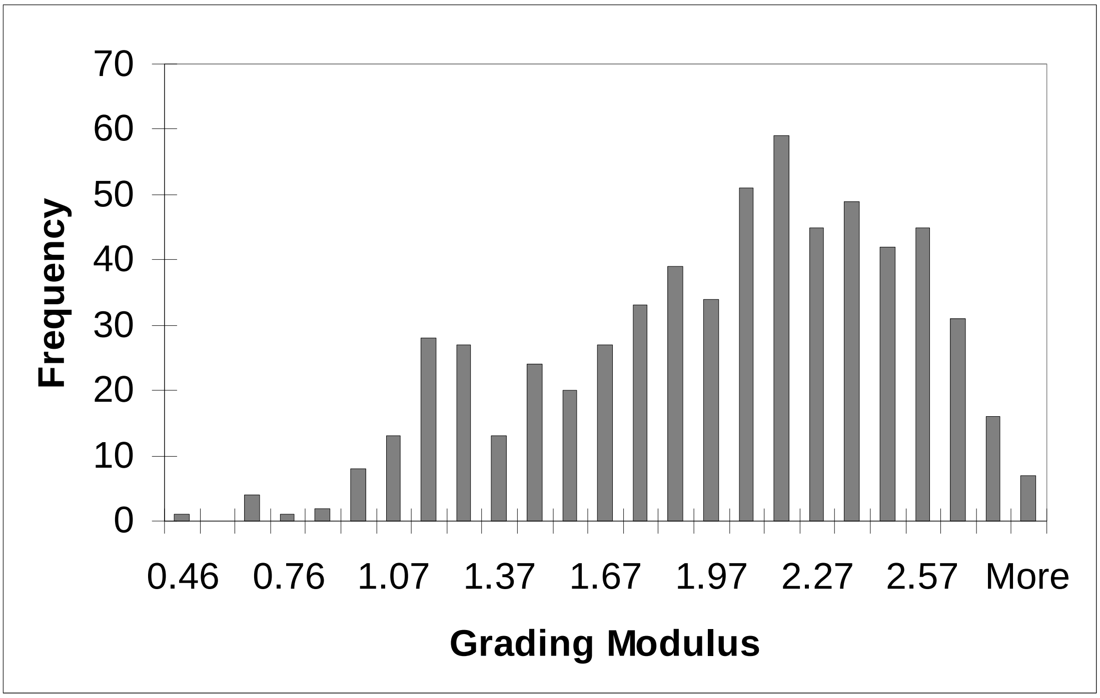


Figure A.49 Frequency Distribution of the Grading Modulus (All groups, 95% Mod AASHTO, dry regions)

- *Grading Coefficient:* As with the grading modulus, a coarser grading is indicated by the grading coefficient, though the mean (18,4) is not as elevated relative to the grading modulus. Also, the parameter is indicated to be more variable than the grading modulus, with a standard deviation and coefficient of variation of 9,36 and 0,51, respectively. The parameter values ranged from zero to 42, whilst the frequency distribution (Figure A.50) indicates a distorted, near normal distribution.
- *CBR at 95% Mod AASHTO (PSCBR):* A mean CBR of 37,4% was calculated for mixed materials compacted to 95% Mod AASHTO density in the dry climatic areas. The CBR values ranged from 1% to 125%. A standard deviation of 21,34 was recorded, whilst the coefficient of variation was found to be 0,57. Finally, an unrefined, normally skewed distribution was found for the CBR, as illustrated in Figure A.51.

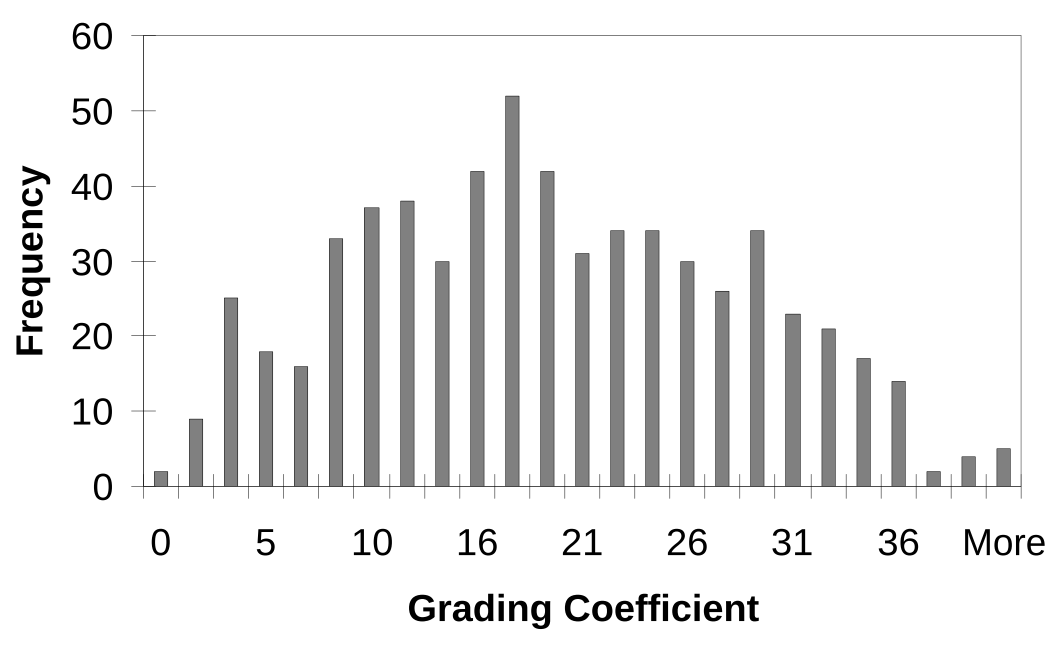


Figure A.50 Frequency Distribution of the Grading Coefficient (All groups, 95% Mod AASHTO, dry regions)

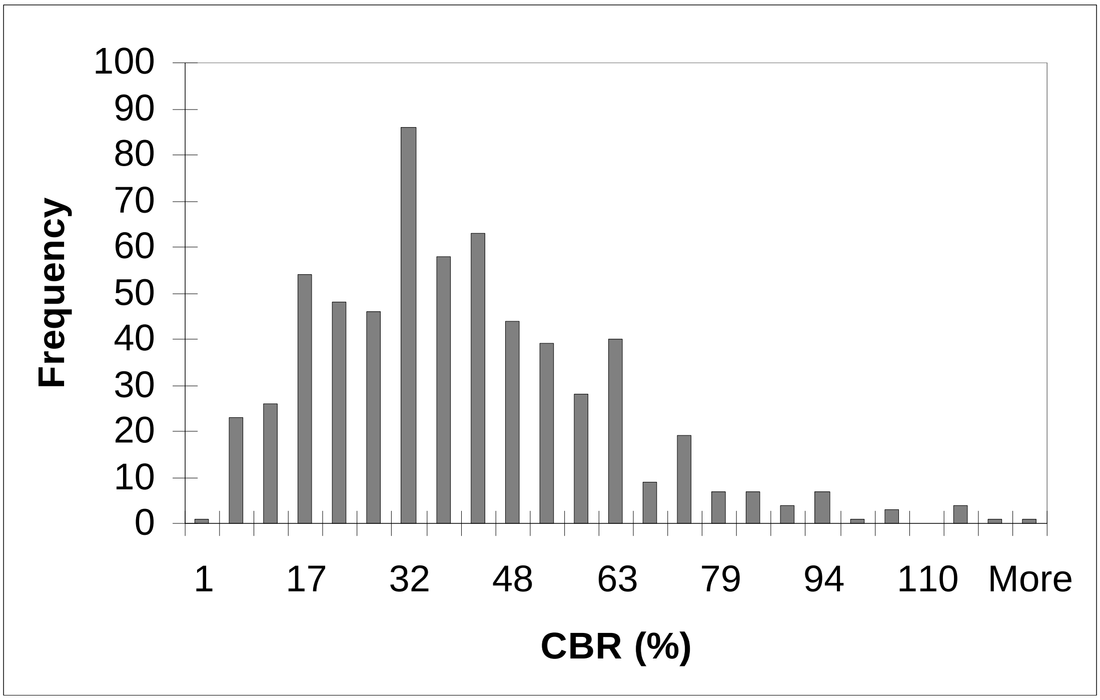


Figure A.51 Frequency Distribution of CBR (All groups, 95% Mod AASHTO, dry regions)

A.4.2 Basic Crystalline Materials

The basic crystalline group comprised some 50 samples, compacted to 95% Mod AASHTO *density. In general reduced means were noted for all parameters, with increased vari*ability (refer to Table A.25).

Atterberg Limits had reduced means compared with the entire group, with standard deviations very similar to the entire group as well. However, coefficients of variation showed a considerable increase, indicating higher variability in the group, after normalisation. A frequency distribution graph of the liquid limit (Figure A.52a) revealed a distribution not entirely compliant with that of the entire group. This reflects the lower mean, as well as a refinement in liquid limit ranges for the basic crystalline group.

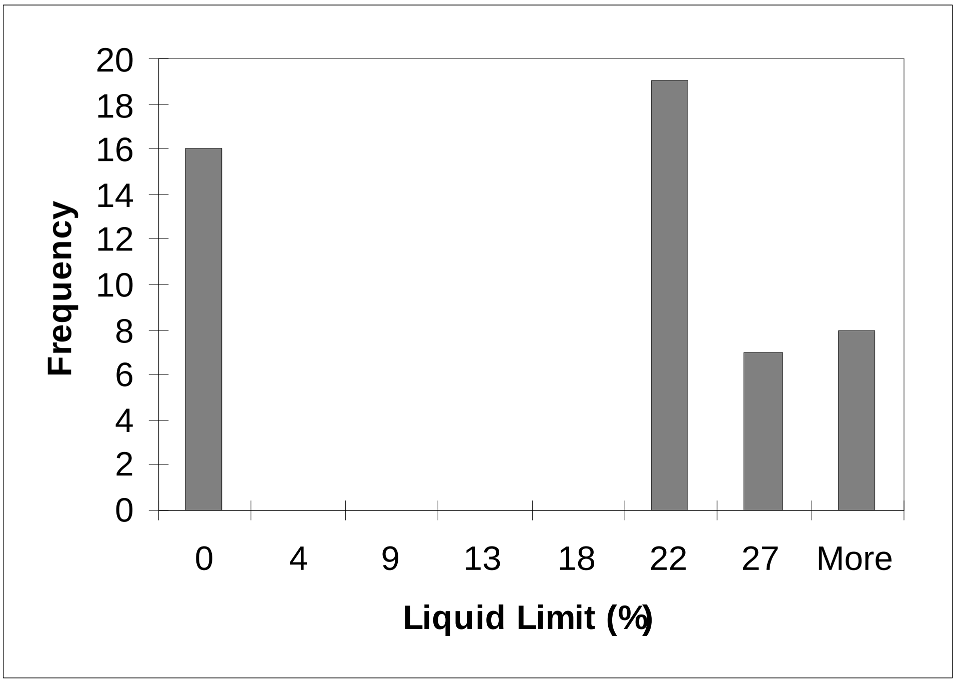
The linear shrinkage, linear shrinkage product and shrinkage product also showed decreased means when comparing them with the entire group. It appears that, in general, the basic crystalline materials have a lower tendency to swell. Whilst standard deviations were slightly reduced from the entire group, coefficients of variation for all three parameters were slightly higher, indicating a more variable nature of the basic crystalline material.

The grading modulus and grading coefficient once more had contradicting results, with the former indicating a finer nature than the entire group, and the latter a coarser nature. As explained before, this is ascribed to the fact that different grading parameters are used to calculate the grading modulus and grading coefficient. Nevertheless, both parameters, particularly the grading coefficient, showed a decrease in standard deviation and coefficient of variation. Whilst the frequency distribution graph of the grading modulus was similar to the entire group ’s, the grading coefficient revealed a negatively skewed histogram (Figure A.52b). This shows specific refinement from the entire group’s frequency distribution and indicates a tendency toward moderately coarse material.

Table A.25 Descriptive Statistics Summary: Basic Crystalline ([illegible]TO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Basic Crystalline : 95% Mod AASHTO									
Mean	15,9	5,0	10,9	2,5	45,9	99,2	1,83	23,0	34,5
Standard Deviation	11,34	9,94,351	7,68	1,82	51,22	90,04	0,40	7,70	15,77
Coefficient of Variation	0,71	0,720,87	0,71	0,73	1,11	0,91	0,390,22	0,34	0,46
Minimum	0	0	0	0	0	0	0,58	2	5
Maximum	31	15	19	7	196	371	2,77	36	67
n	50	50	50	50	50	50	50	50	50

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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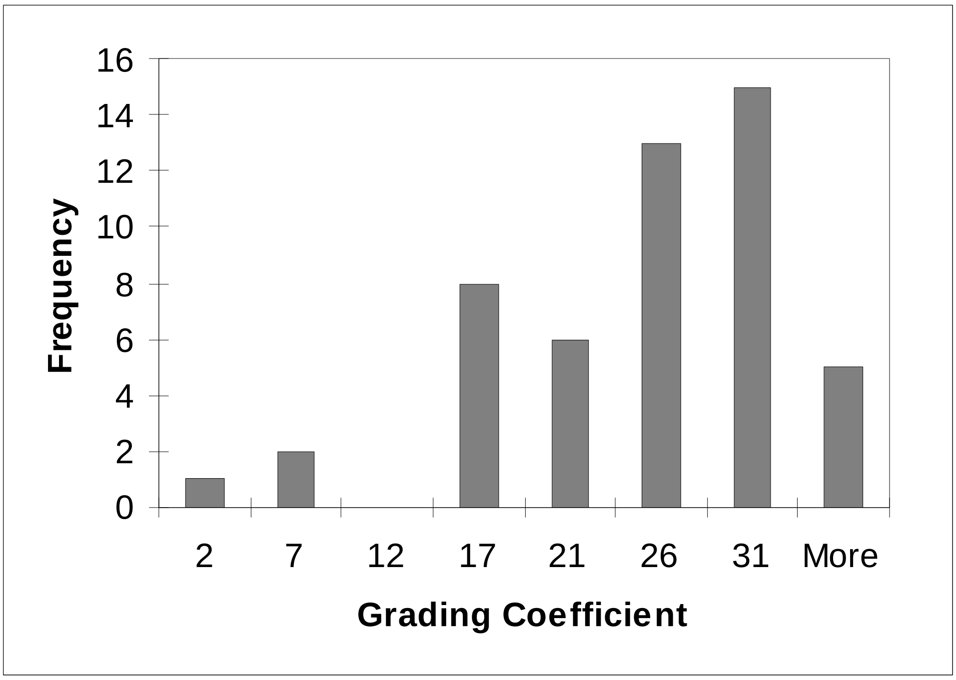

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Figure A.52 Histograms: Basic Crystalline, 95% Mod AASHTO (Dry regions)

Lastly, the mean CBR of the basic crystalline group was calculated to be 34,5% - roughly 2% lower than the mean CBR of the entire group. Some refinement was also indicated by a reduced standard deviation (15,77) and coefficient of variation (0,46).

A.4.3 Acid Crystalline Materials

In contrast to the basic crystalline group, the acid crystalline group – consisting of 66 samples - showed refinement of nearly every parameter considered in the descriptive statistical analysis (Table A.26).

Atterberg Limits had slightly elevated means compared with the entire group. This is unanticipated, as basic crystalline materials were expected to show this trend, but did not. That being stated, the elevated Atterberg Limits were only slightly higher than those of the entire group. In addition to this, the liquid limit, plastic limit and plasticity index showed slightly reduced standard deviations compared with the entire group, whilst coefficients of variation for the same parameters showed a notable improvement. The coefficient of variation still indicates a large variation within the data.

The mean linear shrinkage of the acid crystalline group was recorded as 3,4%. Considering the entire group's mean linear shrinkage of 3,5%, little difference is noted between the two groups. The linear shrinkage also had reduced standard deviation and coefficient of variation. Critically, both the linear shrinkage product and shrinkage product had means significantly lower than those of the entire group, indicating that despite a near equal linear shrinkage (with the entire group), lower P075 and P425 constituents must be prevalent to produce the results at hand. This is not surprising, considering the tendency of acid crystalline material to weather to sandy materials. Both parameters also had largely reduced standard deviations, as well as much reduced coefficients of variation.

As is to be expected, the acid crystalline materials showed a tendency towards coarser material compared with the entire group. The grading modulus and grading coefficient had means of 2,12 and 29,4, respectively. Both parameters also

Table A.26 Descriptive Statistics Summary: Acid Crystalline (D [illegible] TO)

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Acid Crystalline : 95% Mod AASHTO									
Mean	23,3	7,4	15,9	3,4	38,9	93,4	2,12	29,4	43,2
Standard Deviation	10,01	4,11	6,65	1,92	28,05	58,30	0,23	6,77	19,3
Coefficient of Variation	0,43	0,56	0,42	0,56	0,72	0,62	0,11	0,23	0,45
Minimum	0	0	0	0	0	0	1,25	11	14
Maximum	44	17	29	8	141	231	2,64	42	93
n	66	66	66	66	66	66	66	66	66

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

had reduced standard deviations, whilst coefficients of variation indicated significantly reduced variation after normalisation. The grading modulus and grading coefficient had coefficients of variation of 0,11 and 0,23, respectively. Frequency distributions for the two parameters (Figure A.53a and b) showed the tendency to coarse materials mentioned, with negatively skewed distributions in both instances.

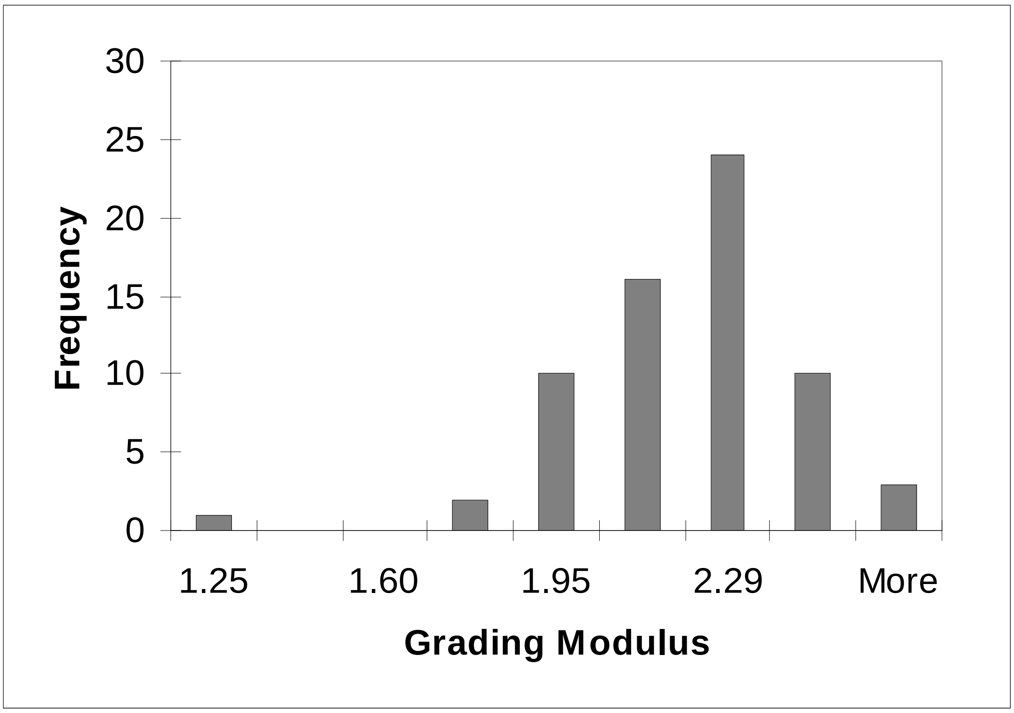
CBR values of the acid crystalline group were found to be elevated, compared with the entire group. A mean CBR of 43,2% was calculated, with a standard deviation of 19,32 and a coefficient of variation of 0,45. The latter two parameters indicate a refinement in the range of CBR values, but still show considerable variation.

A.4.4 High Silica Materials

A total of 77 samples of high silica material were analysed. Descriptive statistics (Table A.27) revealed that Atterberg Limits have slightly lower means than the entire group, whilst also showing little improvement in standard deviations. Coefficients of variation were slightly poorer than that of the entire group, but none of the differences are considered significant.

As encountered with high silica materials in moist climates, high silica materials from dry climates also showed significantly reduced mean linear shrinkage, linear shrinkage product and shrinkage product. All three parameters also had largely reduced standard deviations; however coefficients of variation indicate little refinement in the parameters after normalisation. Figure A.54a illustrates the linear shrinkage 's tendency to lower values, with a predominant peak at 2%. In addition, the frequency distribution of the shrinkage product reflects that of the entire group; however the material's shrinkage product values tend to be lower – as illustrated by Figure A.54b.

Contradicting results were again obtained from the grading modulus and grading coefficient, with the grading modulus indicating a coarse material (mean of 2,34),



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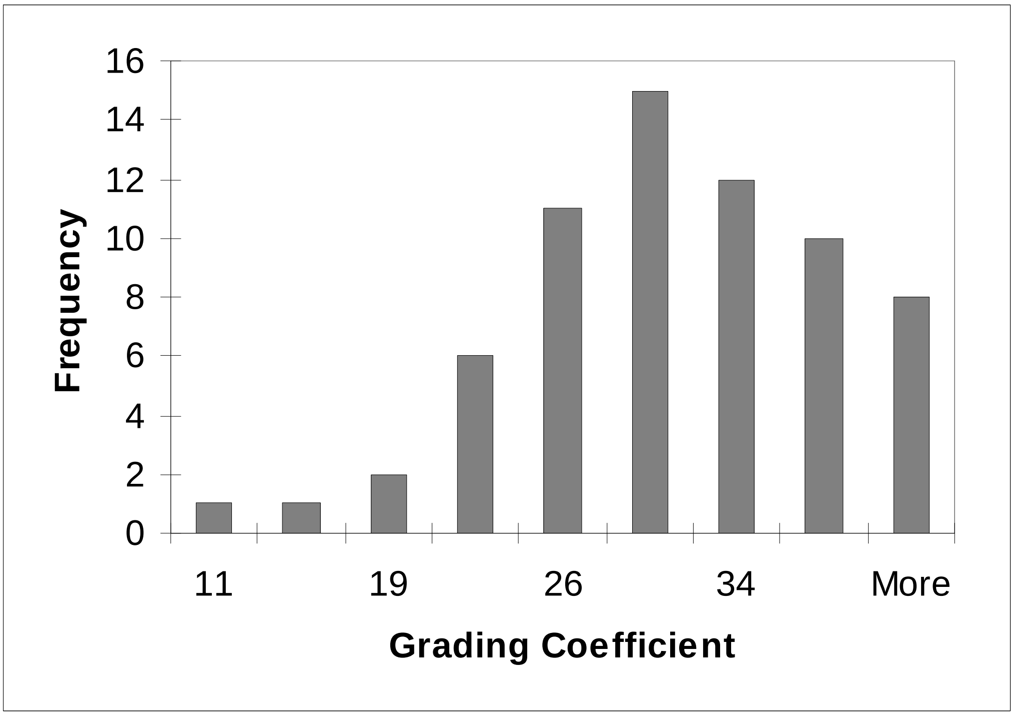

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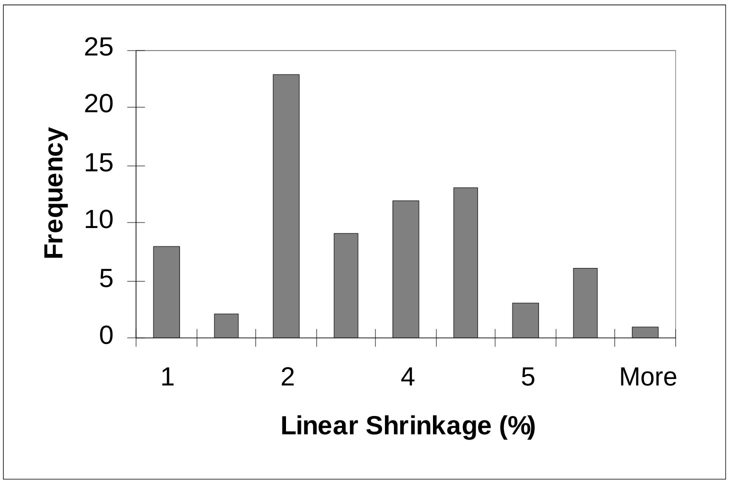
Figure A.53 Histograms: Acid Crystalline, 95% Mod AASHTO (Dry regions)

Table A.27 Descriptive Statistics Summary: High Silica (Dry re[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
High Silica : 95% Mod AASHTO									
Mean	18,5	5,6	12,9	2,8	31,6	74,7	2,34	13,0	47,2
Standard Deviation	10,30	3,93	7,27	1,58	31,58	59,06	0,30	5,41	18,40
Coefficient of Variation	0,56	0,71	0,56	0,56	1,00	0,79	0,13	0,42	0,39
Minimum	0	0	0	1	3	8	1,05	3	9
Maximum	32	17	24	7	154	314	2,74	30	96
n	77	77	77	77	77	77	77	77	77

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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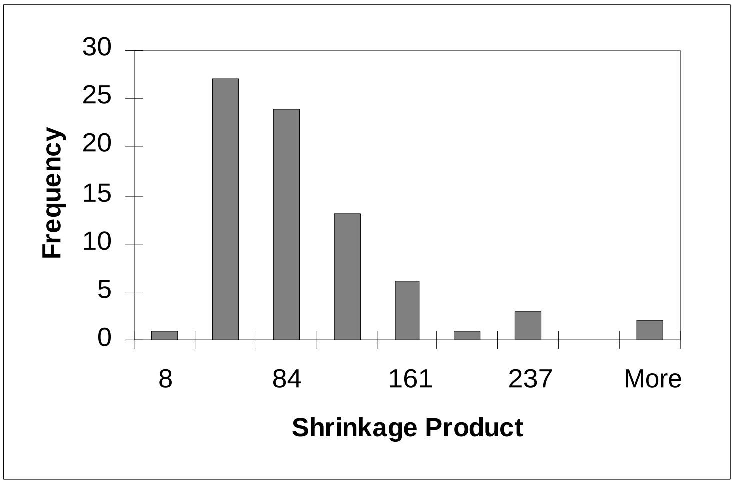

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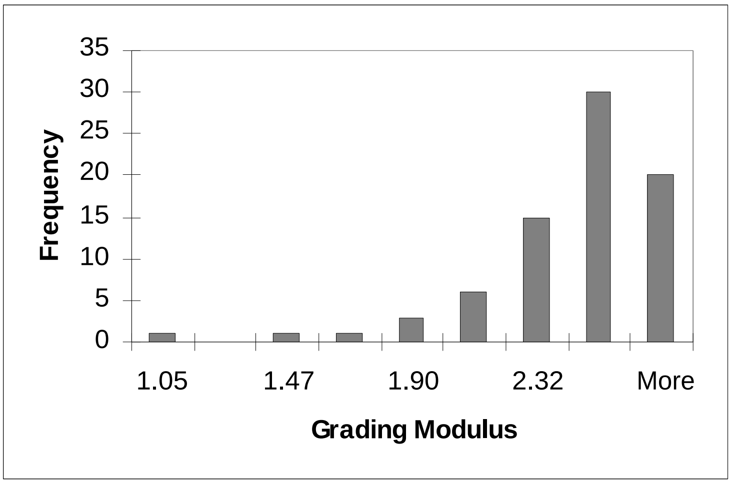

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Figure A.54 Histograms: High Silica, 95% Mod AASHTO (Dry regions) whilst the grading coefficient indicates a finer material (mean of 13,0) compared with the entire group. Figure A.54c shows the negatively skewed frequency distribution of the grading modulus, with a peak located at 2,53. Both parameters also showed reduced standard deviations and coefficients of variation.

A mean CBR of 47,2% was calculated for the high silica group, which is considerably higher than that of the entire group (37,4%). Though the standard deviation of the CBR did not improve much, the coefficient of variation showed a notable improvement which suggests refinement after normalisation.

A.4.5 Arenaceous Materials

The arenaceous material group comprised some 54 samples. Descriptive statistics (Table A.28) revealed that Atterberg Limits are slightly elevated over those of the entire group, whilst the liquid limit, plastic limit and plasticity index all showed a small reduction in standard deviation. More importantly, all three parameters also showed some improvement in coefficient of variation; however the material's Atterberg Limits are indicated to be variable even after normalisation.

Apart from slightly higher mean values, the linear shrinkage, linear shrinkage product and shrinkage product showed little significant improvement with regard to coefficients of variation. The same applies to the standard deviation, with the exception of the shrinkage product which showed a slight improvement.

As before, the grading modulus and grading coefficient contradicted each other's results with the former indicating a coarser material, and the latter indicating a finer material compared with the entire group. Neither parameter showed a particularly improved standard deviation, but the grading modulus had an improved coefficient of variation of 0,20.

The arenaceous group also had a mean CBR of 28,1%, some 9% lower than that of the entire group. Though the standard deviation was improved, the coefficient of variation remained nearly unchanged, indicating variable parameter properties.

Table A.28 Descriptive Statistics Summary: Arenaceous (Dry r[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Arenaceous : 95% Mod AASHTO									
Mean	24,0	7,9	16,1	3,9	69,7	108,7	2,16	12,6	28,1
Standard Deviation	9,81	4,50	6,72	2,43	63,66	85,79	0,42	6,34	16,36
Coefficient of Variation	0,41	0,57	0,42	0,62	0,91	0,79	0,20	0,50	0,58
Minimum	0	0	0	0	0	0	1,19	2	2
Maximum	43	18	29	12	282	324	2,81	30	69
n	54	54	54	54	54	54	54	54	54

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples

A.4.6 Argillaceous Materials

A total of 154 samples were included in the argillaceous material group. The descriptive statistical analysis (Table A.29) revealed that Atterberg Limits have slightly higher means than the entire group, though this is not entirely unexpected. Standard deviations and coefficients of variation also revealed some improvement in the data quality. Both the plastic limit and plasticity index had erratic frequency distributions (Figure A.55a and b) which may be interpreted as poorly pronounced, negatively skewed distributions, depending on the reader's interpretation.

The linear shrinkage, linear shrinkage product and shrinkage product had higher mean values than the equivalent parameters in the entire group. This is emphasised in the frequency distribution of the linear shrinkage (Figure A.55c) in particular, with higher linear shrinkage values being more prevalent. All three parameters also showed improved data quality in that standard deviations and coefficients of variation of all three parameters were refined from the entire group.

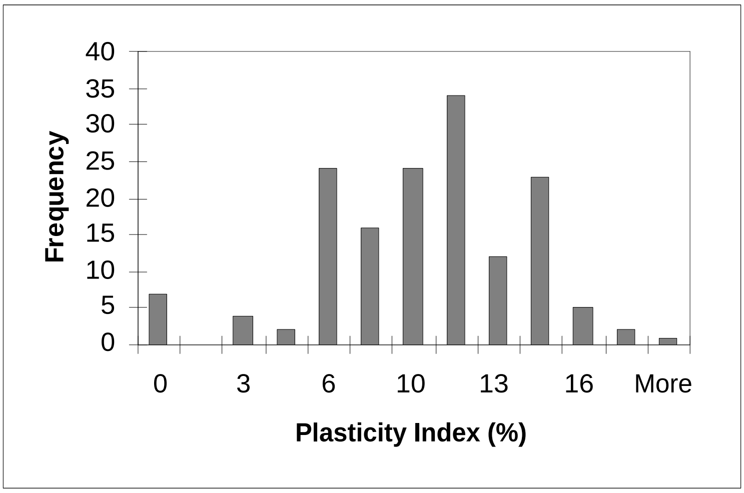
Grading parameters indicated that argillaceous materials are only fractionally coarser than the entire group, with both the grading modulus and grading coefficient showing a slight increase in mean values compared with the entire group. Whilst neither parameter showed any significant reduction in standard deviation relative to the entire group, both parameters had slightly improved coefficients of variation.

A mean CBR of 25,4% was calculated for the argillaceous group, with an improved standard deviation compared with the entire group. Despite this improvement, the parameter's coefficient of variation showed little improvement.

Table A.29 Descriptive Statistics Summary: Argillaceous (Dry)

	LL	**PI**	**PL**	**LS/BLS**	**LSP**	**SP**	**GM**	**GC**	**CBR**
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Argillaceous : 95% Mod AASHTO									
Mean	25,3	9,2	16,2	4,7	80,0	134,3	2,10	20,1	25,4
Standard Deviation	7,76	3,82	5,48	1,84	55,13	88,52	0,47	8,12	14,98
Coefficient of Variation	0,31	0,42	0,34	0,40	0,69	0,66	0,23	0,40	0,59
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	39	19	30	9	349	502	2,87	36	87
n	154	154	154	154	154	154	154	154	154

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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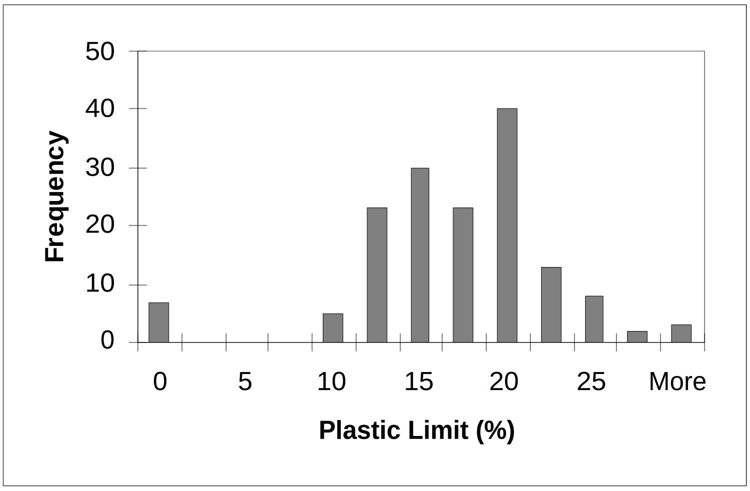

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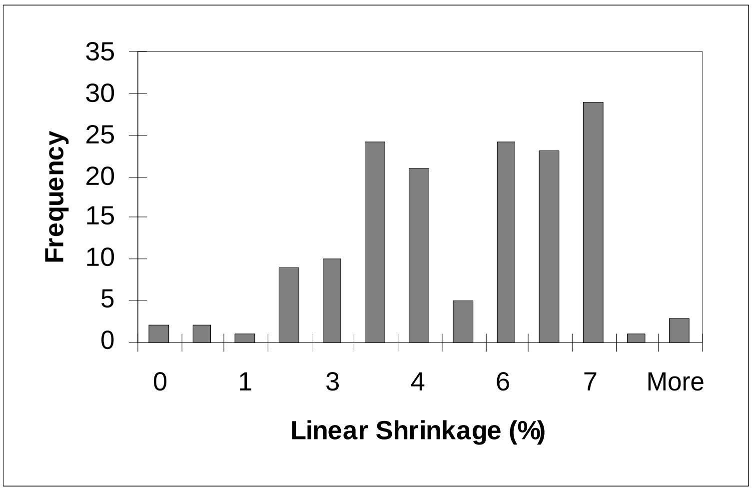

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Figure A.55 Histograms: Argillaceous, 95% Mod AASHTO (Dry regions)

A.4.7 Calcrete Materials

A total of 72 calcrete samples were included in this group. The descriptive statistical analysis (Table A.30) revealed slightly elevated Atterberg Limits, compared with the entire group. This is once again dependant on the host material of the calcrete. As previously noted, the calcrete materials in the dry region are also subject to more variability than the entire group. Whilst all three parameters had larger standard deviations, only the liquid limit and plasticity index had increased coefficients of variation.

The linear shrinkage was found to have roughly the same mean value as the entire group; however the linear shrinkage product and shrinkage product had smaller and marginally larger means than the entire group, respectively. Whilst the linear shrinkage had a larger standard deviation than the entire group, the linear shrinkage product and shrinkage product both had reduced standard deviations. The same trend applies to the coefficients of variation, though despite refinement of the linear shrinkage product and shrinkage product, the parameter data are still highly variable.

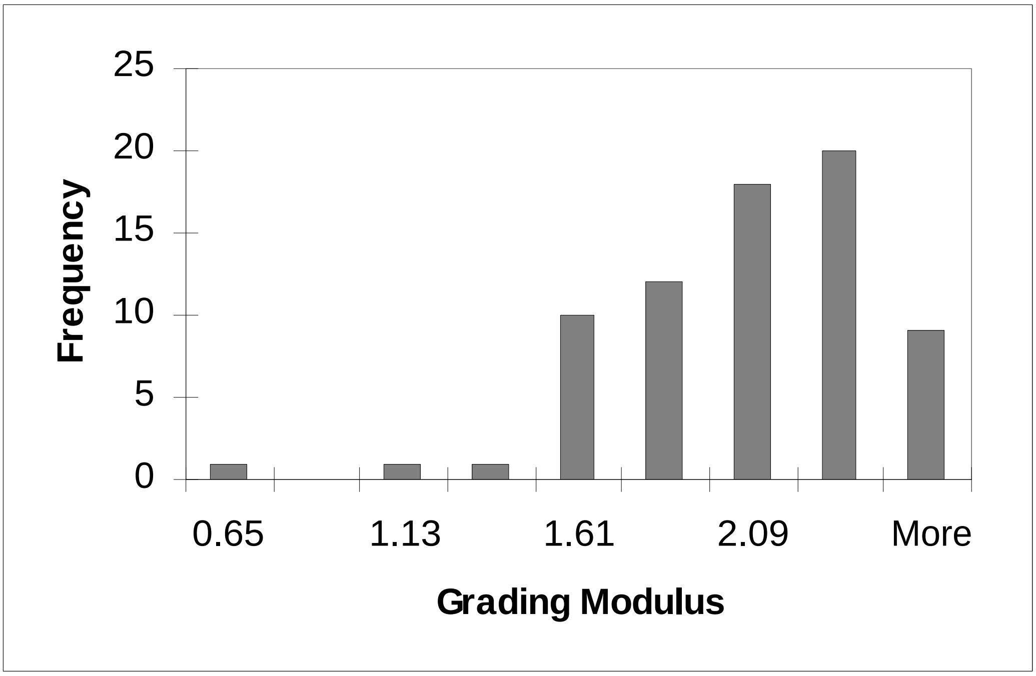
The grading modulus and grading coefficient both revealed means not far off that of the entire group. However, both parameters had reduced standard deviations as well as coefficients of variation. The grading modulus (Figure A.56a) has a negatively skewed distribution with a single peak, clearly showing refinement in grading when compared with the frequency distribution of the entire group. Simultaneously, the erratic distribution of the grading coefficient (Figure A.56b) reflects the distribution observed for the entire group. This suggests to the author that the grading modulus may be a more reliable or constant parameter to consider.

Finally, a mean CBR of 51,9% was calculated for the calcrete materials. Though the standard deviation of the CBR remainder virtually unchanged compared with the entire group, the coefficient of variation improved somewhat.

Table A.30 Descriptive Statistics Summary: Calcrete (Dry regi

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Calcrete : 95% Mod AASHTO									
Mean	24,0	7,6	16,4	3,5	46,4	122,3	1,96	19,9	51,9
Standard Deviation	14,46	6,63	8,89	2,48	36,94	75,23	0,36	5,41	21,61
Coefficient of Variation	0,60	0,87	0,54	0,70	0,80	0,62	0,18	0,27	0,42
Minimum	0	0	0	1	5	22	0,65	10	12
Maximum	73	30	43	12	176	391	2,57	32	114
n	72	72	72	72	72	72	72	72	72

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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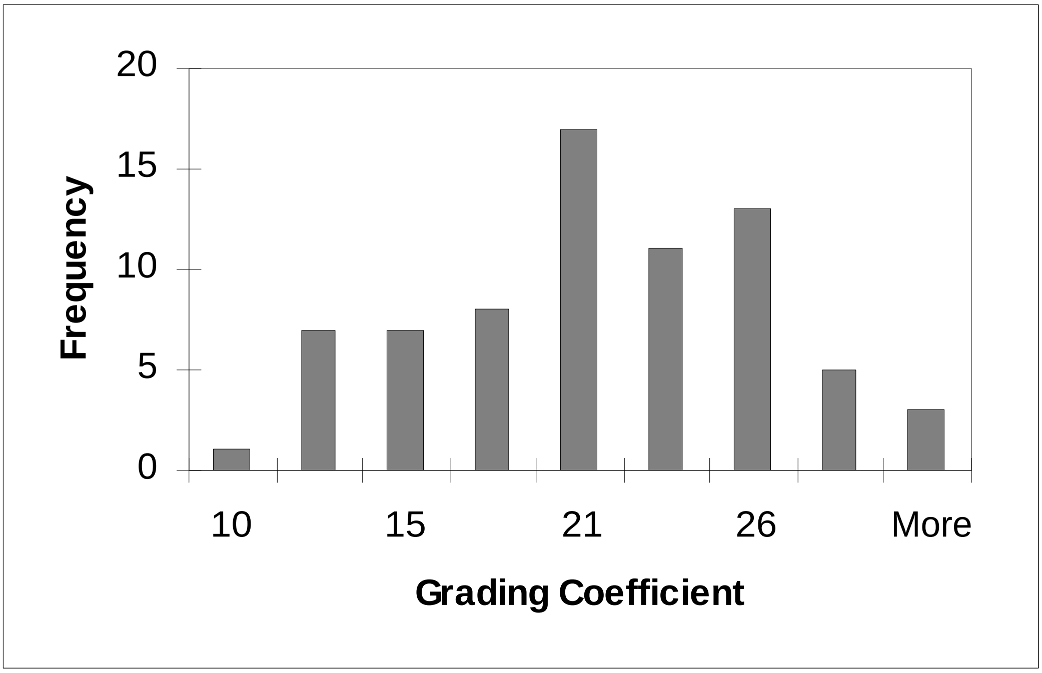

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Figure A.56 Histograms: Calcretes, 95% Mod AASHTO (Dry regions)

A.4.8 Alluvial Materials

The entire sample population of 38 samples came from the same location and as such may not necessarily be representative of all alluvial materials. Nevertheless, the material group had higher Atterberg Limit means, with larger standard deviations too, as illustrated in Table A.31. Reflecting these properties, the coefficients of variation for all three parameters were found to be larger than those of the entire group, indicating more variable properties.

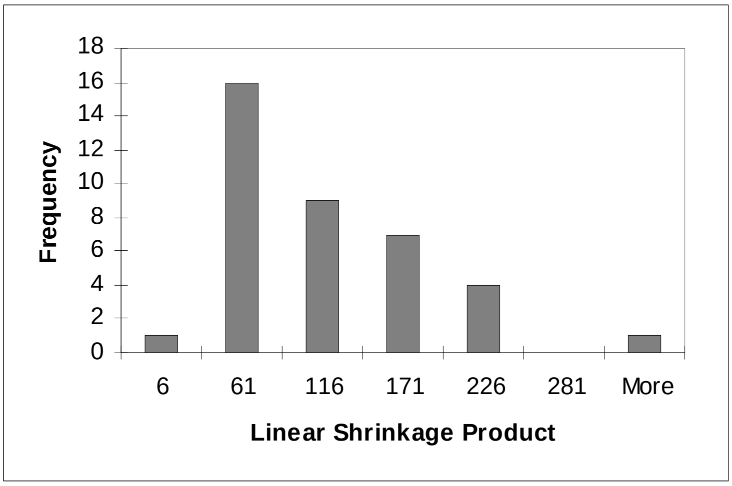
The importance of grading is emphasised by the descriptive statistics of the alluvium. Whilst the linear shrinkage had a mean very similar to that of the entire group, the linear shrinkage product and shrinkage product had means much larger than the entire group, particularly the latter. Seeing as these parameters are the product of the linear shrinkage with the P075 and P425 constituents, respectively, the large difference must therefore be ascribed to the grading only. However, whilst the standard deviations of the linear shrinkage product and shrinkage product were considerably larger than those of the entire group, coefficients of variation of all three parameters revealed a large variation in data. Figure A.57a indicated that the frequency distribution of the linear shrinkage product correlates with the positively skewed distribution of the entire group. Also, the shrinkage product had a distorted, positively skewed distribution, as illustrated in Figure A.57b).

The alluvial materials were found to be finer than the entire group, with mean values for both grading parameters (grading modulus and grading coefficient) being smaller than the entire group's. Standard deviations and coefficients of variation revealed improvement in both parameters' range, with the grading modulus in particular having a coefficient of variation of -0,20. A near-normal distribution was noted for the grading modulus (Figure A.57c).

Table A.31 Descriptive Statistics Summary: Alluvium (Dry reg[illegible])

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Alluvium : 95% Mod AASHTO									
Mean	25,4	8,4	17,1	3,8	86,9	180,1	1,56	17,3	55,0
Standard Deviation	14,90	6,33	9,67	2,54	75,19	129,32	0,31	6,71	23,32
Coefficient of Variation	0,59	0,76	0,57	0,67	0,87	0,72	0,20	0,39	0,42
Minimum	0	0	0	1	6	18	0,97	7	14
Maximum	48	20	31	9	335	490	2,39	34	125
n	38	38	38	38	38	38	38	38	38

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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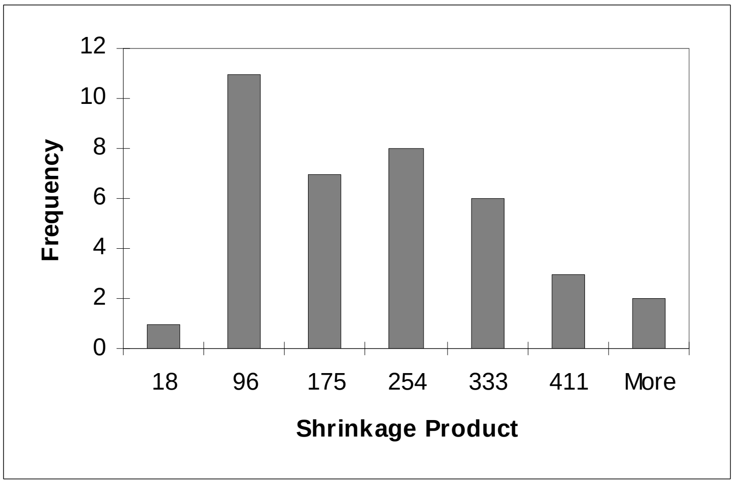

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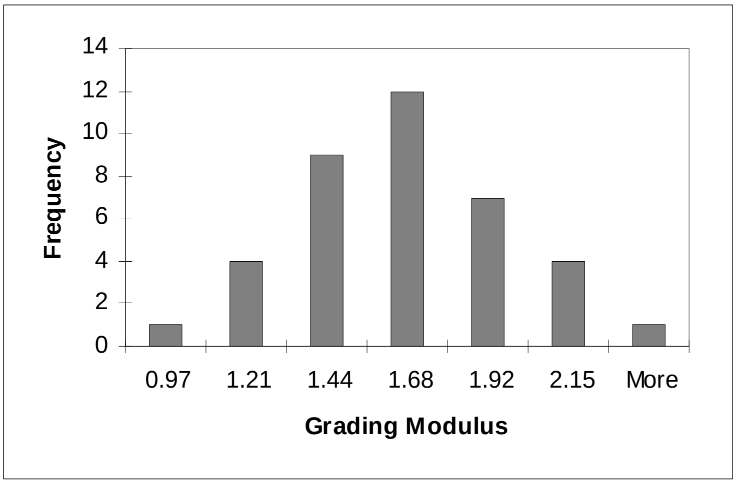


c

Figure A.57 Histograms: Alluvium, 95% Mod AASHTO (Dry regions)

A mean CBR of 55,0% was recorded for the alluvium, compared with 37,4% for the entire group. Whilst the standard deviation was not too dissimilar from the entire group's, a notably improved coefficient of correlation was calculated; however that coefficient still indicates variability despite normalisation.

A.4.9 Colluvial Materials

Some 81 samples of colluvial and aeolian materials were tested from dry regions. In contrast to materials from a moist climate, colluvial materials from a dry climate had lower Atterberg Limit means than the entire group (Table A.32). Standard deviations of these parameters were slightly larger than those of the entire group, whilst coefficients of variation were also larger, indicating more variable materials compared with the entire group.

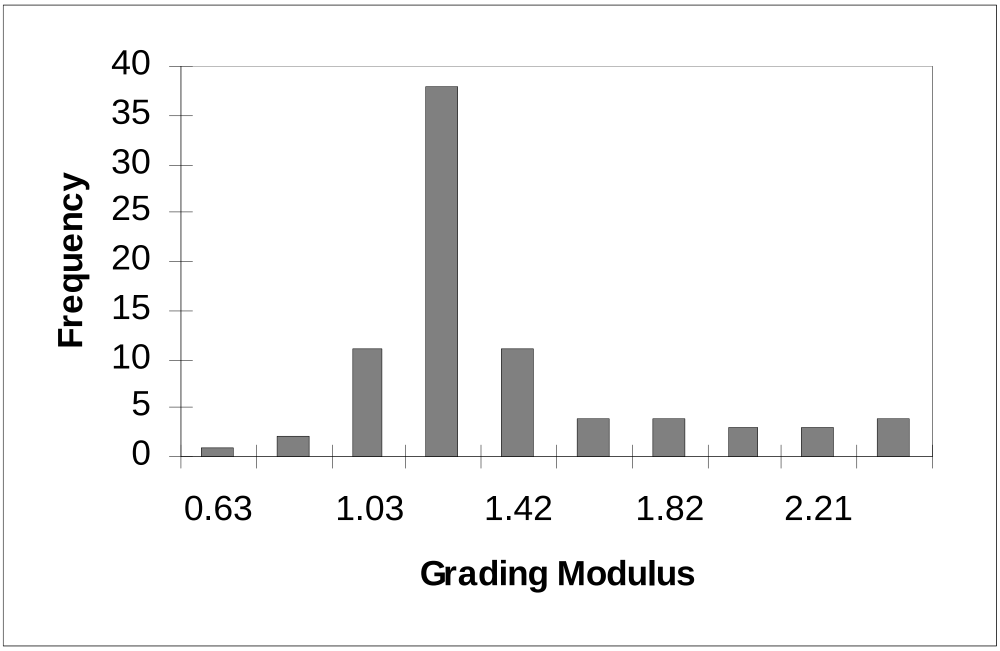
A similar trend was observed in colluvial materials to the one observed in alluvial materials, with regard to the linear shrinkage, linear shrinkage product and shrinkage product. Whilst the mean linear shrinkage in this instance was noticeably smaller than that of the entire group, both the linear shrinkage product and shrinkage product had means greater than the entire group. This is again ascribed to the larger fines constituents (P075 and P425) of the colluvial and windblown materials. Whilst all three parameters showed slightly higher coefficients of variation, the linear shrinkage product and shrinkage product also had considerably larger standard deviations.

Not surprisingly – especially considering the above – the colluvial materials were found to have a lower mean grading modulus and grading coefficient. Whilst the grading modulus showed a notable reduction in standard deviation, the grading coefficient had a slightly larger standard deviation. Both parameters also had an increased coefficient of variation compared with the entire group. The grading modulus showed a localised peak in its frequency distribution (Figure A.58a), indicating that the "coarseness" of the colluvial materials tested was selective. The

Table A.32 Descriptive Statistics Summary: Colluvium (Dry reg

	LL	PI	PL	LS/BLS	LSP	SP	GM	GC	CBR
All Groups : 95% Mod AASHTO									
Mean	21,5	7,1	14,4	3,5	59,4	119,9	1,95	18,4	37,4
Standard Deviation	11,66	4,96	7,70	2,21	58,95	99,34	0,50	9,36	21,34
Coefficient of Variation	0,54	0,70	0,53	0,63	0,99	0,83	0,25	0,51	0,57
Minimum	0	0	0	0	0	0	0,46	0	1
Maximum	73	30	43	12	375	656	2,87	42	125
n	619	619	619	619	619	619	619	619	619
Colluvium : 95% Mod AASHTO									
Mean	15,5	5,3	10,2	2,7	73,7	161,5	1,28	10,1	29,5
Standard Deviation	12,47	5,06	8,06	2,33	88,88	153,39	0,39	9,86	17,00
Coefficient of Variation	0,80	0,96	0,79	0,86	1,21	0,95	0,30	0,98	0,58
Minimum	0	0	0	0	0	0	0,63	0	2
Maximum	42	17	25	10	375	656	2,41	38	78
n	81	81	81	81	81	81	81	81	81

LL = Liquid Limit ; PI = Plasticity Index ; PL = Plastic Limit ; LS/BLS = Linear Shrinkage/Bar Linear Shrinkage ; LSP = Linear Shrinkage Product ; GM = Grading Modulus ; GC = Grading Coefficient ; CBR = California Bearing Ratio ; n = number of samples



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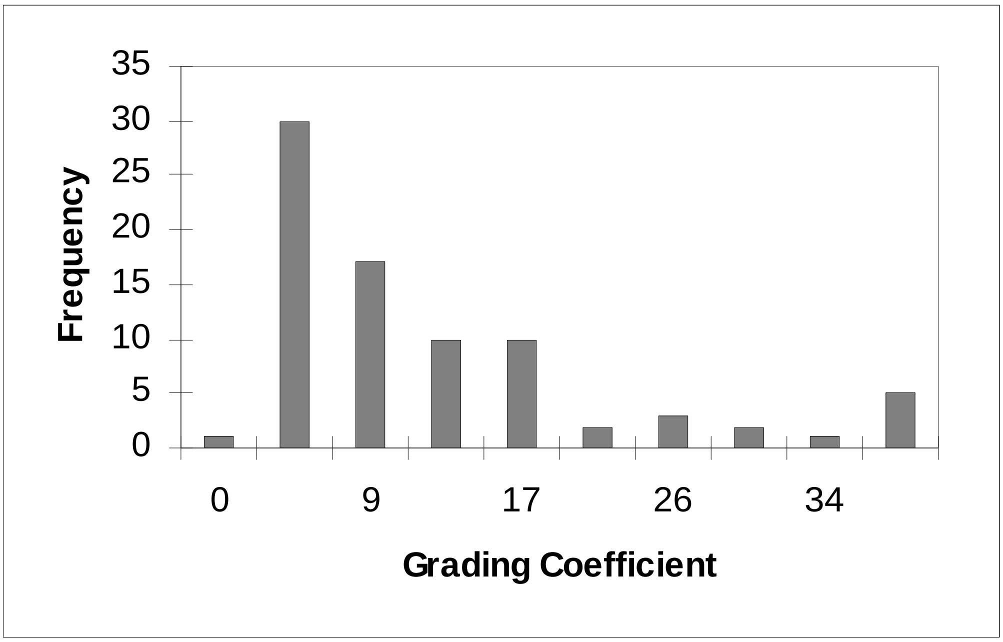

b

Figure A.58 Histograms: Colluvium, 95% Mod AASHTO (Dry regions) grading coefficient had a fairly flat, positively skewed frequency distribution (Figure A.58b) diagram, indicating a tendency towards finer material.

As was observed with the moist climate, the colluvial materials in this instance were found to have a mean CBR of 29,5%, some 8% lower than that of the entire group.

A.4.10 Non-Plastic Materials

The 103 non-plastic materials analysed were, as before, from various material groups. Atterberg Limits were disregarded, as were shrinkage parameters. The grading modulus and grading coefficient had means lower than that of the entire group, indicating a tendency towards finer materials. No significant difference was noted in either parameter's standard deviation, compared with the entire group, whilst the coefficients of variation showed a slight increase.

A mean CBR of 41,6% was recorded, along with a standard deviation of 19,8 and coefficient of variation of 0,28. As such the material shows some refinement from the entire group, but is still deemed variable.

A.5 Descriptive Statistics: Dry Areas: 98% Mod AASHTO

A.5.1 All Materials

The descriptive statistics analysed for all the groups combined were very near identical to those of the 95% Mod AASHTO group. The sample population comprised 624 samples of mixed origins. The only parameter showing a noticeable difference from the 95% Mod AASHTO group, was the CBR values. A mean CBR of 63,3% was calculated – as opposed to a mean CBR of 37,4% for the 95% Mod AASHTO compaction. A standard deviation and correlation coefficient of 38,22 and 0,60 was found, respectively. The CBR range of the 98% Mod

AASHTO group (1% - 230%) was also considerably larger than that of the lesser compacted group.

A.5.2 Basic Crystalline Materials

The dataset of basic crystalline materials is the exact same set used for the 95% Mod AASHTO basic crystalline group. Consequently descriptive statistical properties discussed in section A.4.2 applies here too, with the exception of the CBR values. As is to be expected, the mean CBR of the 98% compacted basic crystalline (56,2%) is higher than that of the lesser compacted group (34,5%).

A.5.3 Acid Crystalline Materials

As discussed above, the dataset used for this analysis is identical to the one discussed in section A.4.3; hence the same descriptive statistics apply. The mean CBR of the 98% Mod AASHTO compaction was 68,3%, compared with 43,2% of the 95% Mod AASHTO compaction. The improvement in CBR is therefore clear.

A.5.4 High Silica Groups

Though three additional samples were included in the 98% Mod AASHTO group than in the 95% group, the difference in descriptive statistics is negligible. The mean CBR is 100,7%, compared with a mean CBR of 47,2% of the lesser compacted group. The CBR values ranged between 21% and 178%.

A.5.5 Arenaceous Materials

The improvement in mean CBR was once again clear. A mean CBR of 43,8% was calculated, compared with a mean CBR of 28,1% for the 95% Mod AASHTO compacted group. All other parameters' descriptive statistics were identical to those described in section A.4.5.

A.5.6 Argillaceous Materials

A single additional sample was included in this group that was not included in the 95% Mod AASHTO group. The additional sample had no noticeable influence on the descriptive statistics discussed in section A.4.6. The mean CBR increased from 25,4% (95% Mod AASHTO) to 39,3% in this group. The CBR values ranged from 1% to 140%.

A.5.7 Calcrete Materials

With descriptive statistics identical to those described in section A.5.7, the range of CBR values ranged from 9% to 193%. A mean CBR of 82,2% was recorded, compared with the 95% Mod AASHTO group's mean CBR of 51,9%.

A.5.8 Alluvial Materials

The mean CBR of the 95% Mod AASHTO group was improved from 55,0% to 92,7% with 98% compaction. The range of CBR values was also increase, with values between 20% and 230%. It must be considered, once again, that all the alluvial materials considered in this analysis were from the same location. Descriptive statistics for the alluvial materials can be found in section A.4.8.

A.5.9 Colluvial Materials

A total of 82 samples made up this group. Despite the addition of one sample to the 95% Mod AASHTO group, descriptive statistics remained virtually unchanged for all the parameters, bar the CBR. A mean CBR of 48,6% was found, with CBR values ranging from 4% to 122%. The descriptive statistics are included in section A.4.9.

A.5.10 Non-Plastic Materials

The group consists of 113 samples of non-plastic materials from mixed origins. The descriptive statistical analysis revealed a mean grading modulus of 1,74 which is slightly finer than that of the 95% Mod AASHTO equivalent group. The mean grading coefficient (13,8), however, indicates a minutely coarser material compared with the same group. The parameters had coefficients of variation of 0,29 and 0,72, respectively, whilst standard deviations were 0,51 and 9,90. The mean CBR of the 98% Mod AASHTO group was calculated as 73,2% (compared with 41,6% for the 95% Mod AASHTO group). The improved mean CBR is clear.

A.6 Descriptive Statistics: Dry Areas: 100% Mod AASHTO

A.6.1 All Materials

The mixed group of material compacted to Modified AASHTO density was composed of 581 samples. Despite the varying number of samples compared with the 95% and 98% Mod AASHTO groups, no noticeable differences were found between this group and the before-mentioned groups. The exception, again, was the CBR properties. A mean CBR of 90,0% was calculated, with CBR values ranging between 2% and 311%.

A.6.2 Basic Crystalline Materials

The same data considered in sections A.4.2 and A.5.2 were considered in this section; hence the same descriptive statistics apply. A mean CBR of 79,5% was calculated at Modified AASHTO density, with the CBR values ranging between 27% and 155%. The mean CBR continues the increasing trend, as can be expected.

A.6.3 Acid Crystalline Materials

Descriptive statistics from section A.4.3 apply. The mean CBR of the 95% and 98% Mod AASHTO density groups were 43,2% and 68,3%, respectively. This mean CBR increased to 93,2% for the group compacted to Modified AASHTO density.

A.6.4 High Silica Materials

The addition of three samples to the 95% Mod AASHTO group made very little difference to the descriptive statistics described in section A.4.4. Whilst the mean CBR values of the 95% and 98% Mod AASHTO density groups were 47,2% and 100,7%, respectively, the mean CBR of the high silica materials compacted to Modified AASHTO density was 150,4%. CBR values ranged from 20% to 297%.

A.6.5 Arenaceous Materials

Only 36 samples of arenaceous materials considered were compacted to Modified AASHTO density. Four parameters showed slight deviation from lesser compacted groups. The liquid limits had a slightly elevated mean of 25,9, with a slightly larger coefficient of variation (0,44). The shrinkage product had a noticeably lower mean (84,5), but the coefficient of variation (0,94) indicates that this may be ascribed to the variability of the data itself.

Whilst both the grading modulus and grading coefficient also showed variation, the parameters contradicted each other. This trend was also observed in lesser compacted groups. Both parameters' standard deviations and coefficients of variation nearly complied with that of lesser compacted groups.

A mean CBR of 51,1% was calculated (compared with 28,1% and 43,8% for the 95% and 97% Mod AASHTO groups, respectively). The CBR values ranged from 4% to 143%.

A.6.6 Argillaceous Materials

This group consisted of 131 samples, some 23 less than the 95% Mod AASHTO group. The difference in sample numbers had little effect on the descriptive statistics discussed in section A.4.6, with only the liquid limit showing a slight elevation in its mean (26,0). The group at hand had a mean CBR of 47,9%, ranging from values of 2% to 178%. The trend of improving CBR values with increasing density is therefore evident again, considering that the 95% and 98% Mod AASHTO groups had mean CBR values of 25,4% and 39,3%, respectively.

A.6.7 Calcrete Materials

The same sample population discussed in section A.4.7 applies here; hence the descriptive statistics are also applicable. Whilst the 95% and 98% Mod AASHTO groups revealed mean CBR values of 51,9% and 82,2%, the group at hand had a mean CBR of 113,4%. The tested CBR values ranged from 14% to 279%.

A.6.8 Alluvial Materials

The same 38 samples considered previously make up the data analysed here. Consequently the descriptive statistics described in section A.4.8 applies here. The mean CBR of this group was calculated as 128,2% (compared with 55,0% and 92,7% of the 95% and 98% Mod AASHTO density groups, respectively). Tested CBR values ranged between 27% and 267%.

A.6.9 Colluvial Materials

Though number of samples (81) making up this group was the same as that of the group comprising the 95% Mod AASHTO group, all the samples were not common to both groups. Nevertheless the difference in descriptive statistics was minimal and seems compliant with the statistics described in section A.4.9. Whilst the mean CBR values of the 95% and 98% Mod AASHTO groups were 29,5% and 48,6%, respectively, the mean CBR of the Modified AASHTO density was 70,1%. The CBR values ranged from 5% to 180%.

A.6.10 Non-Plastic Materials

The same 113 samples discussed in section A.5.10 applies to the section under consideration here. The mean CBR was calculated to be 102,9%, ranging from 4% to 257%. This, again, confirms the increasing CBR with increasing CBR, considering mean CBR values of 41,6% and 73,2% for the 95% and 98% Mod AASHTO groups, respectively.

Addendum B : Example of Model Derivation

B.1 Procedure Discussion

Model derivation and selection was a systematic procedure where four selected models were derived and compared with each other. Three regression methods were considered for specific model derivation purposes, but four models were included (no derivation was done for Kleyn's existing model):

- Weibull Regression: Data analysis and properties indicated that the data used is not strictly linear. After considering logarithmic and exponential regressions, the Weibull regression was recommended (Dr S Das, 2008, personal communication, CSIR, Pretoria). The method is discussed in detail in section 4.9.
- Linear Regression: After initially abandoning the linear regression, it was ultimately included in the research as it could not be totally prohibited by the nature of the data. Linear regression is, however, also not strictly applicable to the dataset used, due to its variability. It was anticipated, though, that limitation was ascribed to the data and not to the regression. As a result, stepwise linear regressions were performed as part of the analysis.
- Kleyn (1955): The method proposed by Kleyn (1955) was included in the analysis, as the method is still in use in South African industry. For the purposes of the comparison, the empirical equation derived by Stephens (1988) and based on Kleyn's (1955) chart was used.
- Kleyn Method Modified: An attempt was made to refine the model proposed by Kleyn (1955). Though the equation derived by Stephens (1988) was a logarithmic function, the function was converted to a linear equation for prediction and verification purposes. As such, the parameters used in Kleyn's method (i.e. plasticity index and grading modulus) were selected and forced through a linear regression.

The Weibull regressions were performed using SAS® 9.1 software, whilst the linear regressions were done using SPSS® 15.0. Whilst the linear regressions delivered a single dataset result, the SAS® results had to be continually refined as described in section 4.10.3. Results from the regressions (both linear and Weibull) were then used to derive prediction equations for the range of CBR values (7% to 25%).

A spreadsheet was created for each material group (in respective climatic and compaction groups). Each spreadsheet included the range of predicted values derived from the four models (i.e. Weibull, Kleyn, modified Kleyn and linear). The first indication of good fit was made by comparing the mean CBR value measured with the mean predicted CBR values of the respective models. Residuals were then calculated by subtracting predicted CBR values from the measured CBR values for each model. A measure of goodness of fit of the model was performed by calculating the mean square prediction error (MSPE) as follows:

$$\text{MPSE} = \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{n}$$

Where
$\hat{Y}$ is the measured CBR value,
Y is the predicted CBR value and
n is the number of datasets used.

This measure was used as it allowed direct comparisons of the four models. In conjunction with the MSPE, the following factors were considered to determine the best model from the four derived:

- Range: The range predicted by some models was found to be very limited, though the MSPE showed no error (i.e. MPSE = 0). Simply stated, if a model showed a very low error but only predicted a range of CBR values between e.g. 10% and 15%, the model was deemed unsuitable.
- Trend: The trend observed throughout model development prevailed even in the refined models (with the exception of Kleyn's model). As a result the amplification of the trend had to be considered. For example, if two models

were to have identical MPSE values but the trend was less pronounced in one model, this model was selected. However, as stated, the trend of over-predicted lower values and under-predicted higher values (in a range of 7% - 25%) prevailed in all derived equations.

- Descriptive Statistics: In cases where model selection proved challenging even after doing the above, descriptive statistics were derived for the models at hand. A final selection was then based on these results, particularly considering the standard deviation and sample variance.

B.2 Example : High Silica (95% Mod AASHTO, Moist)

After running the (three) respective regression analyses, the four prediction models were summarised as shown in Table B.1.

Table B.1 Predictive Model Equations (High Silica, 95% Mod AASHTO, Moist)

Model	n	Equation	MSPE
Weibull	37	CBR = EXP[log(-log(0,5)) × 0,3341 + (2,5398 – (SP × 0,0003) + (r26,5 × 0,0129) + (GM × 0,187))]	48
Kleyn	37	CBR= EXP[((GM × 12 – PI) ÷18,5) + ln(16,7)]	4822
Kleyn Edited	37	CBR = 10,185 – (PI × 0,356) + (GM × 5,653)	0
Linear	37	CBR = 6,513 + (GM × 6,483)	1<

Considering the above, the edited version based on Kleyn's (1955) model and the linear model were identified as the best potential models based on MSPE values. The next step was to compare scatter plots of the two models (scatter plots were developed for all four models in each group). Figure B. 1 illustrates a comparative scatter plot indicating the prediction for the model modified from Kleyn's model and the linear model. The diagram includes a line of equality (i.e. a perfect prediction would plot on this line) and illustrates the Measured CBR on the X-axis and the predicted CBR (CBRe) on the Y-axis.

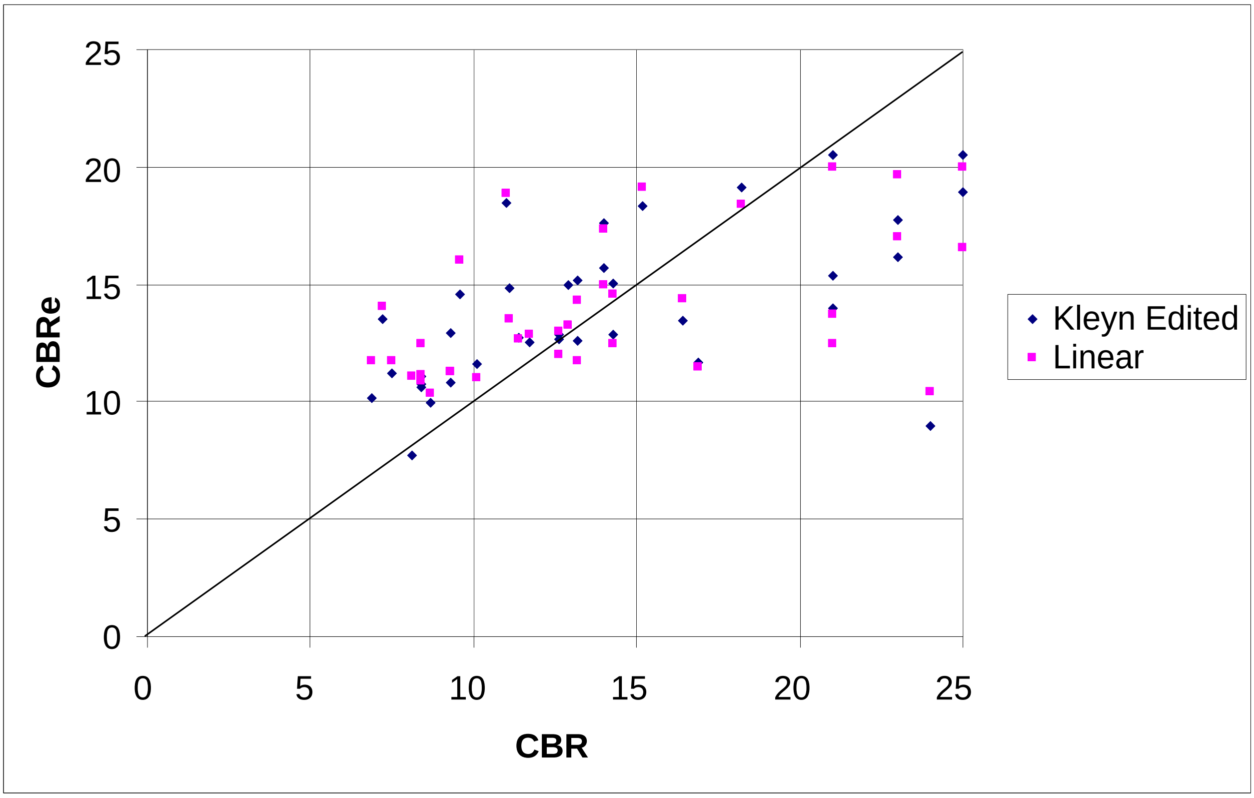

Figure B. 1 Scatter Plot for the Edited Kleyn Model

From Figure B. 1 it is apparent that the best model can not easily be selected based on visual observation. Whilst the model adapted from Kleyn's method had a range of predicted values between 8% and 21%, the linear model predicted values between 10% and 20%. As such, neither model can be excluded based on predicted range as both predicted nearly similar ranges of CBR values.

For the final decision, descriptive statistics were derived for the two ranges of predicted CBR values as derived from the two models. Whilst the model edited from the original model proposed by Kleyn (1955) had a sample variance of 10,6 and standard deviation of 3,3, the linear model had a sample variance of 8,9 and a standard deviation of 3,0. As such the latter model was selected, based on descriptive statistical analysis. Not all models required such extensive analysis (i.e. some models could be selected merely considering the MSPE, trends and predicted ranges).

Addendum C : Master Dataset