Research Consultancy for the Development of Guidelines for The Use of Sands in Road Construction in the SADC Region

Inception Report

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Submission date:
2 May, 2012

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
ASANRA	Association of Southern African National Roads agencies
BRDM	Botswana Road Design Manual
BS	British Standard
BSM	Bitumen sand Mix
CBR	California Bearing Ratio
COLTO	Committee of Land Transport Officials
CSIR	Council for Scientific and Industrial Research
Cu	Uniformity Coefficient
DCP	Dynamic Cone Penetrometer
ESA	Equivalent Standard Axle
ETB	Emulsion Treated Base
FI	Fineness Index
GEMS	Granular Emulsion Mixes
GM	Grading Modulus
ITS	Indirect Tensile Strength
LL	Liquid Limit
LS	Linear Shrinkage
LVR	Low Volume Road
MDD	Maximum Dry Density
NAASRA	National Association of Australian State Road Authorities
OMC	Optimum Moisture Content
PI	Plasticity index
PL	Plastic Limit
PM	Plastic Modulus
P425	Percentage Material Passing the 0.425 mm Sieve
P075	Percentage Material Passing the 0.075 mm Sieve
RD	Roads Department
SABITA	South African Bitumen Association
SADC	Southern Africa Development Community
SAMDP	South African Mechanistic Design Procedure
SANS	South African National Standards
STE	Sand Treated with Emulsion
TMH	Technical Methods for Highways
TRL	Transport Research Laboratory
WACCT	Western Australia Confined Compression Test

GLOSSARY OF TERMS

Aeolian	Wind borne; sediments transported and deposited by wind action
Bioturbation	Soil that has been reworked or mixed by living organisms
Colluvial	Weathered material transported by gravity
Deposition	Laying down of material by agents of erosion
Fluvial	Related to streams and rivers, i.e. deposited by a stream or a river
Kurtosis	The sharpness of the peak of a frequency-distribution curve
Lacustrine	Relating to lakes or a lake environment
Lithified	Conversion to rock-like material
Skewness	Degree of slant of the slope of a frequency-distribution curve
Soil suction	A negative pore water pressure within soil due to capillary and salt effects; it is measured in a log scale of pF units (i.e. 1pF = 10 cm head of water).
Transported soil	A soil which has been removed from its place of formation and redeposited

1. INTRODUCTION

1.1 Background

In many parts of eastern and southern Africa, good quality road-building materials are becoming increasingly scarce, especially for the construction of all-weather roads in rural areas where traffic volumes are generally relatively low (less than about 300 vehicles per day). The principal road building material for these roads is gravel which, in many areas has been heavily utilized and depleted through ongoing construction and maintenance activities; and in extreme circumstances, no suitable gravel is now available for road construction and maintenance purposes. In addition, the haulage of good quality gravel from other areas, over long distances, is prohibitively expensive. Hence, the innovative use of locally available materials, which would have been considered marginal or rejected by traditional specifications for road construction, needs to be investigated for use in the construction of low volume roads (LVRs) in the region.

Fortunately, there is an abundance of naturally occurring sand that could be used in the construction of LVRs to provide an appropriate level of access to many areas. One variety of these sands – Kalahari sands - covers large parts of Botswana, Namibia, eastern Angola, western Zimbabwe (see Figure 1-1) and Zambia as well as the south west of the Democratic Republic of the Congo. Other varieties of windblown sand occur in the coastal regions of KwaZulu-Natal in eastern South Africa, western Namibia, Mozambique and Tanzania.

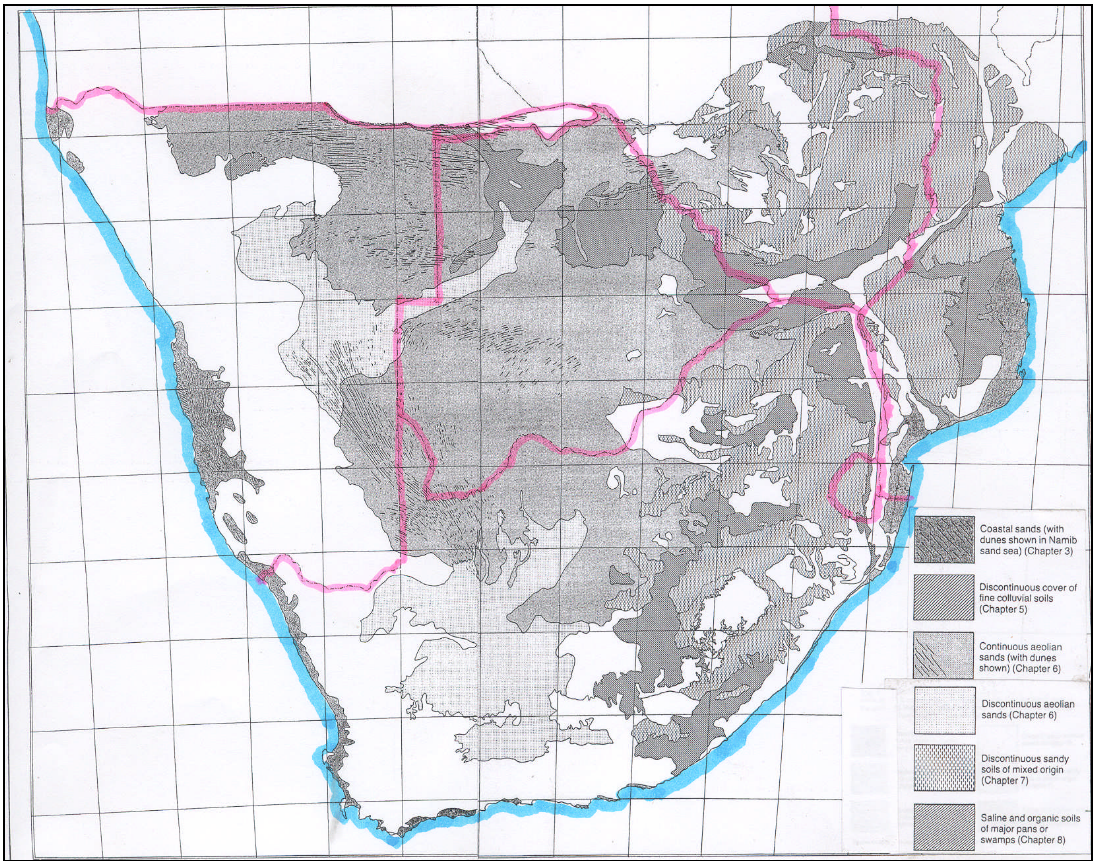


Figure 1-1: The distribution of transported soils in southern Africa (Brink, 1985)

Even though naturally occurring sands seldom satisfy the requirements of traditional specifications for use as a pavement material, especially in their untreated state, they have, nonetheless, been used successfully on a number of road projects at least in Botswana, Namibia, Malawi, South Africa, Zambia and Zimbabwe and elsewhere in the world such as in Western Australia and Brazil.

While technical guidelines for the use of untreated Kalahari sand for the construction of low traffic roads have been successfully developed and utilized in Botswana, and the use of wind blown and coastal sands has been investigated to a limited extent in Mozambique, South Africa and Zimbabwe, the appropriateness and suitability of the technologies used in those countries, along with other appropriate technologies developed and investigated subsequently, need to be extended to all countries within the SADC region.

1.2 Goal, Purpose and Objectives

Against the above background, the main **goal** of the project is to reduce the cost of low volume road construction in the SADC region by utilising naturally occurring sands to the maximum extent possible as a road construction material. In this context, the ultimate **purpose** of the project is to build on existing experience with the use of sand in road construction in the SADC region as a basis for developing guidelines for its use on a wider scale in the member states. In so doing, the main **objective** of the project is to provide guidance on cost-effective technologies using locally available sands that could be used for the construction of low volume unpaved and paved roads in the SADC region.

It should be stressed that the most economic use of sands in LVR construction will be achieved when this material is used as a base layer in its neat (i.e. untreated) state. In the past, the use of sand in this manner would generally not have been considered to be feasible largely because of lack of a thorough understanding of the characteristics and properties of this material, coupled with its lack of compliance with conventional specifications. Fortunately, however, research and experience in Botswana has demonstrated that in appropriate situations, at least one type of Kalahari can provide a suitable construction material in all layers of a road pavement. If sands with similar properties can be located elsewhere in the SADC region, and can be used as an untreated base course for LVRs, then a major advance will have been made in reducing the cost of road construction.

The need for the guideline has been identified as a priority by SADC member states and, with the support of AFCAP, the project is being carried out for the Research and Development Standing Committee of the Association of Southern African National Road Authorities (ASANRA). The application of the guideline, especially in areas where traditional road building materials may be scarce, is timely and is likely to be very beneficial to practitioners in the SADC region.

1.3 Scope of Guideline

The scope of the guideline will include the use of sand in road construction for both unpaved and paved roads in a variety of ways including:

- embankment, subgrade, subbase and base layers of sealed and unsealed roads using both conventional and deep compaction;
- with proprietary chemicals and polymers to improve performance of the structural layers of both sealed and unsealed roads;

- with cement, lime and bitumen stabilization (including foamed bitumen) for use as structural layers in sealed roads;
- for blending (mechanical stabilization) with other materials to improve performance of the structural layers of both sealed and unsealed roads;
- in sand cushioning and track stabilization procedures aimed at improving unsealed road performance;
- with geocells for sand containment, erosion control and slope stability improvement.

1.4 Work Plan

Table 1.1 provides an overview of the work plan for carrying out the project which is self-explanatory.

Table 1.1 – General Approach to Carrying Out Project

Stage 1 *Undertake Technical Review*	Stage 2 *Evaluate Classification System*	Stage 3 *Prepare Draft Guideline*	Stage 4 *Hold Regional Workshop*	Stage 5 *Prepare Final Guideline*
1. Undertake technical review and literature survey	1. Develop sand sampling and lab testing matrix	1. Prepare draft guideline	1. Hold regional workshop to review draft guideline	1. Prepare final guideline
2. Prepare and submit Inception Report	2. Undertake sand sampling in selected countries	2. Undertake peer review of draft guideline	2. Compile workshop proceedings	2. Undertake peer review of final manual
	3. Undertake lab testing at selected laboratory	3. Finalise and submit draft guideline		3. Finalise and submit final guideline
	4. Analyse laboratory test results against classification system			

1.5 Stage 1 – Technical Review

As indicated in Table 1-1, the project is being carried out in five stages commencing with Stage 1 – Technical Review. The objective of this stage is to undertake a technical review of the use of sands in road construction in the SADC region and internationally based on a literature survey of existing documentation including previous studies, guidelines, technical papers, standards and specifications, all as input to this Inception Report and, ultimately, to the final guideline.

In accordance with the ToR, the outputs of the Inception Report include:

i. an indication of appropriate designs for the use of sand in low volume road construction based on the technical review of existing best practice within the region;

ii. a sampling and testing programme in Mozambique, Namibia and South Africa to evaluate the suitability of the Botswana sand classification system;

iii. a structure of the draft guideline.

In order to achieve the objectives of Stage 1, the extensive information and library services provided by both CSIR and TRL were fully utilised. In addition, the ASANRA database of research projects was interrogated to extract any reports of interest to the project. Finally, information was obtained from member states where sand has been used in road construction, particularly in Botswana, Mozambique, Namibia and South Africa.

1.6 Inception Report

The output of the Technical Review forms a significant input to this Inception Report which is structured as follows:

Section 1: Provides the background to the project including its goal, purpose and objectives as well as the scope of the guideline and the work plan for its execution.

Section 2: Presents the general characteristics of the relevant sands, including their definition, distribution, geology, origin and classification.

Section 3: Discusses the physical, mineralogical and engineering properties of sands.

Section 4: Considers the approach to locating sands and outlines the various tests used to evaluate their properties for design purposes.

Section 5: Discusses the specifications used for evaluating the suitability of sands for use in the various layers of a road pavement.

Section 6: Provides guidance on the selection of sands for road construction and considers various issues related to such construction.

Section 7: Provides a summary of the output of the technical review including an indication of appropriate designs for the use of sand in low volume road construction.

Section 8: Outlines the sampling and testing programme that was developed to evaluate the suitability of the Botswana sand classification system for application to the SADC region.

Section 9: Presents a draft structure for the guideline.

Annex A: Presents the Literature Survey references.

2. GENERAL CHARACTERISTICS OF SANDS

2.1 Introduction

The sands of the SADC region comprise various types, the major one (in terms of area of distribution) being the Kalahari sands, with smaller surface exposures of more recent aeolian sands in Namibia (Namib Desert), the Western Cape (Cape Flats Sands), various sands along the Cape southern coast (Strandveld and Algoa) and the eastern and northern areas of KwaZulu Natal (Berea Red, Maputoland and other Quaternary sands), which pass into the coastal areas of Mozambique and reach up to Tanzania. In addition, there are some inland sand deposits in Mozambique resulting from the interaction of some of the large east flowing rivers (Limpopo and Zambezi) with the prevailing winds, e.g. at Chibuto.

The term Kalahari (or *Kgalagadi* as used in Botswana) sand is often used in a loose way to describe sands that are found in the Kalahari region of south and south-western Africa (Carney et al, 1994). This general term belies the wide variety of different types of sands that occur in the Kalahari region by virtue of their different modes of formation and agency of transportation. However, useful predictions about the suitability of these materials for use in road construction can often be made once their geology and origins have been identified, their properties classified, their performance characteristics determined and their distribution ascertained.

This section considers the general characteristics of the sands in the southern SADC region, including their definition, distribution, geology and origin, and classification. In order to place these sands in a general world-wide context, reference is also made to the characteristics of similar sand types found outside of this region.

2.2 Definition

Sand is generally defined as a granular material resulting from the weathering of especially siliceous rocks and composed mostly of silica i.e. quartz, (one of the minerals least susceptible to weathering) with sizes falling in the range 2.0 to 0.06 mm. (Anon, 1974). For convenience, the Southern African and American roads terminology usually places the minimum size at 0.075 mm. However, very few sands contain material solely within this range, either having some fines (<0.075 mm) or a small coarse component (> 2 mm).

The above *generic* description of sand is just that – a very broad, non-specific description that does not adequately describe either the differing mineralogy or physical and mechanical properties of this material both of which influence its engineering properties. The *Kalahari* sands are a particular type of sand found in the Kalahari region of southern and south-western Africa and by virtue of their unique formation they differ genetically from those in many other parts of the region and the world although the wind-blown (aeolian) origin of parts of them make them comparable with the widespread sand-clays of the Australian interior.

Many of the sands are not single sized and contain varying amounts of finer material. This can be from almost nothing to significant amounts and has a major influence on the engineering properties of the sand to the extent that in Australia, many of the useful sands are actually classified as sand-clays (this definition would not comply with the Unified Soil Classification System nomenclature for a sand-clay).

For the purposes of this Guideline, the discussion in this report is focused on the typical sands found in the SADC region, including the Kalahari sands, as well as those in the coastal areas of the region.

2.3 Formation

It is generally accepted that there are three conditions necessary for the formation of large bodies of sands (Bagnold, 1941). These are:

- sufficient sources of materials;
- geological forces (wind, water, etc.) for continual transportation of sand material from one place to another and topography conducive for continued deposition;
- favourable climatic conditions.

Once disaggregated from the original source rock, the resulting material is then eroded and transported by either wind, water or ice, often ending up at the deposits of rivers or lakes, as sand dunes or desserts, or ultimately as sediment in the sea.

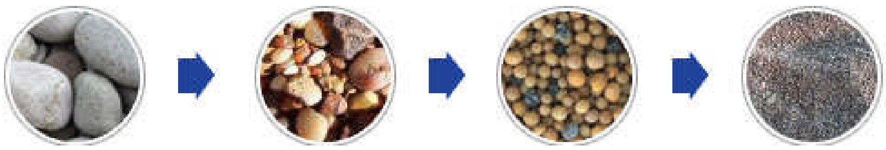


Figure 2-1: Formation of sand by erosion and weathering of rocks

After deposition, the sands are, over time, reworked by groundwater and environmental forces. These tend to alter their mineralogical composition through weathering, leaching and enrichment. In addition, the physical properties of the sand mass and particles are changed through cementation, consolidation, particle leaching and/or disintegration.

2.4 Composition

The composition of sand varies from place to place and is largely dependent on the nature of the source material as well as the weathering process (physical, chemical or both) acting on rock masses which determine the mineralogical composition of the unconsolidated sands, silts and clays produced. Transportation of these particles by water and wind will further modify the material in terms of its particulate size, shape and mineralogical sorting, physical distribution and the degree and type of secondary consolidation – all of which influence the geotechnical behaviour of sands in road construction.

For example, the sands found in desert areas, such as the Kalahari Desert in Botswana, tend to be Aeolian (windblown) deposits which have undergone deposition by wind, while those found on beaches, such as in Cape Town in South Africa, are commonly dominated by silica (silicon dioxide SiO_2), in the form of quartz (one of the minerals least susceptible to weathering) which has been derived from weathering and erosion of the mountain ranges nearby. In contrast, sand from salt pans or lakes, such as Sua Pan and the Makgadikgadi pans in Botswana, are composed of nearly perfect spheres that were precipitated out of the highly salty water. In areas where there is no source of rock fragments, sand is often composed entirely of organic material.

2.5 Distribution

The arid and semi-arid areas of the world, which together occupy more than a third of the earth's land surface, have a number of characteristics in common, one of which is the occurrence of sands and sandy materials over large areas of their surface. These sands occur in all five continents of the world and, collectively, contain probably the largest source of a naturally occurring material for possible use in road construction.

As shown in Figure 2-2, there are vast inland deposits of Kalahari sands that cover large areas of southern and western Africa, south of the equator. This material forms what is believed to be the largest continuous stretch of sand in the world. Today, they begin north of the Orange River in South Africa, embrace the western two-thirds of Botswana, more than a third of Namibia, and stretch north through eastern Angola, western Zimbabwe and Zambia to the Democratic Republic of the Congo. Figure 2-2 also shows the extensive deposits of coastal aeolian, littoral and fluvial sands which occur sporadically around the coast of Southern African.

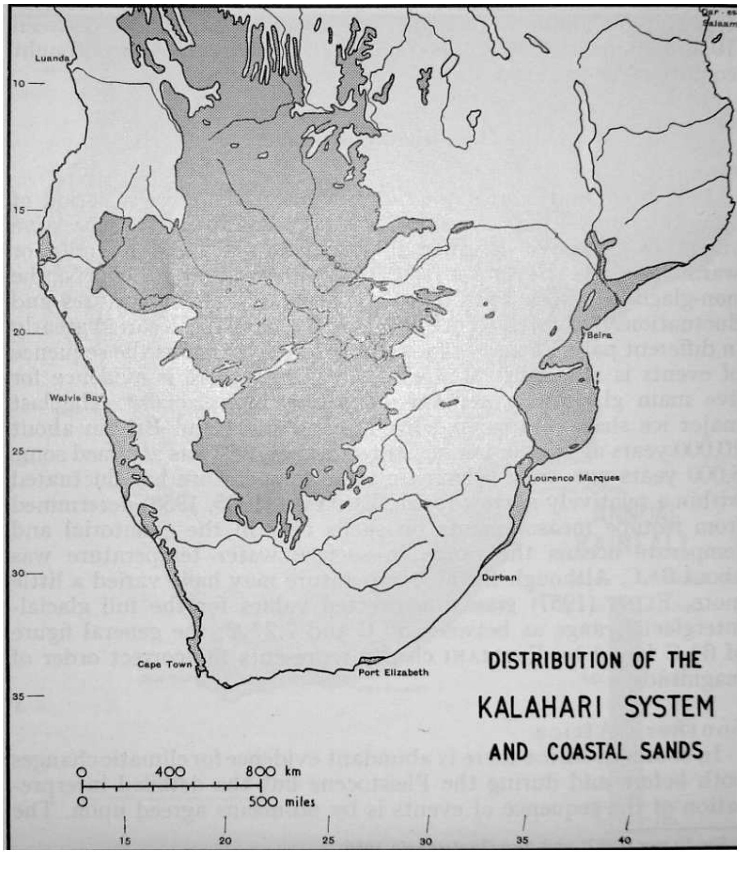


Figure 2-2: Distribution of sands in southern Africa (Cooke, 1964)

Figure 2-3 shows the pedological classes of sands in Southern Africa systems (Brink, 1985) which provide a useful basis for differentiating between the different sand types in the region.

Figure 2-3: The pedological classes of southern Africa (Brink, 1985)

Because of the wide-spread nature of Kalahari and coastal sands in the region, which dominate the vast landscapes of the Northern Cape, Botswana, Namibia, Zambia, Angola and the western parts of Zimbabwe, they should be considered to be of major engineering significance. This is because the scarcity of deposits of conventional road-building materials often makes them the only other source of road building material. Notwithstanding their non-standard properties, experience in some countries in the region and internationally has shown that when appropriately selected, tested and constructed, these materials can fulfill the requirements of all pavement structural layers as well as performing well in a number of other functions including sand seals and sand cushions on unpaved roads. Similar observations have been made regarding some of the coastal sands that occur along much of the eastern cost of Mozambique.

Mitchell (1959) notes that the properties of the Kalahari sands of western Zimbabwe are similar to the sands north of Maputo (Lourenco Marques), “where 150 mm pavements have carried light traffic for many years”. **The interesting point is that the origins of these two materials are totally different**.

2.6 Geology and Origin

2.6.1 General

The geology and origin of the wide range of sand types that occur worldwide varies considerably. However, most of them have been produced by some form of rock weathering in which the constituents have subsequently been transported by wind or water. The following examples illustrate the diversity of geology and origin of sands worldwide:

- *Australia:* the sand-clays in South Australia (Wylde, 1979) are derived from stranded beach ridges and consist of rounded to sub-angular quartz grains, cemented together and containing some clay and iron staining (Sandman et al, 1974). Other Australian sands have been described as river channel to flood plain, deltaic or wind-blown (Wylde, 1982).

- *Brazil:* the Brazilian sands tend to be derived from the weathering and transport of sandstones and consist of sand-size quartz with kaolinite and ferruginous oxides (Aranovich and Heyn, 1984). However, the majority of fine-grained lateritic soils in Brazil are actually classified as clay soils (Nogami and Villibor, 1992).

- *Fiji:* the coral sands of Fiji are derived from the coastal erosion of limestones and consist predominantly of calcium or magnesium carbonate.

- *Southern and Western Africa:* The original Kalahari sands were derived from the erosion of underlying rock and subsequent transport and redistribution. This was carried out by rivers into lakes and by wind. The surficial sands observed today were deposited primarily by wind.

- *South-eastern South Africa:* The Berea Red Sands have a distinct origin, resulting from the weathering of Mio-Pliocene aeolian calcareous deposits. The feldspathic component of this material produced a significant clay content (3 to 40%) (Maud and Botha, 2000).

- *Namibia: The* Kalahari Sequence is contiguous with and mostly similar to the Kalahari sands of Botswana and South Africa and consists primarily of vegetated static dunes. The Sossus Sand formation of the Namib Sand Sea (desert) is a highly active recent sand formation consisting of a wide range of dune types (Lancaster, 1986). These sands are predominantly quartz with up to 10% feldspar. Coastal sands also occur extensively in the country.

2.6.2 The SADC Region

The widespread sand deposits of the Kalahari region are assigned to the informal “Kalahari Beds” in Botswana, a lithostratigraphic term referring to the “loosely consolidated deposits between a few metres and nearly 400 metres thick (Carney et al, 1994). Botswana probably has the main concentration of these sands but they extend south and eastwards into South Africa and west and northwards into Namibia. In South Africa the equivalent sands are classified as the Gordonia Sand Formation within the Kalahari Group (Brink, 1985) and in Namibia as the Kalahari and Namib Sequences (Geological Survey of Namibia, 2006).

The Kalahari Beds consist of an accumulation of aeolian, fluvial and lacustrine deposits lying unconformably on eroded rocks of Karoo and pre-Karoo age. At the base of the Kalahari beds, some arenaceous deposits indicate deposition by paleo-river systems, probably the original Upper Zambezi and Orange or Limpopo River Systems. Deeply weathered bedrock overlain by extensive deposits of siliceous duricrusts that formed during the African erosion cycle (about 120 million years ago and lasting about 100 million years) also occurs at the base of the Kalahari Beds. Between 80 and 100 million years ago, a basin had been defined and an internal drainage system was in existence (Partridge and Maud, 1987).

The main depositional (aggradational) phase of the Kalahari basin, however, is considered to have started only about 2 million years ago on an erosional landscape known as the African Surface, following major regional uplift of the southern African sub-continent. The actual evolution of the

Kalahari beds was affected significantly by climatic changes with alternating wet, semi arid and arid periods resulting in the formation of alluvial deposits and silcretes, calcretes and sands respectively (Partridge and Maud, 1987).

An old classification of the Kalahari Formation (Du Toit, 1954) that could have implications affecting the use of the sands in road construction indicated two distinct strata, a lower sequence (Kalahari beds) consisting of lithified material and overlying Kalahari Sands, which are unconsolidated (Dingle et al, 1983). These have been further differentiated into four units based on data from the Northern Cape of South Africa (Smit, 1977), as follows (from top to bottom):

- aeolian sands, rarely > 20 m thick;
- fine grained clayey and calcareous sandstones, with silcrete and calcrete, up to 80 m thick;
- red calcareous clay containing layers of fine gravel or coarse sand with sandstone lenses, up to 100 m thick, and
- clayey gravel and gravelly clay, up to 100 m thick.

These strata have been observed in parts of Botswana and in Namibia and Zimbabwe as well. The lower layers were named the Botlete Beds (Passarge, 1904). However, for the purpose of this project, only the upper Aeolian sands are relevant to the road construction industry.

Baillieul (1975) identified four major sand areas in Botswana, each having distinct types of Kalahari sand depending on their mode of formation. These are shown in Figure 2-4.

Figure 2-4: Map of Botswana showing the four major sand areas (after Baillieul, 1975)

Description of Sand Types

Area I: Fine grained (mean diameter 0.17 to 0.23 mm), well to moderately well sorted, quartz sand with the particles coated with a skin of red iron oxide. Where the particles have been affected by water, (fluctuating water table or adjacent to the Okavango Delta) this coating has been removed and the sands are grey in colour. The sands have been formed in an aeolian environment.

Area II: The sands are slightly finer (mean diameter 0.14 to 0.2 mm) than those from Area I with similar sorting. They comprise particles of two distinct origins - well-rounded polished quartz grains of aeolian origin and finer (0.125 mm), angular feldspathic particles derived from the underlying Ghanzi sandstones.

Area III: These sands are similar to those of Area II but lack the feldspathic component. Their composition reflects that of the underlying Karoo sandstones. They still, however, show evidence of an aeolian origin.

Area IV: The sands in Area IV are thin and are directly related to the underlying bedrock. They are coarser than the other three types and have been derived predominantly by fluvial action and bioturbation.

Much of the Kalahari sand exposure consists of vegetated dunes and these have been divided into three groups, centred in Botswana (after various authors quoted in Lancaster, 2000). It can be assumed that the properties of these sand dunes would vary similarly as the type of sand classified by Baillieul (1975) does. These groups include an eastern group, mostly in western Zimbabwe and north-eastern Botswana, a northern group west and north of the Okavango Delta and a southern group in the south western Kalahari of Namibia, Botswana and the Northern Cape Province.

These dune groups have specific dune alignments, types of dunes, dimensions and heights as well as vegetation characteristics. The southern dunes are probably those that have been investigated most and generally consist of moderately sorted medium fine sands with a mean grain size of 170 to 340 µm. It is notable that the dune crests tend to be slightly coarser but better sorted than adjacent dune flank and inter-dune areas (streets) (Lancaster, 2000). It has also been noted that the sands become finer and better sorted in a south easterly direction, parallel to the net direction of sand transport as shown in Figure 2-5 with the mean sand size and standard deviation shown as Φ-units (see Figure 2-7, Section 2.5.3).

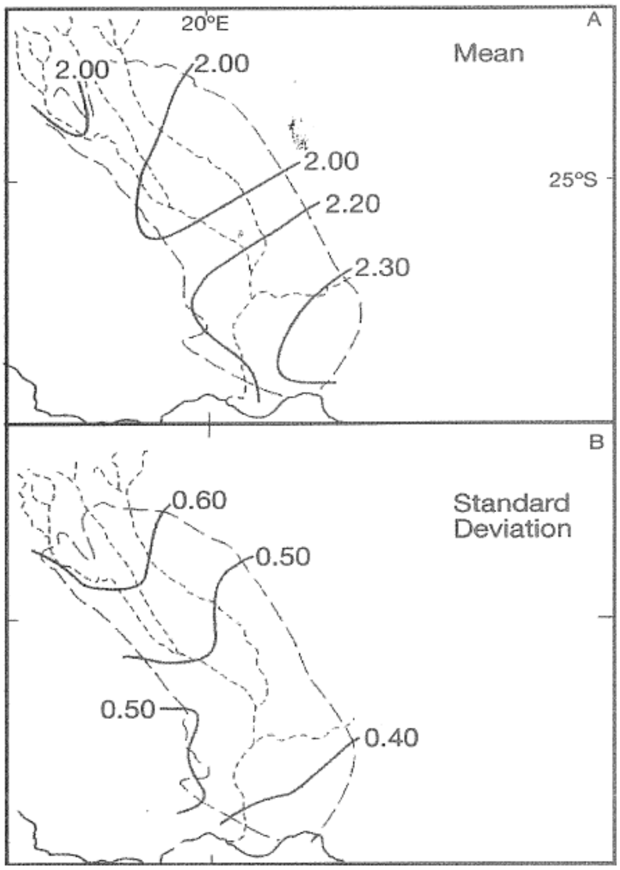


Figure 2-5: Diagrams of grain size and sorting (Φ units) in south west Kalahari (Lancaster, 1986)

A similar investigation of the sands in the Namib Sand Sea (Lancaster, 1986) has produced a somewhat different mean particle size and standard deviation (Figure 2-6). The mean particle size is generally finer and the sands are better sorted.

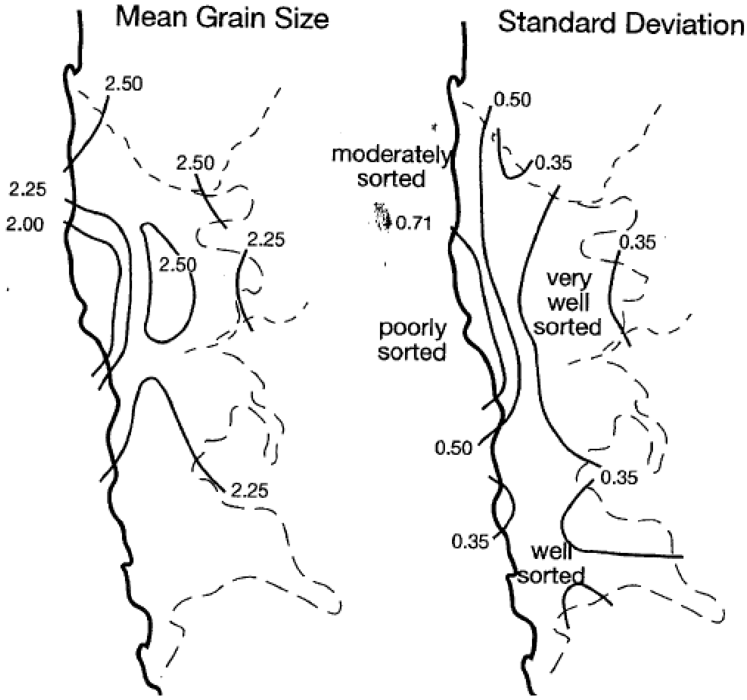


Figure 2-6: Grain size and sorting of Namib Sand Sea sands (Lancaster, 1986)

In southern Mozambique and northern KwaZulu Natal, the sands are more of a coastal and dune cordon origin (Figure 2-2), although further north they do extend inland along major river systems where the localised combination of fluvial and aeolian conditions has produced thick deposits of sands that are potentially useful for road construction. These materials also contain redistributed yellowish red, grey and white sands occurring as both active and older anchored dunes.

2.7 Classification

Various systems have been developed to classify soils and provide only a *general* guide to their engineering properties of which particle size distribution and plasticity are the principal ones. This enables engineers to understand the general, rather than particular, properties of the soils of other countries or regions.

2.7.1 AASHTO Classification System

An example of such a system that is commonly used in the region is the AASHO (now AASHTO M-145) system in which soils having approximately the same general load bearing capacity are grouped together to form seven basic groups which are designated from A-1 to A-7 (Table 2-1). In general, the best soils for subgrades are classified A-1 and the poorest A-7. Thus, it may be assumed generally that structural thickness requirements of the pavement progressively increase as the soil classification group increases from A-1 to A-7.

Table 2-1: AASHTO M-145 Classification System for Soils and Soil-Aggregate Mixtures (M145)

General Classification	Granular Materials (35% or less passing No. 200)							Silt-Clay Materials (More than 35% passing No. 200)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5; A-7-6
Sieve Analysis: Percent passing:											
No. 10	50 Max.										
No 40	30 Max.	50 Max.	51 Min.								
No. 200	15 Max.	25 Max.	10 Max.	35 Max.	35 Max.	35 Max.	35 Max.	36 Min.	36 Min.	36 Min.	36 Min.
Characteristics of fraction passing No. 40:											
Liquid Limit				40 Max.	41 Min.	40 Max.	41 Min.	40 Max.	41 Min.	40 Max.	41 Min.
Plasticity Index	6 Max.		N.P.	10 Max.	10 Max.	11 Min.	11 Min.	10 Max.	10 Max.	11 Min.	11 Min.
Group Index	0		0	0		4 Max.		8 Max.	12 Max.	16 Max.	20 Max.
Usual Types of Significant Constituent Materials	Stone Fragments Gravel and Sand		Fine Sand	Silty or Clayey Gravel and Sand				Silty Soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good							Fair to Poor			

The Kalahari and coastal sands typically classify as A-3 or A-2-4 (sometimes A-2-5) materials with the AASHTO classification or SW, SP or SM in the Unified Soil Classification System (ASTM D 2487-06). By way of comparison, the typical sands in Australia classify similarly (Jewell, 1970; Pederson, 1978; Paige-Green, 1983) those in Brazil classifying predominantly as A-4 but also as A-2-4, although plasticity indices are generally higher (Utiyama, 1977). Sands in parts of the Middle East are similar to the Kalahari sands, classifying primarily as A-3 and A-2-4 with some A-4 materials (Bindra, 1987). The French have their own 6-group classification system for soils using grading, plasticity and sand equivalent (Chauvin, undated) – sands are classified as A (1-4) or B (1-6).

The Berea Red Sands of South Africa which grade into southern Mozambique generally classify as A-2-4 but some of them have been classified as A-6 (Bergh et al, 2008).

2.7.2 British Standard Classification System

This system classifies sand on the basis of three grain sizes as follows:

- Coarse: 0.6 – 2.0 mm
- Medium: 0.2 – 0.6 mm
- Fine: 0.06 – 0.2 mm

The AASHTO, Unified and British classification systems for engineering purposes differentiate sand type on the basis of differences between the grain diameters. However, such systems may not be the most useful or convenient scale to use when geological processes which affect the characteristics of sands that are to be examined (Bagnold, 1941). In such cases, it has been found far better to use a log-scale which exhibits the ratios between the grain diameters (McManus, 1982).

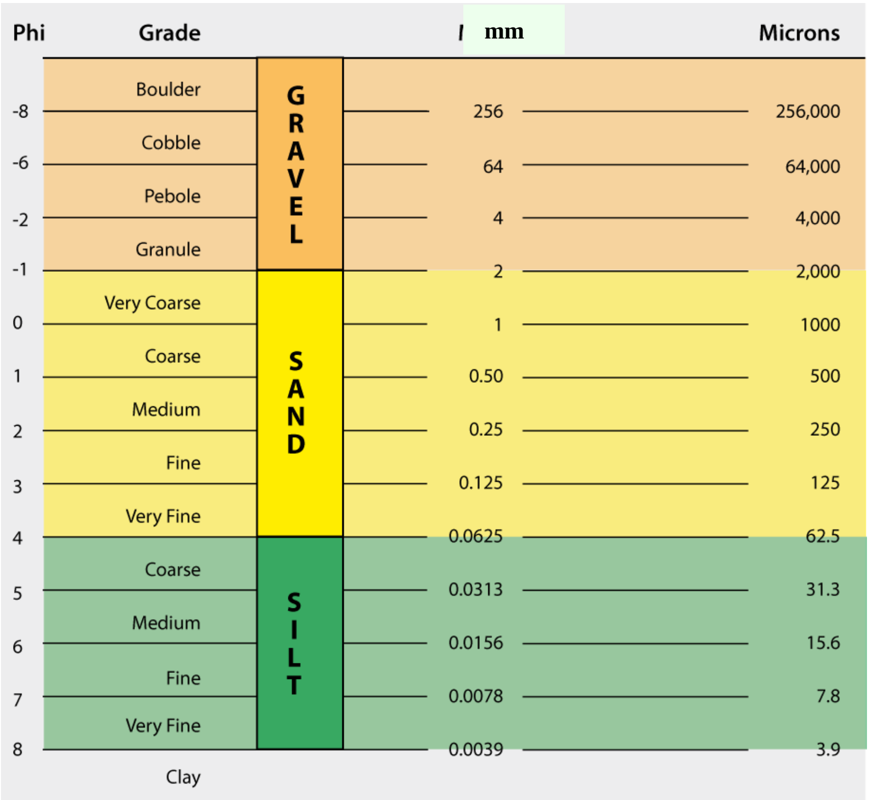
2.7.3 Wentworth Particle Size Classification for Sand (Wentworth, 1922)

The Wentworth scale for measuring grain size uses a geometric interval of ½ to define the limits of each size fraction in which sand is divided into five sub-categories based on size as follows:

- Very coarse sand: 1 – 2 mm
- Coarse sand: 0.5 – 1 mm
- Medium sand: 0.25 – 0.5 mm
- Fine sand: 0.125 – 0.25 mm
- Very fine sand: 0.0625 – 0.125 mm

The above sizes are based on the **"Φ sediment size scale"**, a size scale which is commonly used in sedimentology (Krumbein and Pettijohn,1938; Folk, 1954) and in which Φ is the logarithm to the base 2 of the grain diameter. In this scale the use of Φ, an arbitrary and artificially derived grain size unit, allows the particle size distribution (PSD) to be represented as a single point on a plot of mean particle size against standard deviation in Φ units and thus allows other properties of the sands to be related to that plot – an approach that has been used for improved selection procedures of sand in road construction (Metcalf and Wylde, 1984).

For comparative purposes, Figure 2.7 shows the relationship between grain size data expressed in Φ units, millimetres and microns (micro meters) (Anderson, undated).



The Phi scale
In previous research on sediments, grain size data is given in phi (Φ) intervals rather than in microns or mm as statistical and graphic presentations are much simpler when phi diameters are used. Phi is defined as:

$$\Phi = -\log_2 d$$

where d = particle size in mm.

(A particle size of 0.5 mm = φ of 1 and a particle size of 0.125 mm = φ value of 3).

Figure 2-7: Alternative measures of grain size (Φ, mm and microns)

In general, the major role of international classification systems, such as the AASHTO system, is to enable engineers to understand the general, rather than particular, properties of the soils of other countries and to be able to communicate on a common basis. Thus, a regional system, based on the properties of regional on sands, will generally be preferable and should be used in conjunction with broader classifications. This is one of the major aims of the guideline – *to customise a broad, international classification system for sands in general, to one which reflects the performance characteristics of sands that occur in the SADC region.*

3. PROPERTIES OF SANDS

3.1 Introduction

As may be inferred from the work done by Baillieul (1975) and others (Carney, et al, 1994; Brink, 1985) the sands of the Kalahari region occur either as:

- *aeolian* (windblown) deposits which have undergone redistribution by wind, or as

- *soils of mixed origin* which have resulted through the operation of a number of processes including bioturbation, redistribution by wind during arid periods, and pedogenesis.

Because of their areal extent in southern and western Africa, both types of sand are of major engineering importance, particularly in relation to transportation routes (road, rail) and other infrastructure (dams, mines, etc). However, as determined by Baillieul (Baillieul,1975), because of their different modes of formation, they display very different engineering properties, with the soils of mixed origin sometimes exhibiting problems such as *collapse settlement* – a phenomenon which is of special significance in civil engineering works, including roads and building foundations. Thus, the successful use of sands in various aspects of road construction requires a full understanding of their various engineering properties.

The following sub-sections of the literature review consider the various properties of sands and their practical significance in road construction.

3.2 Physical

3.2.1 Colour

The colour of the Kalahari sands as determined using the Munsell System (ASTM D 1535-80) varies from dusky red at one extreme, through brown, orange, yellow, white, grey and black! Figure 3-1 illustrates the wide range of colours exhibited by the Kalahari sands that are found in Botswana.

Sand colours as determined from the Munsell Chart with soil in the dry condition.

Figure 3-1: Typical range of colours of Kalahari ands found in Botswana

The red and yellow colouration of the soils is derived from the mobilisation of iron oxides (Cooke, 1964) during in situ weathering of feldspathic and ferromagnesian minerals. Such sand types are prevalent in Area IV of the Baillieul map of Botswana (e.g. along the Serowe-Orapa road). In contrast, where the sands have been affected by a fluctuating water table, such as in the vicinity of the Okavango Delta (Area I of the Baillieul map), the skin of iron oxide has been removed and the sands are grey in colour (e.g. the Maun-Shorobe road). In further contrast, the aeolian component of the sands found in Area II of the Baillieul map is creamish white in colour (e.g the Nata-Maun road in Botswana).

The various colours of sands found in Botswana – colours that have also been reported in many countries in the SADC region, including Mozambique, Namibia and South Africa – show a very striking and clear relationship between iron, (as Fe_2O_3) content and clay fraction (Cf) (Figure 3.2). There is also a strong, logical connection between the colour of the sand and its iron oxide content.

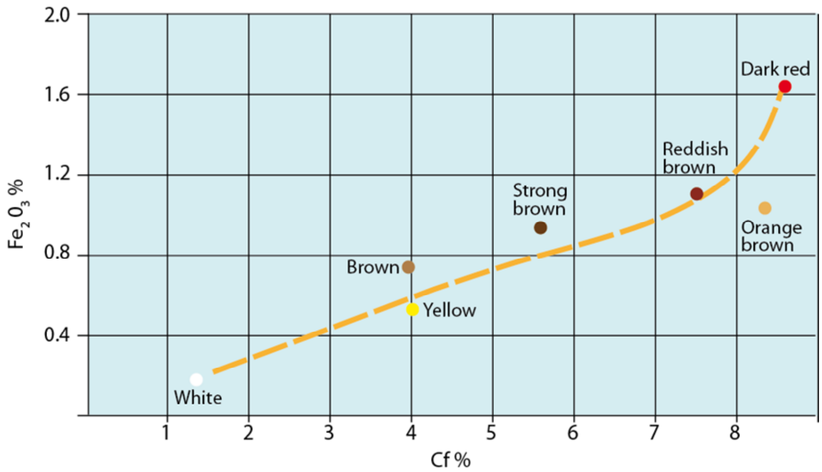


Figure 3-2: Iron oxide content versus clay fraction

Existing evidence from a number of road projects in Botswana indicates a rough correlation between sand colour and other engineering properties such as grading, plasticity, strength and compactability. This relationship will be investigated further with the samples collected from Mozambique and Namibia.

3.2.2 Particle shape

The shape of sand particles has a significant influence on its compactability, density and stability and, hence, the overall engineering behaviour of the material. For a specific grading, this parameter controls the manner and degree of particle interlock upon which is dependant such components as shearing resistance, crushing resistance and flexural or tensile strengths. Thus, smooth rounded particles would offer less resistance to rearrangement than angular and/or elongated particles with rough surfaces and, therefore, other things being equal, the former would be expected to give higher densities for a given compactive effort.

The definition and measurement of particle shape is a complex subject. However, am elementary definition of shape is shown in Figure 3.3 (Lees, 1964). Based on the simple measurement of longest, intermediate and shortest dimension of a sand particle, its *form* can be classified into one of four classes:

- *Oblate:* Particles which are tabular or shaped like a disk.
- *Equant:* Particles which are equidimensional.
- *Bladed*: Particles which are elongated and somewhat flattened.
- *Prolate:* Particles which are rod-shaped.

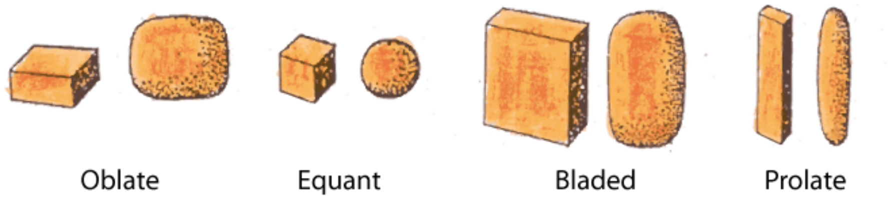


Figure 3.3 – Particle form

The above classification is a broad one and shape can be further described in terms of different degrees of *roundness* as illustrated in shown in Figure 3.4.

Figure 3.4 – Degree of particle roundness

Particle shape is best determined visually using a low magnification binocular microscope although a good indication of this property can be determined in the field using a strong hand lens (10 X).

Kgalagadi sands exhibit a wide range in particle shape, which is influenced by their mode of formation. In this regard, aeolian sands tend to exhibit a more rounded shape than sands of mixed origin, a factor that significantly influences their compactability characteristics and related strength and bearing capacity as discussed above (Semmelink, 1992).

3.2.3 Texture

The texture of sand is influenced by its grain size, sorting, rounding and maturity (see Figure 3.5).

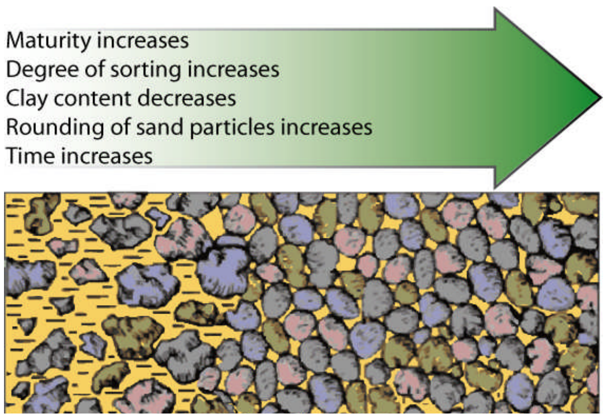


Figure 3.5 – Factors influencing sand texture

Grain size: Is a measure of the diameter of a sand particle and is a result of several factors, including composition, durability, severity of weathering conditions, transport distance from its site of origin, and physical sorting by wind and/or water currents.

The distribution of grain size in a sand sample is generally measured by sieving which essentially measures the maximum diameter of a sand grain in the size range 0.06mm to 2mm (equivalent to 62.5 to 2,000 microns or, on the Phi scale, 4Φ to -1Φ.

Material in the silt range (material finer than 0.06mm) or the clay range (material fines than 0.002mm) is normally determined by undertaking a hydrometer analysis. ***The determination of these fractions is very important as they affect the engineering characteristics and performance of sands as pavement layers in terms of plasticity, strength and bearing capacity.***

As the percentage of soil finer than 0.075 mm increases, terms such as silty sands and clayey sands are used. The majority of Kalahari sands would be classified typically as fine to medium or coarse sands with some loamy sands or sandy loams.

Sorting: Is the range of sizes in a sand. Poorly sorted sands show a range of grain diameters, while well-sorted sands have a similar size (see Figure 3.6).

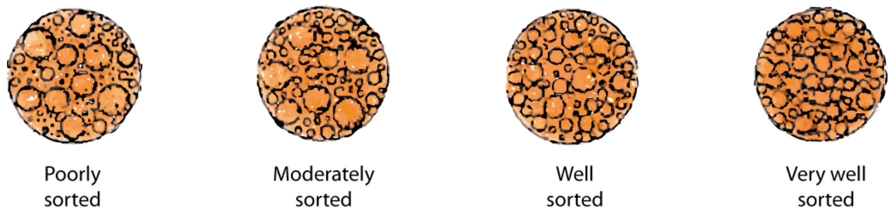


Figure 3.6 – Degree of sorting

An important distinction must be made between the definitions of sorting used by sedimentologists and civil engineers. A well-graded material in geology is one that has a relatively small range of particle sizes whereas engineers refer to well-graded materials as those with a wide range of particle sizes.

- ***Rounding:*** The presence or absence of corners and sharp edges on the sand particle. Particles with many edges are "angular". Particles lacking edges are "rounded" (see Figure 3.4). Roundness is not the same as spherical. An oblong particle can also be highly rounded.

  Generally speaking, the more well rounded the individual grain, the greater the energy involved in transport or the longer the duration of transport. Aeolian sands tend to be well rounded by high energy collisions and abrasions.

- ***Maturity:*** Is a relative measure of how extensively and thoroughly a sediment (sand size and larger) has been weathered, transported and reworked towards its ultimate end product, quartz sand. As a general rule, the greater the transport distance and the greater the length of time in the transport medium the more mature a resultant sediment becomes. Maturity is gauged largely in terms of grain size, grain sorting and grain roundness in terms of *immature*, *submature*, *mature*, and *supermature.*

Table 3.1 – Classification of sand maturity (Folk, 1980)

	Immature	Submature	Mature	Supermature
Sorting	Extremely poorly to very poorly sorted.	Poorly to moderately sorted	Moderately to well sorted	Well to very well sorted
Grain size	Very coarse	Coarse	Medium	Medium
Roundness	Angular	Subangular	Rounded	Well rounded

Both shape and texture play an important rile in the performance of sand as a pavement material. Although the influence of shape and texture are not very critical in the effect on the compactability of sand, they are very critical in the case of the bearing capacity in terms of CBR and most likely in terms of elastic properties as well (Semmelink, 1992). As the sand grading changes from a well-graded material to a uniformly graded or poorly graded material the influence of shape and texture is reduced.

3.2.4 Grading

Knowledge of the grading of sand is one of the most valuable guides to its engineering behaviour. As might be expected from sands derived from different origins, their gradings differ somewhat in relation to their mode of formation. Generally, however, as illustrated in Figure 3-7, they tend to exhibit an S-shaped curve (Botswana Roads Department, 1992) with 80 – 100% typically passing the 0.425 mm sieve and a 5 to 15% silt and clay fraction which influences a number of the soils properties such as plasticity and compactability. Evidence from road projects in Botswana indicates that, in general, aeolian sands tend to be *uniformly* graded (typically A3 AASHTO classification with a Uniformity Coefficient, Cu, approaching 1, i.e. Unified Classification of SP) in contrast to the more *well graded* sands of mixed origin (typically A-2-4 AASHTO classification with a high Uniformity Coefficient, e.g. 5 – 10, i.e. Unified Classification of SW). These factors have a bearing on their suitability for use in various layers of a road pavement.

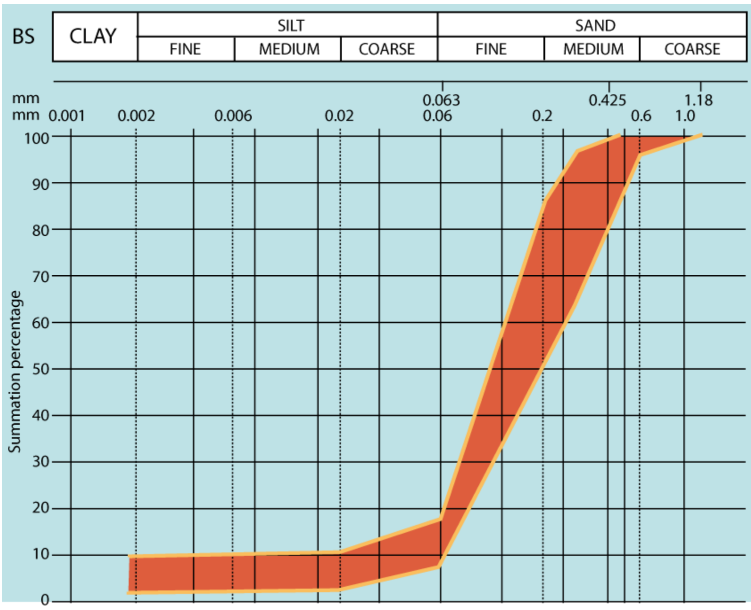


Figure 3.7 – Grading envelope for typical Kalahari sand types found in Botswana

Experience from Namibia (Dierks, 1992) indicates that the relatively high strength of Kalahari sand in that country in comparison with Namib sands is due to their more non-uniform gradings and -0.075 mm fines (up to 10% and more) with the consequent higher CBRs. Dierks also reports that although the PI on the fraction passing the 0.425 mm sieve is very low (mostly non plastic), the PI on the fraction of the Kalahari sand can be up to 15. These findings tally very closely with the Botswana experience.

By way of comparison, Figure 3-8 shows the grading of a typical Namib dune sand with a Kalahari sand from which it is readily apparent that the Namib dune sands are significantly finer than the Kalahari type sands.

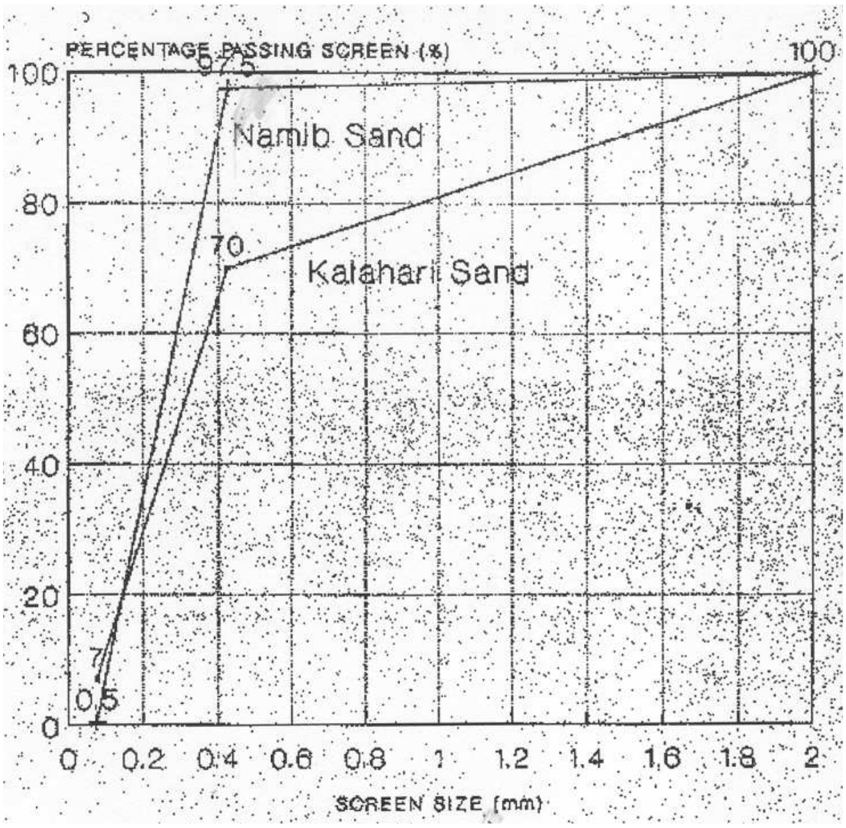


Figure 3-8: Gradings of typical Namib and Kalahari sands

It is also interesting to note the outcome of recent research work carried out in Mozambique as part of the *Performance Characterization of Cement Treated Sand Base Material of Mozambique* (de Vos 2007). In that project, the results from the sieve and hydrometer analyses for both red and yellow sands, which are considered to be representative of the greater geographical area of coastal plains and dunes in the southern part of Mozambique, were reported as follows:

Table 3-2: Summary of particle size distributions for red and yellow sands (de Vos, 2007)

Fraction Size	Fraction	Red Sand (%)	Yellow sand (%)
2.0 > % > 0.425 mm	Coarse sand	15.3	61.8
0.425mm > % > 0.05mm	Fine sand	72.8	32.9
0.05mm > % > 0.005 mm	Silt	6.8	1.3
0.005 mm > %	Clay	5.1	4.0
0.05mm > % > 0.005mm	Silt + Clay	11.9	5.3
	Passing 0.075 mm	14.0	5.3

The results from Table 3-2 indicate that the silt content of the red sand is five times greater than that for the yellow sand while the percentage passing the 0.075 mm sieve for the red sand is three times greater than the yellow sand. Also, the fine sand fraction of the yellow sand is more than twice that of the red sand. The grading modulus for the red and yellow sands from Mozambique were reported as 1.1 and 1.3 respectively. (N.B: Grading modulus GM = [300-(P2+P425+P075] /100 where P2, etc., denote the percentage passing through the sieve size).

3.2.5 Plasticity

Kalahari sands exhibit variation in plasticity depending primarily on their mode of origin and the consequent presence or not of either clay minerals or, possibly in some cases, salts deposited by the evaporation of salt-laden ground water. Determination of plasticity in the traditional manner, i.e. on material passing the 0.425 mm sieve (P425), invariably tends to mask the plasticity that can be mobilised in the silt and clay fraction of the sand (P075). All these sands show non- or only slight plasticity on the P425 fraction but significant plasticity on the P075 fraction *which is of critical significance when the sands are being considered for use as construction materials.*

As indicated in Table 3-3, in Botswana there also appears to be a correlation between sand colour (influenced by mode of formation) and plasticity. Thus, in general, the whitish aeolian sands tend to exhibit no, or little plasticity (even on the P075 fraction) compared with those reddish brown sands of mixed origin which exhibit higher plasticities on both the P425 and P075 fractions (influenced by iron oxide coating which imparts a reddish colour to the sand). It is anticipated that this feature should be common to most sands in the SADC region that have an aeolian or partly aeolian origin.

Table 3-3: Atterberg Limits and Linear Shrinkage for seven sand types occurring along the Serowe-Orapa road, Botswana (Mockett and Barton, 1990)

Colour Type	Dark Brown	Reddish Brown	Yellow	White	Brown	Orange Brown	Red
LL (%)	56	65	48	27	41	50	54
PL (%)	36	38	29	20	24	32	35
PI (P063)(%)	21	28	19	8	17	18	20
LS (%)	17.0	18.0	11.0	5.0	11.0	13.0	16.0

As might be expected, the plasticity of sands is influenced by their clay content which is evident in the Atterberg limits.

3.3 Mineralogy

Knowledge of the mineralogy can assist in assessing the expected performance of the sands. This is particularly applicable to the fine or clay component and whether the grains are quartz or less durable feldspars, basalt or other rock and/or mineral types. Similarly, the chemical properties may also be useful indicators of the behaviour of the materials.

The presence of iron and/or aluminum oxides in the sand clays of Western Australia certainly appears to facilitate "self cementation" as shown by Emery et al (2007) where indirect tensile strengths (ITS) between 250 and 570 kPa were measured on materials extracted from roads as well as after drying back in the laboratory (Main Roads, 2002).

The results of the chemical analysis of Botswana sands of different colour determined from X-ray fluorescence (XRF) analyses indicated that the better performing sands, i.e. the red sands all have the sum of their iron and aluminum oxides in excess of 18 per cent. These findings are supported by recent research work in Mozambique (de Vos 2007) which also show that the red sands exhibited higher percentages of iron and aluminum oxide than the yellow sands.

3.4 Engineering

3.4.1 Collapsible Sands

Certain types of Kalahari sands exhibit a *collapsible fabric.* This results from the generation of clays and iron oxides within the soil mass during weathering of susceptible particles. As a result, these sands possess an open structure, their void ratio is high and there is very little interlock between the sand grains; the structure is held together by the clay and iron oxide/hydroxide bridges. As long as the sand is not disturbed and is kept dry, these bridges provide considerable bearing strength. However, if the sand is wetted, the bonding bridges between the grains soften. Under load above a certain limit, the bridges break and collapse occurs as illustrated in Figure 3-9.

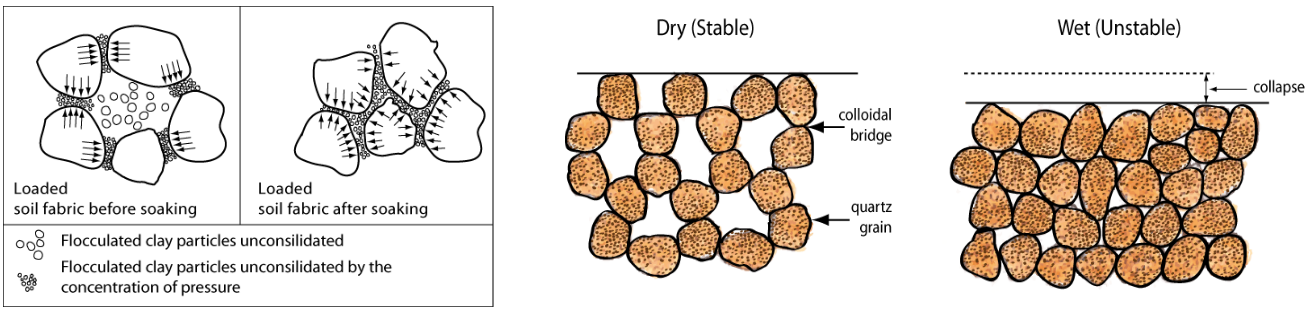


Figure3-9: Graphical illustration of collapsible sand fabric (Brink, 1985) and mechanism of collapse

When sands collapse, they can spontaneously lose up to 20% of their original volume. This can be of particular significance to roads, airfields and railways, where the subgrade is subjected to increased load and increased moisture content. To reduce the chances of such collapse occurring in practice, current specifications often require that subgrade soils with a collapsible fabric be densified to a depth of about 1 m (Weston, 1984). However, this can be a very costly requirement to meet in practice, particularly in arid or semi-arid areas where water is often scarce and expensive. Options for dealing with this problem are discussed in Section 5.2.

The *collapse potential index* provides a useful guide to the collapse properties of a particular sand. Typical guideline values are given in Table 3-4 (BRDM, 1982). These results illustrate the collapse potential of the reddish brown sands encountered in Area IV of the Baillieul map and support the assertion made by Brink (1985) that any geotechnical investigations carried out in areas occupied by aeolian deposits should be designed to identify collapsibility and, if necessary, should include tests to quantify the magnitude of collapse that could occur.

The description and classification for collapse potential (CP) is shown in Table 3-4 which was originally developed for gauging the severity of differential settlement of structures, but can be a useful guide for roads. In this regard, the collapse potential would be determined at a loading equivalent to the overburden pressure of the pavement (typically of the order of 36 kPa for a road on a low embankment) and at saturation moisture content.

Table 3-4: Collapse potential related to severity of problem (Jennings and Knight, 1975)

Collapse Potential	Severity of Problem
0 – 1%	No problem
1 – 5%	Moderate trouble
5 – 10%	Trouble
10 – 20%	Severe trouble
> 20%	Very severe trouble

An example of the properties of a typical collapsible Kalahari sand in Botswana and the effect of application of compaction using a high energy impact compactor are shown in Table 3-5.

Table 3-5: Typical properties of collapsible reddish brown sand (Serowe-Orapa Road, Botswana)

Property	BRDM guideline for CP	Average results
Dry density (kg/m^3)	< 1600	1432.0
% passing 2.0 mm and retained on 0.075 mm	>60%	85.0%
% passing 0.075 mm	< 20%	17.5%
Relative density	< 85%	75.4%

Depth below surface (mm)	Collapse Potential	
	(200 kPa)*	(36 kPa)**
200 - 350	11.5%	6.3%
450 – 600	11.2%	7.1%
700 – 850	9.3%	5.0%
1000 - 1150	7.5%	3.6%
Based on a guide to the potential severity of the collapse problem proposed by Jennings and Knight (1975), the sand subgrade would fall in the "trouble" to "severe trouble" category.		

* as specified by Jennings and Knight
** estimated at in-service loading

Photo 1 – A collapse settlement in excess of 150 mm was obtained along a section of the Serowe-Orapa road after compaction to near refusal by a 25 kJ high energy impact compactor.

3.4.2 Compaction Characteristics

Laboratory investigations carried out by many practitioners reveal that Kalahari sands do not always exhibit the typical parabolic dry density/moisture content curve exhibited by other soils (Figure 3-10). Instead, the compaction characteristics of some of these sands are such that they can be compacted over a wide range of moisture contents, without a significant change in density.

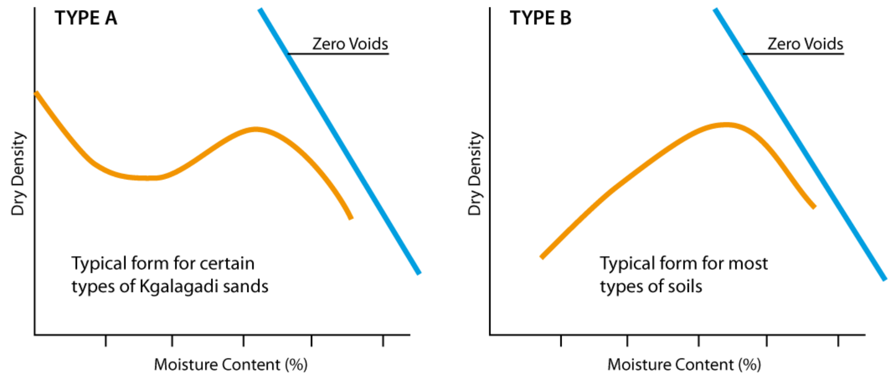


Figure 3-10: Typical forms of compaction curve for sands.

For some Kalahari sands, the density obtained in a dry condition can be markedly greater than that obtained at any finite moisture content. However, as much as there may be a temptation to employ "dry compaction" in practice, other pertinent factors are noteworthy. For example, high air voids and high soil suction values both have a potential for causing post-construction problems (albeit reduced ones in semi-arid climates) such as greater susceptibility to loss of strength, should the degree of saturation increase in service, resulting in deformation of the pavement structure. Materials compacted in their dry state also do not have an inherent strength developed by soil suction as they dry back from the optimum moisture content.

3.4.3 Permeability

The permeability of Kalahari sands is most influenced by the size, shape and connectivity of the water passages which are themselves largely affected by the grading and segregation of the soil. In general, an increase in plasticity will reduce permeability whereas segregation of grading sizes will increase permeability.

Typical permeability coefficients for other sands are shown in Table 3.6 (Lee, White and Ingles, 1983).

Table 3-6: Typical permeability coefficients for sands

Sand Type	Coeff. Perm. (cm/sec)	Qualitative Description
Clean coarse sand	$1 – 10^{-2}$	Medium
Graded sand	$10^{-2} – 5 \times 10^{-3}$	Medium
Fine sand	$5 \times 10^{-3} - 10^{-3}$	Medium to low
Silty sand	$2 \times 10^{-3} - 10^{-4}$	Low
Very fine uniform sand	$6 \times 10^{-3} – 10^{-4}$	Low
Dune sand	0.1 – 0.3	High

There is a perception that sandy materials are free draining and water-related problems affecting roads are minimal in sandy areas. This is not necessarily true (Brink, 1985) and has important implications for the use of Kalahari sands in road pavements, particularly as regards the important factor of avoiding permeability inversion within the pavement structure. The finer and less well-sorted sands are, the lower their permeability (Masch and Denny, 1965). This can be observed by the long periods during which rainwater stands on the sides of roads in, particularly, red sand areas.

3.4.4 Suction

Soil suction is primarily a function of the soil grading and inter-particle voids, which are indirectly indicated by plasticity through the fineness of clay minerals. A typical equilibrium curve showing the relationship between the moisture content and suction (pF units) for wetting and drying cycles is shown in Figure 3-11 which indicates that (1) the suction pressure increases with decreasing moisture content and (2) for any given suction pressure, the moisture content increases with increase in clay content.

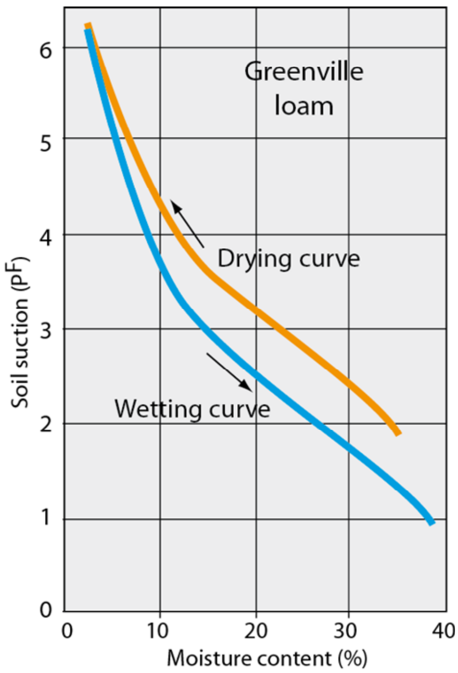


Figure 3-11: Soil suction/moisture content relationship (Wooltorton, 1954)

The development of soil suction strength allows some sands (particularly those with an appreciable fines content) to generate relatively high strengths in service as they dry back from their moisture content at compaction processing to their equilibrium moisture content – typically 0.6 – 0.7 of OMC (Emery, 1992). The soil suction generated over this range of moisture content will be considerably higher than those existing under soaked conditions. However, if the sand is to retain its suction generated strength then the soil suction must be maintained by ensuring that the moisture content in the pavement layers does not increase above the OMC of the material. This can only be achieved if the road surfacing is impermeable and effective drainage is in place.

4. PROSPECTING AND TESTING OF SANDS

4.1 Introduction

Because of their areal abundance in southern and western Africa, sands are of potentially major engineering importance for use in the construction of LVRs. However, in an area that is as vast as the southern African region, the major challenge is to find a reliable procedure for locating those sands that are likely to be suitable for incorporation in a LVR pavement.

4.2 Prospecting

The 1 in 6 million scale maps of southern Africa in Brink (1985) showing the distribution of transported soils according to origin (Figure 1-1) and the similar scale map showing the pedological classes of soils (Figure 2-2) provide some information on the nature of the sands that may, with some refinement, be used for the location of suitable sands for construction. The Soil Maps of the particular countries and soil profile information also contain useful information. For example, the Kalahari sands are mostly classified as arenosols. Although there are many subdivisions of arenosol (and mapping units), each has a specific description of the colour, particle size distribution (classification) and nature. The relevant soil profile description and standard soil analysis results provide comprehensive information on various properties of the materials that can potentially be usefully applied to material location. It is interesting to note that arenosols make up the largest proportion of the sandy materials (five different sand types predominate) in the Sao Paulo region of Brazil (Utiyama et al, 1977).

The sand sampling programme for the next phase of the project has been developed with the objective of sampling as wide a variety of sands as possible based on the information provided in Figures 1-1 and 2-2. Following the testing of the various sand types, it will then be possible to categorise them for use in the various layers of a LVR pavement based on their properties and previous experience of their performance history. Thereafter, Figures 1-1 and 2-2, as well as the country-specific soil maps, could possibly be refined to provide a more reliable guide to locating sands that are potentially suitability for use in the various layers of a LVR pavement. This refinement will be investigated further following the testing of the sand samples and the analysis of the results.

4.3 Testing

The testing of sands should generally follow standard techniques, although certain inherent characteristics require special considerations.

4.3.1 Test methods

It should be noted that there are significant differences between certain test methods specified by the BS standards and the TMH methods, particularly with respect to plasticity index and bar linear shrinkage. Moreover, some countries (e.g. Botswana, Namibia and South Africa) use TMH1-type test methods whilst other countries in the SADC region (e.g. Tanzania, Malawi) use BS methods. It is therefore important not to mix test methods because the differences in test procedure will result in quite different results. It is proposed to use the recently revised South African SANS test methods, which replace the TMH1 test methods, in the testing of the sand samples.

4.3.2 Grading

The grading of sands should always be carried out using a wet preparation method such as TMH1 Methods A1(a) and A5 (NITRR, 1986) (now SANS 3001: GR1) in order to ensure that all cementing bridges are broken and that the small quantities of plastic fines are released for determination of the Atterberg Limits. The standard range of sieves employed and recommended in TMH1 includes only the 0.425 and 0.075 mm screens that will typically retain any sand material. It is recommended that for these materials, the 0.300 (or (0.250) and 0.150 screens are also included and where the fraction passing 0.075 mm exceeds about 15 per cent, a hydrometer analysis is also carried out using Method A6 (NITRR, 1986). This will give a better indication of the distribution and sorting of the material.

Studies in Australia (Wylde, 1982) indicate that, despite the fine nature of sands, the process of excavation, mixing and compaction physically damages the sand constituents, particularly releasing the fines. It is thus desirable that grading analyses for design are carried out on material that has been subjected as far as possible to these process or processes that simulate these actions.

4.3.3 Atterberg Limits and Linear Shrinkage (Soil Constants)

Routine testing of the Atterberg Limits following TMH1 Methods A2 and A3 (NITRR, 1986) (SANS: 3001: GR10, GR11 and GR12) usually indicates that the materials are non- or slightly plastic. For sands, it is imperative that the Atterberg Limits are determined on the fraction finer than 0.075 mm, this almost invariably giving a Plasticity Index (PI) in the range 5 to 20 per cent. This property can then be expressed as the Fineness Index (FI), which is the product of the PI on 0.075 mm sieve and the percentage passing the 0.075 mm screen. This property is a useful indicator of the compactability of sandy materials (Mainwaring, 1968) as discussed in a following section.

From experience of testing the Kalahari sands in Botswana, it is noteworthy that the use of the Cassagrande bowl type Liquid Limit Device (as adopted in TMH1) proved to be unsuitable for determining the Liquid limit of the relatively less plastic sands. This was because there was a tendency for the groove that was cut in the paste either not to close or to slump on the first blow during the operation of the device. For this reason, it was necessary to resort to the use of the BS 1377 Cone Penetrometer for determining the Liquid Limit of the sand samples. It is important to note that both the BS cone and cup Liquid Limit devices yield a Liquid Limit and therefore also a PI on average 4 units higher than the TMH1 ASTM type of LL device (Sampson and Netterberg, 1984).

The bar linear shrinkage should always be measured with the Atterberg Limits. This should also be done on the minus 75 µm fraction, although there is a dearth of experience in interpreting this property.

4.3.4 Sand Equivalent

The sand equivalent test (TMH1 Method B19) is a particularly useful test for sands as it gives an indication of the sand component as well as its quality, in terms of clay type and quantity. The French (Chauvin, undated) make use this test in their classification of sands for road construction.

4.3.5 Compaction characteristics

The laboratory compaction of fine cohesionless materials using dynamic compaction methods (eg TMH1 method A7 (NITRR, 1986) (SANS 3001: GR30) can be difficult, producing unreliable results due to shearing of the material during compaction. The use of the BS 1377 vibrating hammer method (Test 14) (British Standards Institution, 1990) is thus recommended. As indicated from research work carried out in Botswana (Guideline No. 11 – The Use of Kgalagadi Sands in Road Construction) and illustrated in Figures 4-1 and 4-2, the benefits of using vibratory over dynamic compaction for a given sand type are:

- a reduction in air voids
- an increase in density
- an increase in strength (CBR)

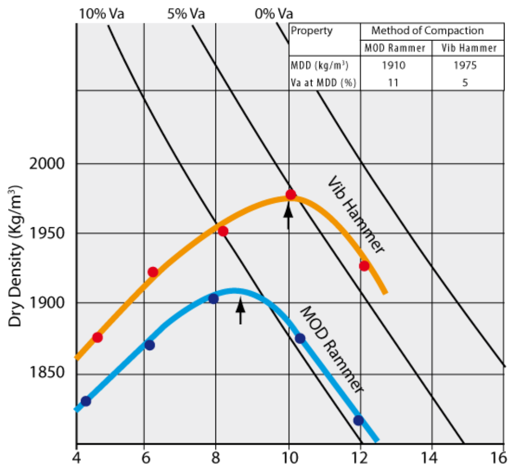


Figure 4-1: Density/voids relationship

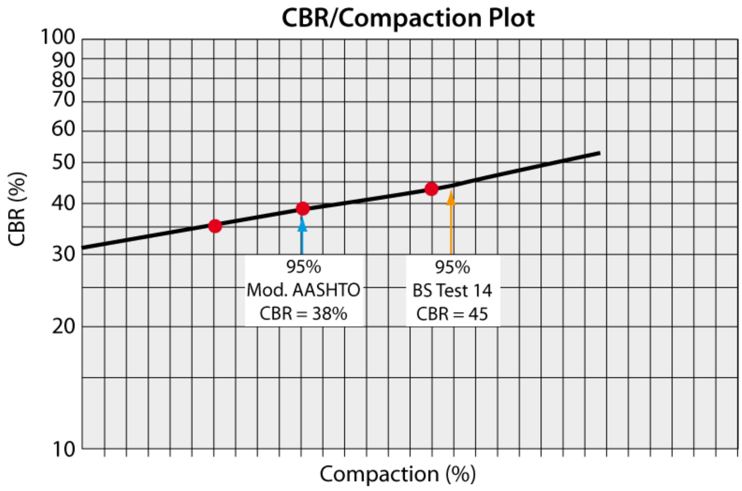


Figure 4-2: CBR/compaction relationship

In practice, therefore, the full strength potential of sand can be better exploited by specifying that the stipulated field density be assessed by the laboratory vibrating test method rather than the dynamic test method.

Sands with some cohesion can be compacted using the traditional TMH1 dynamic compaction technique, but they usually require a rubber mat on the surface to avoid excessive displacement of the sand.

4.3.6 Strength

The California Bearing Ratio (CBR) is traditionally used for the specification and control of materials. This test normally uses a dynamic compaction technique. Where the density of the material is specified to be tested using a vibrating hammer, the CBR should be carried out on specimens prepared in the same manner and to the same density.

In Australia, the Western Australia Confined Compression Test (WACCT), similar to the better-known Texas triaxial test in many respects, is used to evaluate the strength of sandy materials Wylde, 1979; Jewell, 1970; Main Roads Department, 1975). In Zimbabwe, one of the few countries that have specifications for the use of sand as base and subbase, the Texas Triaxial classification method is also used for material selection (Zimbabwe Ministry of Roads. 1979).

The strength of sands appears to be very moisture-dependent, and during strength testing, the sensitivity of the specific sands to moisture should be evaluated. The strength of sands with CBR values in excess of 60 per cent when one per cent dry of optimum moisture content has been recorded to drop to 30 to 35 per cent at optimum and to between 5 and 10 per cent when one per cent above optimum (Paige-Green, 1983).

It is interesting to note that in Western Australia (Main Roads, 2002), the base course requirement for using sand-clay is an unsoaked CBR of at least 80% at 95% Mod AASHTO density.

4.3.7 Modulus of Resilience

Mechanistic pavement design requires more sophisticated testing and properties. The use of repeated load Triaxial testing is necessary for this and has been used (Aranovich and Heyn, 1984). However, facilities for carrying this out are limited and expensive.

4.3.8 Methylene Blue Absorption

This is another useful test that indicates both the quality and quantity of fines in sand (Chauvin, undated). There are a number of test methods available, but no rigorous comparison appears to have been carried out. More use should perhaps be made of this test.

4.3.9 Salinity

Salinity of the sands can be tested using the electrical conductivity as described in Guideline 6 (Botswana Roads Department, 2001). It is suggested that the quick method provided in Guideline 6 is used, as there is less subjectivity with respect to obtaining the saturation moisture content required by TMH1 (Method A21) (Department of Transport, 1986). This is often a problem with sandy materials.

4.3.10 Durability

The durability of Kalahari sands is seldom a problem and no current routine tests can deal with the nature of the material. Materials with high non-quartz contents (e.g. from Baillieul's Areas II and IV) may include soft feldspar or basalt grains. The effect of these can be assessed by carrying out an extended sand equivalent test. In this test, the standard method is followed and the test is repeated with 10 minutes of agitation. A significant increase in the sand equivalent value for the latter test indicates the potential for softer particles to degrade in service.

4.3.11 Collapse settlement

Where there is any doubt that the material does not have a collapsible structure, oedometer testing should be carried out to assess the collapse potential. Although the double oedometer test is regarded as the classical means of quantifying collapse, a single oedometer test known as the collapse potential test is simpler and quicker. In this test, a sample is loaded to 200 kN and then saturated (Brink, 1985). The reduction in voids ratio is mathematically expressed as the collapse potential and this related to the thickness of potentially collapsible material can quantify the magnitude of collapse that could occur.

4.3.12 Mineralogy and chemical properties

Specialised techniques such as X-ray diffraction (XRD) and X-ray fluorescence (XRF) can be used to determine the mineralogical and chemical properties of sands. However, these techniques are relatively expensive to use and only in exceptional cases will provide value for money.

5. SPECIFICATION FOR USE OF SANDS

5.1 Introduction

Sandy materials do not comply with the requirements of conventional road material specifications, especially for structural pavement layers. They are typically excluded because of their particle size distributions, although their plasticity and strength characteristics frequently fulfil the specified requirements. However, sands have been successfully used in Botswana, Australia and Brazil for almost all layers in roads.

Work in Australia has shown that when using sand, performance differences appeared during construction rather than in service (Metcalf, and Wylde, 1984).

5.2 Subgrade

Many roads constructed in the SADC region will have predominantly sandy subgrades. Subgrade materials generally have relatively wide specification limits in terms of their mechanical properties and strength and unless totally problematic and require removal, of necessity become part of the pavement structure. Most sands when compacted to the appropriate density will easily comply with the specified requirements. However, the Botswana Road Design Manual (BRDM) has specific requirements pertaining to materials with potentially collapsible grain structures (Clause 5-102.5.2 (Ministry of Works, Transport and Communications, 1982).

Pavement subgrades usually fail through being too weak to support the applied loads, through excessive volumetric movement or as a result of insufficient compaction. Provided sand subgrades are compacted to the required standard, their chance of failure is relatively low.

Standard CBR testing is carried out after 4 days of soaking. It has been proposed that in arid areas, unsoaked CBR tests could be used for more economic designs (Emery, 1992). Because of the reliance of sandy materials on the soil suction for some of their strength and the relatively low permeability of the sands, it is, however, recommended that in non-arid areas soaked designs be generally used for sandy subgrades.

Where subgrade compaction problems are encountered, particularly with the more uniform sized sands and manifested as a tendency for shearing of the material during compaction, particuallery when excessive vibration is used (Chauvin, undated; Murphy, 1918) a method specification based on controlled compaction trials should be considered.

Recent work in Botswana has shown that roads with Kalahari sand subgrades resulted in deep pavements with n-exponent values (for carrying out traffic equivalency calculations) of less than 2 (Paige-Green and Overby, 2010). This has a significant impact on the determination of equivalent standard axles in pavement design over sand subgrades.

5.3 Fill and Selected Layers

Materials for fill generally require similar quality as subgrade, the only difference being that they are imported to provide the required pavement shape and levels. Discussion pertaining to in situ subgrade is generally relevant to fill materials, although most collapse potential of the material would generally be lost during extraction from borrow, haulage and compaction.

The non-cohesive nature of the sands, however, can result in compaction difficulties because of non-confinement. This may require construction of a wider fill in order to provide a greater degree of confinement in the central pavement area and rolling from the outside inwards, only.

Most Kalahari sands will comply with the standard fill requirements but good supervision and control of compaction is essential. It is recommended that the materials be compacted to refusal, rather than the 90 or 93 per cent of BS 1377 Test 14 that is specified, provided that refusal density is in excess of the specified limit. The South African requirement for sand (with less than 20 per cent finer than 0.075 mm) in roadbed and fill is a minimum compaction of 100 per cent Mod AASHTO density (COLTO, 1998).

Low densities in fills will result in settlement if the fill becomes submerged and traffic continues to use the road. The presence of perched water tables can also lead to this problem.

The successful vibratory and impact compaction to 100 per cent Mod AASHTO density of single size Kalahari sands at in situ moisture content (0.4 – 1.0 per cent) in embankments up to 4 m high has been reported along the 180 km road from Uppington to Twee Rivieren road in the Kalahari Gemsbok National Park (Palmer et al, 1992). These non-plastic (PI measured on the -425mm sieve) sands exhibited mean CBR values of 23% and 32% at 98% and 100% Mod. AASHTO respectively, thereby indicating the benefits of compaction to the highest practicable field density.

5.4 Subbase

Standard specifications for subbase usually preclude the use of sands on the basis of the minimum grading modulus (1.5). Despite this, many sands will provide the specified CBR of 45 per cent at the specified density (95 per cent Mod AASHTO) stipulated by standard specifications in the region (e.g. COLTO, 1996).

Kalahari sands have been successfully used as subbase on a number of projects in Botswana, including the Serowe-Orapa road for which the following specification was successfully derived:

(a) CBR value to be a minimum of 35% at 95% Mod. AASHTO;

(b) The PI on the material passing the 0.075 mm sieve, to be a minimum of 5 and a maximum of 20

(c) The Fineness Index:- the percentage passing the 0.075 mm sieve x the PI on the 0.075 mm fraction to be a minimum of 30 and a maximum of 200

(d) A maximum of 20% passing the 0.075 mm sieve

5.5 Base

It is not uncommon for certain untreated sands to exhibit relatively high CBR strengths, often in excess of 80 per cent, at the equilibrium moisture content that typically prevails under paved roads in the southern African region (Emery, 1992), and these materials when adequately compacted in the field are likely to perform satisfactorily. Figure 5-1 illustrates the variation in strength with moisture content for a red Kalahari sand that was used successfully as neat base on a section of a low volume road pavement in Botswana (the Serowe-Orapa experimental section). The sand sample was compacted at OMC and dried back to various moisture content ratios before its strength was determined.

The reason for the good performance of the red sand has been attributed to the high suctions that the material exhibits (due to its fine grading and the relatively high plasticity of the minus 75µm fraction) and the resulting high strengths when dry.

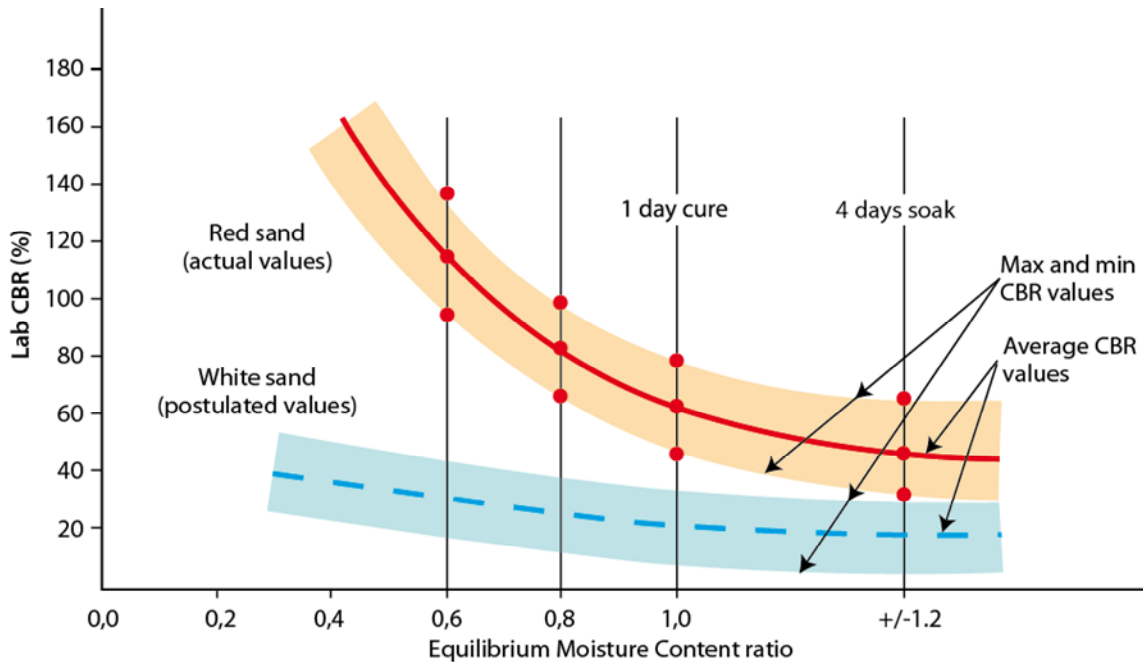


Figure 5-1: CBR of Kalahari sand sample at various moisture content ratios

Specifications for the use of sand in bases have existed in Zimbabwe, Australia and Brazil for many years (Netterberg and Paige-Green, 1988). The Zimbabwe specification (Zimbabwe Ministry of Roads, 1979) is particularly relevant to Kalahari sands whilst the Brazilian one is more relevant to fine-grained lateritic soils with good CBRs (Utiyama et al, 1977). The Australian specifications tend to be mostly localised within the local states, although a special provision for the use of sand clays was made in the old NAASRA pavement materials guide (National Association of Australian Road Authorities, 1980).

The most recent specifications for the use of sand as base course have been developed from research work in Botswana (Botswana Roads Department, 2010) where, on the basis of somewhat limited (100m test section), performance-based, information the following requirements are stipulated for the prevailing road environment:

- Atterberg Limits: $5 < BLS_{0.075}/\varphi_{mean} < 10$
- Min soaked CBR @ 100% Vib Hammer 60%
- $Al_2O_3 + Fe_2O_3$ (%) > 8

The more traditional, and costly, method of using sand as a base course material is to stabilize it – a topic which is discussed further in Section 5.9.

Adhesion of chip seals to fine base courses can be problematic – this can be improved by ensuring that low viscosity primes are utilised (National Association of Australian Road Authorities, 1980) but use has been made in Australia of armouring. In this process, a layer of aggregate (13 to 19 mm) is rolled into the top of the base. Problems with obtaining a smooth surface usually occur if the material has dried out significantly prior to rolling in the armouring.

Sandy bases can also have high bitumen absorption characteristics and primes can be rapidly absorbed into the base. In these cases, a double prime has been successfully used (Murphy, 1981).

5.6 Surfacing

Kalahari sand is too fine and uniform for chip seals and is unsuitable for use, even for conventional sand seals. They have apparently been used locally in Zimbabwe as fine aggregate for bituminous surfacings, but no details regarding this have been located. Experience in Botswana indicates that Kalahari sand seals without a surface dressing or graded gravel seal beneath them deteriorate within a few months due to cattle damage (Overby, 1982).

Sand has, however, been used regularly as a cover seal on single (and occasionally on double) Otta seals (Botswana Roads Department, 1999). Typically a 60 % Emulsion or an MC3000 binder is sprayed at between 0.7 and 1.0 ℓ/m^2 and immediately covered with Kalahari Sand at a spread rate of about 0.014 m^3/m^2. This must be rolled with a pneumatic tyred roller, ensuring that the sand is evenly spread and rolled. A light drag must be used to remove any unevenness. The road should be immediately opened to traffic. Sand dislodged by traffic should be broomed back onto the road until the balance between binder and sand is correct and no further sand is lost or bleeding occurs.

The use of Kalahari sands as a sand seal has also been described in Namibia (Marais and Freeme, 1977) where a single sand seal of windblown sand was placed on a cutback binder (sprayed at 1.37 to 1.76 ℓ/m^2) after allowing it to penetrate the bitumen stabilized sand base and thicken. No traffic was allowed on the seal for about 2 months and the seal gave good service for about two years.

The use of primer seals in Australia is almost standard practice in rural areas – these often consist of local sand placed on a heavy bituminous binder primer, which is provided as an initial waterproof wearing course until a conventional chip seal is placed during the hot and dry part of the year (Pederson, 1978). Local river and dune sands have also been successfully used as aggregate for seals (Pederson, 1978).

5.7 Wearing Courses for Unsealed Roads

Sands are not generally suitable as wearing courses for unsealed roads. Although the fines have some plasticity (cohesion), it is generally insufficient to resist the abrasive forces of moving wheels and the materials corrugate rapidly and deteriorate to thick, loose layers that are impassable to most vehicles.

The sands are, however, very effective for sand cushioning (Jones, 1995). In this process, a well-compacted gravel wearing course (usually of marginal quality) is covered with a thin layer (about 40 mm) of relatively single-sized sand. This upper sand layer is maintained on a regular basis, using a towed grader and drag, such that vehicles do not traffic the base material.

5.8 Shoulders and Side Slopes

The use of sands on shoulders and side slopes can result in severe erosion by rainfall, road surface runoff and wind. A reduction of the pavement and shoulder crossfall to between 1.0 and 1.5 per cent reduces the velocity of runoff and minimises the potential for erosion. Sideslopes should be constructed to a maximum batter of 1: 4 or flatter (1:8 on Serowe-Orapa road in Botswana (Pinard et al, 1999). Although providing structurally sound shoulders, the problem of erosion of sand-clay shoulders by vehicles and wind generated by vehicles is severe in Australia (Jewell, 1970; Paige-Green, 1983).

Significant problems with wind erosion of sand shoulders in Australia have been observed. The wind-shear generated by rapidly moving vehicles, particularly large goods vehicles, results in detachment of sand grains from the shoulder and loss of shoulder shape. This is exacerbated on roads with reduced widths, where a tendency for vehicles to move their outside wheels onto the shoulder when overtaking results in wear of the shoulder.

The application of a bitumen seal to the shoulders, although increasing the cost of the road, significantly reduces problems related to erosion of the sand.

The establishment of vegetation to protect sand slopes on fill is usually not practical or reliable enough in the short term. Erosion can be minimised by placing a gravel cladding layer on the slopes where such material is available. Poor quality calcretes and silcretes that are not suitable for use in pavement layers will usually perform adequately as sideslope cladding in the short term while vegetation establishes itself.

5.9 Stabilization

5.9.1 General

Various types of soil stabilization have been undertaken in the Southern African region for over 50 years in a variety of circumstances and for a variety of reasons using a variety of stabilizing agents as summarized below.

Stabilizer	Type of stabilization
• Granular materials	Mechanical stabilization
• Portland cement • Lime (quicklime and hydrated lime) • Pozzolans (fly ash) • Bitumen and tar • Proprietary chemicals	Chemical stabilization

The choice of stabilizer is influenced by the properties of the material to be stabilized and the cost of stabilization. The traditional guidance to the choice of stabilizer is summarized in Figure 5-2. More recently, combinations of both bitumen and cement have been used, prompted by the evidence that suggests that adequate strengths can be achieved while cracking is substantially reduced due to a much lower cement content.

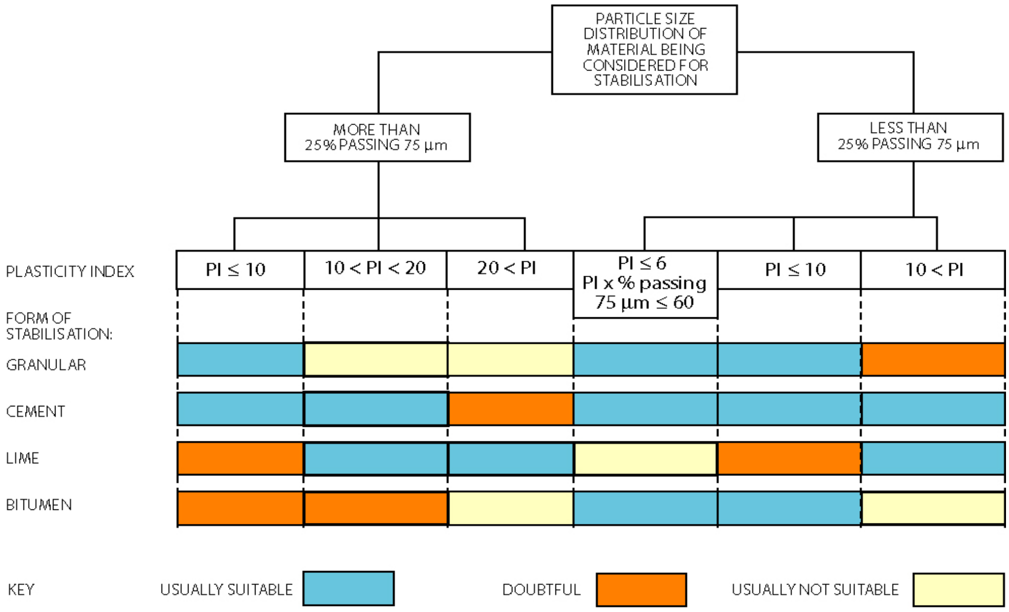


Figure 5-2: Guide to the method of stabilization (Austroads, 1998)

5.9.2 Mechanical stabilization

Mechanical stabilization is one of the cheaper means of improving the quality of sands. Such stabilization can be achieved by blending sand with other materials. For example, blending of windblown sands with between 20 and 40 per cent (typically about 25 per cent) clayey silt or clayey sand has been successfully used in Australia (Leach, 1960. In Botswana, Kalahari sands have been blended with marginal quality calcretes to improve the quality of the calcrete gravel material. Material with a plasticity index of about 9 per cent increased in CBR by about 30 percentage points to in excess of 80 per cent after blending in 20 per cent Kalahari sand (Overby, 1981; Strauss and Hugo, 1979).

5.9.3 Pozzolanic stabilization

(1) Lime: Most sands do not have sufficient clay to react adequately with lime, and cement is the usual choice for stabilization. However, should there be adequate quantities of amorphous silica in the sand it will react with the lime to form a strong material adequate for use in a LVR pavement. There has been mixed success with the use of lime in the Southern African region for which some examples are presented below.

Namibia: In the 1980s, lime was used on a sandy calcrete section of the Grootfontein-Rundu road in which both the base and subbase were stabilized (3% and 2% respectively). However, some time after construction, failures were reported and attributed to the degradation of the stabilizing agents and their cemented products through the process known as ”carbonation” which inhibits the effective formation of cementitious products in soil-cement and soil-lime reactions (Netterberg and Paige-Green, 1984).

South Africa: Bergh et al (2008) describe the effect of lime treatment on the Berea Red Sands found in South Africa for which CBR values of untreated material were between 18 and 28% at 98% Mod AASHTO and increased to in excess of 90% with up to 4% lime. Samples of the stabilised sands that were collected from these roads indicated that they were still in relatively good condition after more than 30 in service and they still exhibited significant strength. In contrast, at least one section of the a road with a lime stabilized Berea red sand is known on which scabbing of the surfacing occurred due to a weak carbonated upper basecourse (Netterberg, personal communication, 2012).

(2) Cement: Cement stabilization provides a high strength, relatively stiff and inflexible pavement. This type of structure requires good support to limit the total pavement deflection to low values and to ensure that the layers do not fail due to excessive flexing. It also usually produces marked block cracking which is often the result of traffic loads rather than shrinkage stresses (Bofinger, 1971). Such roads need to be carefully sealed to avoid water ingress and pumping of the stabilized and underlying materials. There has been mixed success with the use of cement in the Southern African region for which some examples are presented below.

Mozambique: Cement stabilization has been used extensively since the mid-1960s on a number of trunk roads in Mozambique, such as the EN1 road south of the Save river where very high cement contents (typically 8%) were required to achieve the required strength. However, such high contents of stabilizer have resulted in significant shrinkage cracking, leading to reflective cracking propagating through the surfacing and consequent high maintenance requirements (Carvalho, undated).

Examples have also been reported of failures in the top few millimeters immediately beneath the surfacing layer of sands stabilized with 2% cement (Carvalho, undated). This had caused the surfacing to become loose, followed by a tendency to strip off. Although not diagnosed as such, this type of failure has the hallmarks of degradation of the pavement layer due to carbonation as now reported by Paige-green at al, 1990.

More recently, cement stabilization has been the subject of research which aims to characterize cement stabilized sand bases under Accelerated Pavement Testing (de Vos, 2007). The main objective of such work is to develop more appropriate pavement design methods for Mozambique which take account of the mostly single sized sands found in the coastal plains and dunes in the country. The development of these new designs is still a work in progress.

Botswana: Cement stabilization has hardly used in Botswana. There is one reported example of a 25km section of the AI highway between Artesia and Dibete which was stabilized with 3% cement and which has apparently performed satisfactorily for more than 25 years. However, there was scabbing of the surfacing in areas due to a weak, carbonated upper basecourse (Netterberg, personal communication, 2012.

5.9.4 Bitumen

Bitumen is used commonly as a stabilizing agent for many materials. However, it is noteworthy that neither of the older Guides to Bitumen Stabilized Materials (GEMS) (Sabita, 1993) or bitumen modified bases (ETB) (Sabita, 1999) include the possible use of sands, probably more through a lack of information than by design. Even the most recent guideline (Asphalt Academy, 2009) excludes the use of sands. Despite this, successful stabilization of sands has been carried out in a number of countries in Southern Africa and the use of foamed bitumen is increasing in popularity and success with this technique using sands for low volume roads has been reported (Paige-Green and Gerryts, 1998). Some examples of the use of bitumen for stabilization of sands are presented below.

Mozambique: In Mozambique hot sand asphalt was used up to the early 1970s before the war of Independence (van Wijk and Carvalho, 2003). More recently, cold bitumen sand mixes (BSM) also referred to as sand treated with emulsion (STE) were constructed as a demonstration project at Marracuene (Guiamba et al, 2010) with the aim of producing a relatively flexible bitumen emulsion/sand admixture (5.6% emulsion) that would be more forgiving to axle overloading and less susceptible to shrinkage cracking commonly associated with cement stabilization. *What is most interesting is that these sands were described as having a red colour, similar to the Berea red sand in South Africa, and were non-plastic (on the 0.425 mm sieve) with 8 – 14.4% passing the 0.075 mm sieve – properties which, on the basis of limited experience from Botswana, could well be adequate for use as an untreated base course for a low volume road.*

Namibia: Various types of sand bitumen stabilization have been carried out in Namibia over many decades using cutback tar and bitumen (emulsion and foam) (Dierks, 1992). For example, on trunk road 8/6 from Kongola to Katima Mulilo (Trans-Caprivi Highway) a mixture of Kalahari sand and calcrete nodules were stabilized with a relatively small amount of bitumen (Strauss and Hugo, 1979) and the road is reported to have performed satisfactorily over its design life.

Botswana: Bitumen stabilization has been undertaken only in the form of experimental sections. Such trials were undertaken at Jwaneng in 1980 where both in situ cold mix and foamed asphalt was used and on the Serowe-Orapa road where various percentages of bitumen emulsion were used with different types of sand. The lessons learnt from the monitoring of these sections indicated the scope for using this type of stabilization on full scale projects (Netterberg, 1998).

South Africa: Bergh et al (2008) describe the effect of bitumen emulsion treatment on the Berea Red Sands. The materials tested had CBR values of 30 to 60 % in the untreated form which increased to between 58 and 70% on treatment with between 1 and 2% anionic bitumen emulsion with 1% cement. It was notable that by adding some -9.5 mm graded aggregate, both the natural and emulsion treated CBR strengths increased significantly (73 to 96 and 112 to > 120% respectively).

5.9.5 Bitumen and cement: In recent years, bitumen emulsion has become more readily available and is increasingly being used together with cement for stabilization of sands. International evidence suggests that adequate strengths can be achieved, and cracking can be substantially reduced, due to a much lower cement content. However, there is still insufficient experience to determine whether pavements constructed in this way will be sufficiently durable over the intended life of the road, and to establish optimal proportion of cement and bitumen binder.

Mozambique: Bitumen/cement stabilization was undertaken on the section of the ENI between Chicumbane and Xai Xai where 2% cement and 3% bitumen were initially used but subsequently changed to a more conservative 3% cement and 3% bitumen due to uncertainties over the long term durability the cement/bitumen emulsion combination of stabilizing agents. Significant sections of the road were surfaced with a chip seal and other section with hotmix asphalt.

Disconcertingly, a number of failures occurred along the recently completed Xai Xai Chizabuka section of the road in Gaza to complete failure of the Gorongoza-Caia section in Sofala and the Macomia-Oasse road in Cabo Delgado. The reasons for such problems have still not been ascertained and are the subject of on-going investigations.

Namibia: In the upgrading of the Trans-Caprivi highway, both cement and bitumen emulsion were used for stabilization of the sandy-calcrete reclaimed old sand asphalt basecourse-Kalahari sand pavement. However, even during construction, failures occurred for a variety of reasons including inadequate mixing of the stabilizers, carbonation of the upper base layer, etc.

5.9.6 Other

(1) Polymers: There have been other instances where the quality of sands has been improved using different forms of stabilization. These include the use of proprietary chemical soil stabilizers and polymers which were investigated in Namibia (Mgangira, 2007) and from which it was concluded from laboratory results that some Kalahari sands have the potential to improve their performance when treated with synthetic polymers. However, the use of such polymers in the field and their long term performance and cost-effectiveness are yet to be ascertained.

(2) Tar: Although there have been many cases of the use of coke-oven tar being used as a stabiliser for road materials including sands (1970-1990), its use is not discussed further in this document owing to recent limitations on the use of tar due to its potentially detrimental health effects.

(3) Geocells: These are essentially a form of cellular confinement comprising a geo-synthetic material designed to confine soil or other cohesionless material. After tensioning, granular material, coarse aggregate or lean concrete is vibrated into the cells to produce a load distributing pavement layer.

Geocells have been used in a variety of applications in Southern Africa for which a number of case studies have been reported (Visser, AT and Hall, S. 2003). Geocells also find application in situations where very steep grades preclude the use of either gravel or bituminous surfacings. Although geocells are potentially suitable for use with sand for low volume roads, there are no reported full-scale examples of this application in the SADC region. However, interestingly, the US Corps of Engineers report in a sand road case study (Presto Products Company, 1991) the successful use of sand as the infill material for their Geoweb Cellular Confinement System (a type of geocell) in the construction of roads in the Algerian Sahara Desert.

Sand filling of geocell by front end loader

Use of sand-filled geocell by 40 tonne truck

5.9.7 Summary of experience with stabilization

Experience with the use of chemical stabilization as a means of soil improvement in Southern Africa has been very mixed. As a result of a number of reported failures in the region, studies were carried out by the CSIR for the South African Roads Board (South African Roads Board, 1990). These studies indicated that road failures could be attributed partly to the degradation of the stabilising agents and their cemented products through a process known as “carbonation” (Netterberg and Paige-green, 1984) in which distress manifests itself in roads constructed with stabilized bases as follows:

- Surface disintegration of the primed base during construction
- Loss of the seal during service
- Partial or complete loss of cementation and strength
- Rutting, shearing, pumping and cracking
- Increasing plasticity index

The above are inter-related effects since some lead on to others. The effects suggest that carbonation can contribute to premature distress in some circumstances.

As a result of reports circulated at that time to road authorities both in South Africa and elsewhere in the region, there was a general loss of confidence in the chemical stabilization process and some countries in the region discontinued the use of chemical stabilization in road projects.

Further studies carried out by the UK Transport Research Laboratory on the *Performance of Chemically Stabilised Road Bases* by the UK Transport Research Laboratory (Gourley and Greening, 1999) have indicated that road failures could be attributed partly to the degradation of the stabilising agents and their cemented products through ‘carbonation’. However, they also emphasized that there are also many examples within Southern Africa where the use of chemical stabilization has been very successful, even on roads that have received little maintenance. This conflicting evidence has resulted in considerable uncertainty about the use of stabilization as an option for road projects.

More recently, a literature survey undertaken as part of a major project on the *Performance Characterisation of Cement Treated Sand Base Material of Mozambique* (de Vos, 2007). concluded that:

- A number of pavement design methods used worldwide are being used in Mozambique. Some are not necessarily applicable to Mozambican conditions resulting in the implementation of inappropriate designs and construction techniques leading to poor performance.
- The South African Mechanistic Design Procedure (SAMDP) is extensively used in Mozambique. However, the SAMDP is based on transfer functions developed for South African materials and conditions that have been found inappropriate for Mozambican conditions.
- The lack of knowledge about the appropriate engineering properties of locally available road building materials, mostly sands but also finely graded materials, is the main cause of unsuccessful projects. Main contributors to the premature failures of pavements appear to be:
    - specification of incorrect type of stabliser or incorrect stabilizer content;
    - inappropriate construction practices;
    - lack of understanding of behaviour and the long term performance of the materials;
    - very high axle loads and extreme climatic conditions;
    - inability to maintain roads due to lack of funds.

In view of the very mixed experience with the use of various stabilizers for use with sands and other materials in Southern Africa, it is apparent that there is an urgent need to undertake a study with the following objectives:

a) Establish reasons for the disparate performance of chemically stabilised road bases in the region

b) Evaluate the performance of chemically stabilised sand road bases in relation to current pavement design criteria

c) Make recommendations and provide guidelines for the chemical stabilization of sands/sandy materials which are based on performance data, so that confidence is restored in this method of improving sands for use in road bases in the region for both low volume and high volume roads.

The above study would be most beneficial to a country such as Mozambique where sand is generally the only type of material that can be used for road construction in much of the country.

6. CONSTRUCTION ISSUES

6.1 Introduction

Previous research work shows that the selection of sands for road construction should be based on criteria other than the conventional material properties. In Australia, sands have been classified using traditional sedimentological parameters (Metcalf and Wylde, 1984). On this basis, fine-grained, uniformly graded (poorly sorted0 materials that were linked to pavement failures were excluded. The technique uses the sedimentological Φ-scale ($\Phi = -\log_2$(particle size in mm)) (Paige-Green and Pinard, 2011) and characterises the material by its mean particle size (in Φ units) representing the fineness of the material, and the standard deviation of the grading (in Φ units) representing the degree of sorting of the sand.

6.2 Material Selection

Figure 6-1 shows the selection of materials based on the sedimentological parameters discussed above. Other parameters related to grading are the skewness and kurtosis, which are used extensively in sedimentology to identify specific properties and for the comparison of different sands (Krumbein and Sloss, 1963; Mayer, 1986). The Coefficient of Uniformity is another grading parameter that deserves attention in the specification of sandy soils (Utiyama et al, 1977)

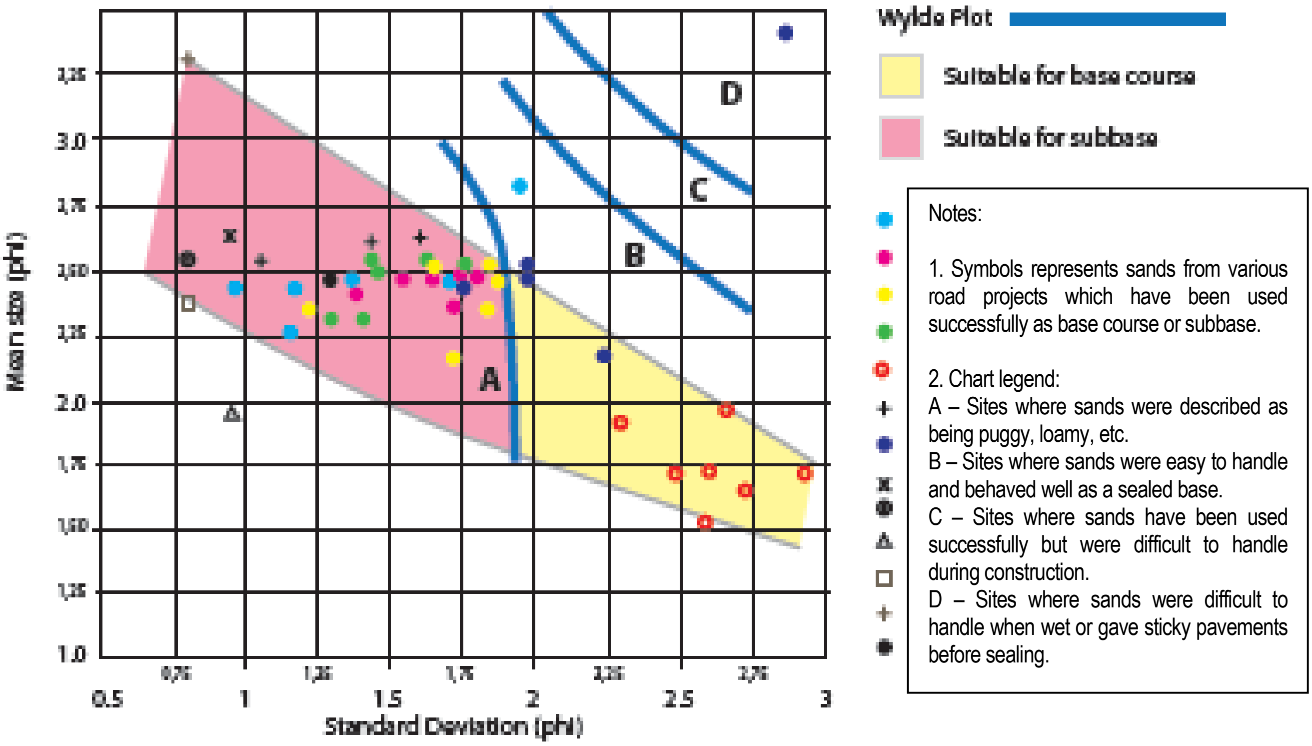


Figure 6-1: Classification of sands based on grading (Metcalf and Wylde, 1984)

In New South Wales (Australia), the 'T' value (a value derived from the deviation of the grading of the soil mortar from the maximum density grading) is used as an indication of whether a material will perform satisfactorily (Murphy, 1981; Giffen et al, 1978).

Despite the preceding discussion, the proposed Brazilian specification is based on traditional test methods including grading, Atterberg Limits, CBR and CBR swell (Utiyama et al, 1977). These require 20 to 45 per cent passing the 0.075 mm sieve, 85 to 100 per cent passing the 0.425 mm sieve, a plasticity index of 6 to 9 per cent, a minimum CBR of 80 per cent and a maximum CBR swell of 0.1 per cent.

The use of the Western Australian Confined Compression Test (WACCT) or Texas Triaxial Test should be investigated for use in Southern Africa (Zimbabwe makes extensive use of the Texas Triaxial Test), particularly for marginal and non-standard materials.

6.3 Construction Considerations

6.3.1 General issues

General guidance for construction in Kalahari sand is provided by the Zimbabwe Manual – Part F: Construction (Ministry of Roads and Road Traffic, undated) and may be summarized as follows:

- Due to the unstable grading and non-plastic properties of Kalahari sand, it is not considered practical or economical to attempt earthworks operations except during or soon after rains.
- As soon as the natural moisture content to a depth of at least 1 m below ground level reaches the limit at which compaction may be attempted, then the road bed must be compacted using the heaviest plant available. This will generally cause the road bed level to drop at least 100 – 150 mm.
- Fills should be kept as low as possible and formed with borrow material. Side drains will only be cut where necessitated by natural cross-fall. It will be sufficient if the lowest edge of the subgrade is kept 75 mm above original ground level. High fills may be compacted in large lifts or more using the appropriate (impact) compaction equipment.
- Particular care should be taken on all cuts and fills to avoid erosion damage and reinstatement of natural grass cover should be encouraged. Fills greater than 1.5 m in height should be clad with suitable cohesive material as soon as possible after construction.
- The sand subgrade cuts easily under traffic, and it is, therefore, necessary to keep the sand wet and graded to shape immediately in front of lorries dumping.
- Fill or shoulder slopes constructed of the lighter soils, unless cladded will usually require protection from road water, particularly on curves. This can be achieved by means of kerbed and channel shoulder drains discharging at intervals into paved flumes which carry the water beyond the toe of the slope. The whole slope must be planted with a suitable grass, a practice which is desirable on all fills, of whatever material.
- The face of every cut must be protected from surface water by means of cut-off drains.
- Where cuts have a large surface area in plan, it may be desirable to provide surface water drainage, by means of benches at a suitable slope, to take water to the extremities of the cut. Great care is required to ensure that these drains will neither silt up nor erode, otherwise, they may do more damage than they are designed to prevent.
- Erosion control in side drains having steepish grades is best achieved by paving or cement stabilizing the drain.

In order to maintain its density and strength, sand needs to be confined. This can be achieved by keeping the pavement levels as low as possible, but this is not always desirable, as the pavement drainage characteristics are reduced. By widening the layer to be compacted and using flat side slopes, a similar effect can be achieved whilst improving the pavement drainage and overall structural capacity. It can, however, be difficult in many circumstances to achieve high densities with fine materials (Murphy, 1981) but as high a density as possible should be achieved. Frequently, compaction of fine materials results in poorly bonded lenses, compaction planes and layers of fines on the surface – in these cases, the top 10 to 20 mm should be cut to waste (Murphy, 1981) and provision for this should be made.

Removal of the collapse potential of the sands requires a high degree of compaction. Using conventional plant (ie, heavy vibrating rollers), the application of large quantities of water is necessary. Where compaction water is scarce or expensive, high-energy impact compaction is a cost-effective solution. Sands should be compacted to at least 90 per cent Mod AASHTO to a depth of 500 mm below the fill or selected layers and to at least 95 per cent Mod AASHTO for the upper 150 mm of this layer. It is recommended, however, that the material is compacted to refusal for the heaviest plant on site provided that this density is equal to or exceeds that specified above.

It has been suggested that the bulk of the collapse potential of sand subgrades be removed from the upper 700 to 1000 mm of the subgrade to ensure stability of the pavement structure (Giffen et al, 1978; Weston, 1980). This is normally difficult to achieve with conventional plant, although good results have been reported by Mainwaring (1968), Weston (1980) and Schwartz et al (1981). This typically requires that the sand is brought to a relatively high moisture content prior to compaction – often a costly and time consuming exercise in hot, arid environments. In these cases, construction should be programmed to ensure that subgrade compaction is carried out primarily during the rainy season.

The use of high-energy impact compaction on these sands has produced good results (Pinard et al, 1999; Wolmarans and Clifford, 1975). This type of compaction produces much deeper effect than conventional plant and relies on high energy to collapse the materials instead of moisture. Significant economies in terms of water usage are thus achieved.

The compactability of sandy materials has been related to the Fineness Index (Table 6-1) (Baart, 1961; Mainwaring, 1968).

Table 6-1: The relationship between compactability and Fineness Index

Fineness Index	Compactability
< 200	Good – suitable as subgrade with in situ compaction
200 – 400	Water penetration difficult for in situ compaction; Not suitable as subgrade; May be used as fill
> 400	Poor workability; sponges under roller; not suitable for fill

A frequent problem observed during the compaction of essentially uniform sized sandy materials is the tendency for shearing of the material during compaction, particularly when excessive vibration is used (Chauvin, undated; Murphy, 1981). The use of heavy static rollers at slow speeds can overcome this but generally, it is necessary to carry out compaction trials using combinations of padfoot or grid rollers, pneumatic tyred rollers and vibratory compactors of different sizes to determine the optimum combination. Generally high amplitude, low frequency vibrating roller operations are more likely than low amplitude (< 1.1 mm), high frequency (> 35 Hz) operations to cause shearing (Murphy, 1981).

The compaction moisture content is also critical and although various proposals between 60 and 100 per cent of Mod AASHTO OMC are suggested, there appears to be no general recommendation. In Queensland, Australia, it is suggested that non-plastic sands are compacted at 60 per cent of OMC (higher than this results in excessive movement under the roller) but the more plastic sands (PI 3 to 4) should be compacted at about 40 per cent of OMC (Paige-Green, 1983). One of the compounding factors may be that the optimum moisture content differs for different compaction efforts and that determined in the laboratory may or may not necessarily be applicable for the plant actually used on site. Compaction trials are the best way of determining the optimum moisture content for any combination of plant. The Australian technique for this is to prepare strips of material at various moisture contents, partly compact these with the same number of roller passes and find the one with the highest density (i.e. optimum moisture content (OMC) for the plant used). Compact a further test strip at the identified OMC to determine the optimum number of passes to achieve maximum density (Wylde, 1979).

It has been found that by allowing the material to dry back to a moisture content of between 2 and 4 per cent before priming, the reflection of long term shrinkage cracks through the seal can be avoided (Sandman et al, 1974).

The use of dry compaction (i.e. at natural moisture content, which could be between 1 and 3 or 4 per cent) can produce the same density as conventional compaction at OMC. The air voids are, however, significantly higher in this material and the benefit of suction forces developed during drying back of moist compacted materials is lost. The implications of this should always be considered when dry compaction is a possible option. These materials are usually more porous than when wet compacted (Murphy, 1981). Dry compaction is used extensively for subgrades in the Sahara, where water is at a premium, with apparently good results (Horta, 1987).

Trials using bitumen stabilized sands in northern Namibia in the 1960s (Marais and Freeme, 1977) indicated that a number of techniques were necessary to facilitate construction. These included:

- Working of sand at 10 to 12 per cent moisture to allow plant to move on it;
- Use of pulvimixer and grader to mix the bitumen adequately;
- Aeration of the mixed material with a disc harrow to attain adequate stability;
- Control of “conditioning” period before compaction using vane shear test;
- Compaction with a sheepsfoot and 30 tonne pneumatic tyred roller;
- Allow cutback prime time to penetrate before applying Kalahari sand as aggregate.

6.4 Drainage

The drainage of pavement structures containing sand layers is imperative. However, it has been suggested (Overby, 1990) that side-drains should be avoided where possible to reduce the likelihood of water ponding. Depressions within the road reserve should be levelled.

Where rock or hardpan layers, such as of calcrete or silcrete occur at shallow depths beneath surficial sand, the possibility of perched water tables is high. Under these situations, precipitation frequently lies at the surface for weeks or even months and can result in severe softening and/or collapse of poorly compacted sand layers. The importance of appropriate drainage cannot be overemphasised. Attempts should be made to fracture hardpan calcrete or silcretes layers forming perched water tables using high energy impact compaction or heavy vibrating rollers, in order to reduce the possibility of their stopping the infiltration of water.

It is interesting to note that where there is a possibility that the water table rises within 600 mm of the finished road level, the use of untreated Kalahari sands in Zimbabwe is not permitted (Mitchell, 1982).

7. SUMMARY OF TECHNICAL REVIEW

7.1 General

The technical review of the use of sands in road construction was informed by a large number of references, some seventy, that were collected as part of a comprehensive literature survey and desk study. Many of the references were reviewed previously in the development of the Botswana guideline on *The Use of Kgalagadi Sands in Road Construction.* However, this guideline focused on the use of one type of sand – Kgalagadi (Kalahari) sand – in a specific geographical area – Botswana. In contrast, the current guideline focuses on all types of sand found with a vast geographic area – the SADC region which occupies all of southern Africa. As a result, the review of the documentation collected was much wider ranging than that for the Botswana guideline.

7.2 Outcome

The outcome of the technical review has revealed a number of interesting facts concerning the use of sand in road construction which will provide valuable inputs to the development of the SADC guideline. These may be summarized as follows:

Occurrence and properties

(1) Vast areas of the southern Africa region are covered by extensive deposits of both Kalahari and coastal sands. The properties of these sands vary widely in relation to their geology and origin which affects their mineralogical composition and engineering properties ultimately influences their suitability for use in the different layers of a road pavement.

Classification

(2) Various systems are used to classify sands including, commonly, the AASHTO Classification System, the Unified Soil Classification System (USCS) and the British Standard System. The less commonly used Wentworth Particle Size Classification System which is based on the **"Φ sediment size scale"**, has been used both in Australia and Botswana for improved selection procedures of sand in road construction. This system offers scope for further customization to the SADC region.

Physical

(3) **Colour:** Evidence from a number of road projects in Botswana indicates a rough correlation between sand colour (reflective of iron oxide content) and other engineering properties such as grading, plasticity, strength and compactability. This correlation will be further tested on the basis of the results obtained from the wide range of sand types being investigated.

(4) **Grading:** Knowledge of the grading of sand is one of the most valuable guides to its engineering behaviour. Sands derived from different origins (i.e. sands of aeolian origin versus sands of mixed origin), exhibit different gradings which have a bearing on their suitability for use in various layers of a road pavement.

(5) **Plasticity**: Determination of plasticity in the traditional manner, i.e. on material passing the 0.425 mm sieve (P425), invariably tends to mask the plasticity that can be mobilised in the silt and clay fraction of sand (P075). Most sands show non-plasticity on the P425 fraction but significant plasticity on the P075 fraction *which is of critical significance when the sands are being considered for use as construction materials.*

(6) **Particle shape**: Sands exhibit a wide range in particle shape (angular, sub-angular, sub-rounded, rounded, well rounded) which is influenced by their mode of formation and, in turn, which influences their compaction characteristics and related strength and bearing capacity.

Mineralogy and chemistry

(7) A knowledge of the mineralogy of sand can assist in assessing its suitability for use in the various layers of a road pavement. The amount of iron and/or aluminum oxides appears to be strongly correlated with its strength (CBR), i.e. the higher the oxide content, the higher the CBR value is likely to be.

Engineering

(8) **Collapsible sands**: Certain types of sand exhibit a so-called "collapsible fabric" (essentially a highly voided, open structure which is held together by colloidal bridges of clay and iron oxide or hydroxide) and are prone to collapse upon wetting and/or imposed loading. However, the cost of rectifying this type of problem for LVRs is unlikely to be warranted.

(9) **Permeability**: In general, the permeability of a sand is inversely related to its plasticity, i.e. the higher the plasticity, the lower the permeability. Thus, some sands are not free draining – a factor that has important implications for the use of such materials in road pavements, particularly as regards the measures required for dealing with permeability inversion.

(10) **Suction**: The development of soil suction allows some sands (those with relatively high plasticity and related cohesion) to generate relatively high strengths in service as they dry back from their compaction moisture content. However, this "dry" strength can only be relied upon for pavement design purposes if measures can be put in place to prevent loss of this elevated strength by wetting up of the material.

(11) **Erodibility**: The erodibility of sand depends on its texture and physical properties. In general, sands with a high percentage of fine sand and silt fractions tend to be the most erodible whilst those with some plasticity provide a natural cohesion and are less prone to erosion. For the erodible sands, particular attention needs to be given to provision of erosion protection measures and the adoption of an appropriate road cross section (as shallow side slopes as possible).

Testing of sands

(12) **Test methods:** There are significant differences between certain test methods specified by the BS standards and the TMH or SAN methods, particularly with respect to the Liquid Limit and related plasticity index and bar linear shrinkage It is therefore important not to mix test methods because the differences in test procedure will result in quite different results.

(13) **Grading:**
In order to ensure that all cementing bridges are broken and that the small quantities of plastic fines are released for determination of the Atterberg Limits, the grading of sands should always be carried out using a wet preparation method and ensuring that the additional sieves between 2mm and 0.075mm are included. Where the fraction passing 0.075 mm exceeds about 15 per cent, a hydrometer analysis also needs to be carried out. This will give a better indication of the distribution and sorting of the material.

(14) **Atterberg Limits and Linear Shrinkage:** It is imperative that the Atterberg Limits are determined on the fraction finer than 0.075 mm (in addition to the standard 0.425mm sieve) , this invariably giving a Fineness Index (FI) in the range 5 to 20 per cent which would not be measurable on the fraction finer than 0.425 mm. When used to determine the Fineness Index (FI) of the sand (the product of the PI on material passing the 0.075 mm sieve and the percentage material passing the 0.075 mm sieve) this property can provide a useful indicator of the compactability of the material.

(15) **Compaction**: The laboratory compaction of many sands using dynamic compaction methods can be difficult, producing unreliable results due to shearing of the material during compaction. Thus, the use of the BS 1377 vibrating hammer method is recommended.

(16) **Strength**: The strength of sands appears to be very moisture dependent, and during strength testing, the sensitivity of the specific sands to moisture should be evaluated as a basis for determining the appropriate strength for pavement design purposes.

Specification of sands

(17) General

Specifications for the use of untreated sand in road bases have existed in Zimbabwe, Australia and Brazil for many years. More recently, performance-based specifications for Kalahari-type sands have been developed from research carried out in Botswana and provide a point of departure for assessing the suitability of other sand types in the region for use in the various layers of a road pavement.

Use of sands

(18) Fill and selected subgrade

Experience from many countries in the region has shown that most types of sand can be used successfully as fill or selected subgrade provided they are adequately compacted and confined.

(19) Subbase

Sand has been used successfully as subbase in a number of countries in the region, although they do not comply with the standard specifications, generally on the basis of inadequate grading modulus (minimum of 1.5).

(20) Base

Botswana is one of the few countries in the region where untreated Kalahari sand has been used successfully as basecourse in an experimental 100 m section, although sands have been used extensively in Australia. The reason for the good performance has been attributed to the high suctions that the materials have (due to their fine grading and the plasticities of the minus 75µm fraction) and the resulting high strengths when dry. Investigations are underway in Mozambique, Namibia and South Africa to ascertain whether untreated sand has been used as basecourse in these countries and, if yes, for further back analysis and comparison with the Botswana sands and related specifications.

(21) Surfacing

Kalahari sand is too fine and uniform for use in surface treatments or for sand seals. However, they have been used with some success as a cover seal to Otta Seals and on a sand asphalt base course.

(22) Stabilization

Sands in the region have been stabilized with lime, cement, bitumen and a combination of these stabilisers in an attempt to improve their properties for use in road pavement layers (subbase or base course). However, for a number of reasons, the outcome of such initiatives has been very mixed and it is apparent that there is a need to establish reasons for the disparate performance of chemically stabilised road bases in the region.

8. SAND SAMPLING AND TESTING PROGRAMME

8.1 Introduction

As indicated in Table 1.1, Stage 2 of the project requires the development of a sand sampling and laboratory testing programme as a basis for undertaking the subsequent field sampling and laboratory testing. Accordingly, this section:

(a) Outlines the general approach adopted in determining the locations of the sand samples to be collected;

(b) Presents the locations of the sites from where the sand samples are to be collected;

(c) Presents the programme for the laboratory testing of the sand samples.

8.2 Sand Sampling Locations

8.2.1 General approach to determining site location

The sand sampling sites have been identified on the basis of expected differences in the sand properties and with the objective of achieving as wide a geographical coverage as possible. The sites were selected based on consideration of the following:

- satellite imagery,
- soils and geology maps,
- local information from the roads agencies
- discussions with other individuals familiar with the local terrain

The southern African maps provided by Brink (Figures 1-1 and 2-2) proved a good basis for differentiating between the sand types in the Mozambique and Namibia. Once the different areas had been delimited on the maps, GoogleEarth was used to identify the proposed sample sites within each area. Potential problems with collecting and removing samples from conservation areas also influenced the selection of the sampling sites.

In order to ensure that the samples were representative of those likely to be used in practice, existing (old) borrow pits that could be located on GoogleEarth were used as far as possible. This will facilitate relatively easy access to the sites without requiring significant off-road equipment or experience.

8.2.2 Site locations - Mozambique

The majority of sands in Mozambique occur in the southern half of the country, although the coastal sands re-appear in the extreme north eastern areas running into Tanzania. Sampling was thus mainly centred in the coastal areas of the south and eastern regions and the interior fluvio-aeolian sands.

Borrow pits are scarce and the vegetation cover is significantly thicker than in Namibia. Access in the sandy areas of the country is also somewhat limited. For this reason, many of the samples need to be collected from adjacent to the roads where identified, by removing the upper organic/topsoil horizon and then obtaining the sample (probably at depths of about 500 mm – the actual depths will be recorded).

The sites proposed for sampling are pin-pointed on the Google Earth map in Figure 8-1 (m38, m39, etc.) and exclude a further 10 samples that should also be obtained from the previous and on-going TRL experimental sections. The co-ordinates of the sampling locations are presented in Annex 8-A. These coordinates are not meant to precisely locate the sand sample location. Rather, they provide guidance on the approximate location of the sample which will depend on the prevailing ground conditions and other related considerations.

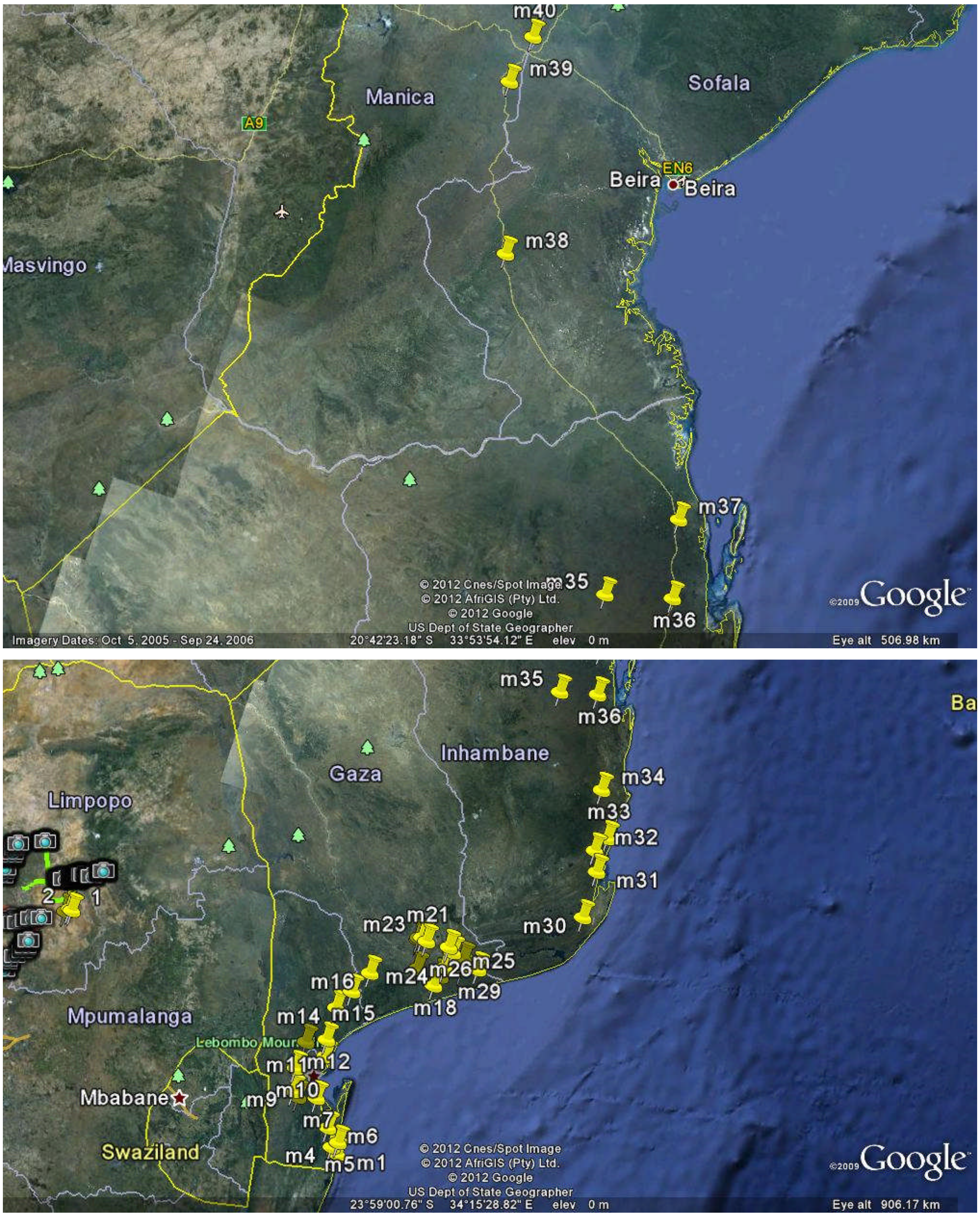


Figure 8-1: Location of sand samples in Mozambique (truncated map)

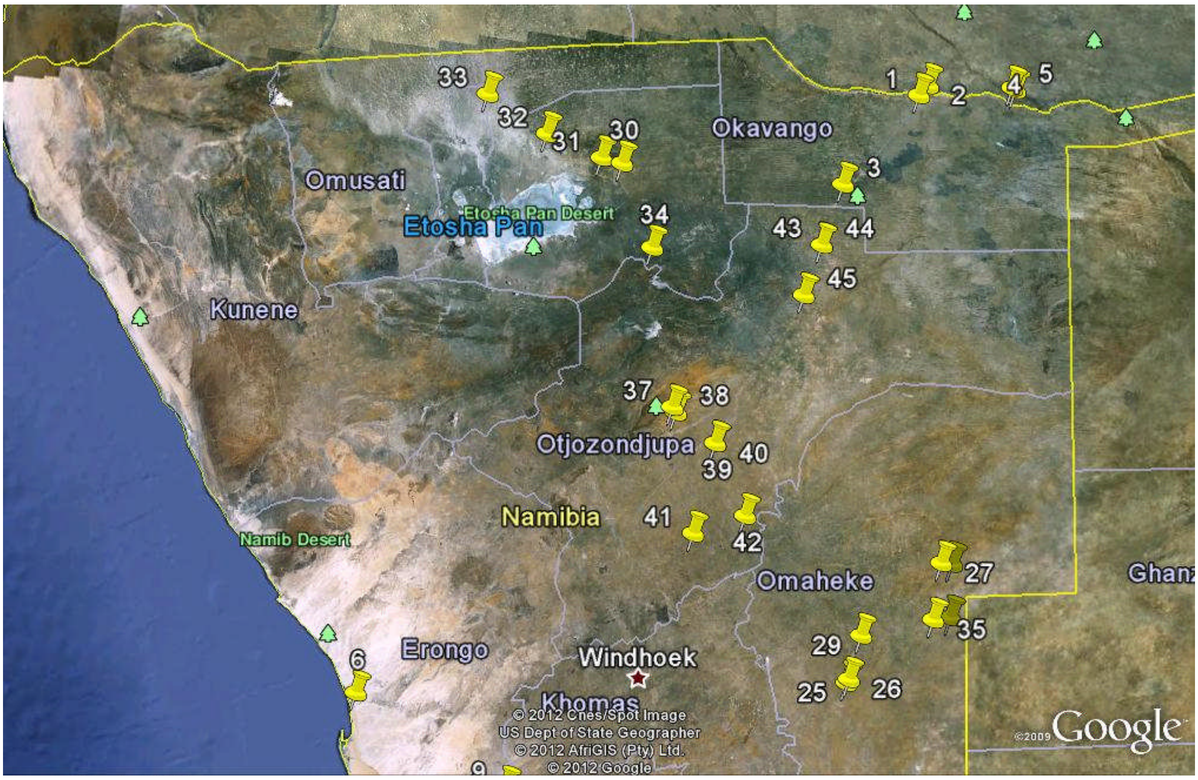
8.2.3 Site Locations - Namibia

Based partly on Baillieul's map of sands of Botswana (Figure 2-3), it appears that the different sands identified by him in the north-west and western areas of Botswana (Areas I, II and III) extend into Namibia with similar properties.

The three zones of interest in Botswana that extend into Namibia, together with the young sands of the Namib Desert, and the likelihood that the sands in the northern part of Namibia probably differ from those more eastwards, result in a total of 6 zones for sampling.

It is likely that the sands in the eastern Caprivi area may differ from the six zones proposed for sampling, although they do abut against Areas I and II identified by Baillieul. However, sands in this area are not being sampled for logistical and cost reasons as well as the likelihood that the potential degree of development in this highly elongated area does not warrant their investigation.

On the above basis the sites proposed for sampling are pin-pointed on the Google Earth map shown in Figure 8-2 while the co-ordinates of the sampling locations are presented in Annex 8-B.



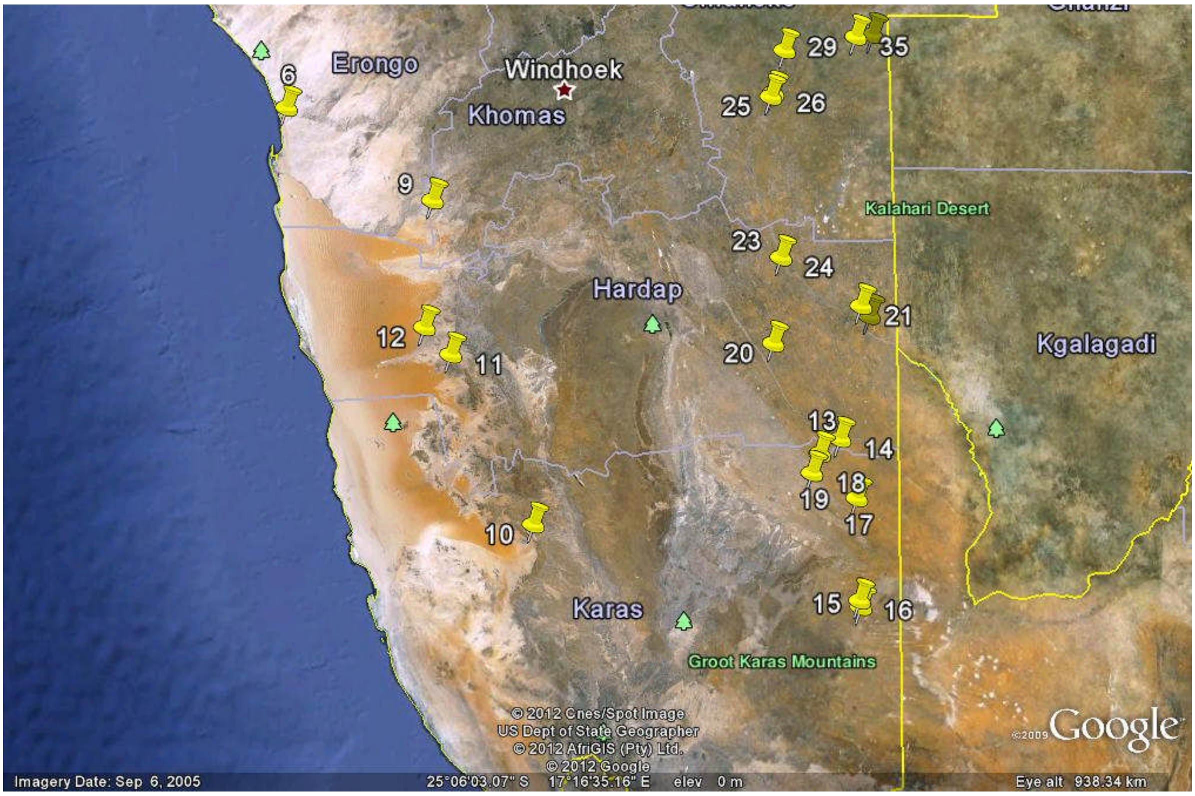


Figure 8-2: Location of sand samples in Namibia (truncated map)

8.2.4 Site Locations – South Africa

The project plan does not include routine samplin in South Africa. Only sampling of roads in which sand has been utilised as a neat base course is required. Discussions with staff of the Kwazulu Natal Road Department have so far failed to identify any roads using Berea Red Sand as base course. Discussions in this regard are continuing.

8.3 Sand Sampling Procedure

8.3.1 Off-Road Sand Sampling

The sampling procedures to be followed at each site will be as follows:

1 The sample should be taken from the site at a depth of between 400 and 600 mm beneath the existing surface.

2. The site should be inspected and materials that appear to be most suitable for construction should be sampled. This decision should be based on the materials being as widely graded as possible (in other words, containing material finer than 0.075 mm and preferably extending over a relatively wide particle size range within the sand, silt and clay-sized definition).

3. Where dunes are sampled, the more widely graded material normally located at the base of the dune or in the “streets” between the dunes should be sampled – if in doubt more than one sample (that appear visibly different in colour or grading) should be obtained.

4. Each sample should consist of 10 kg of material. Where an obvious shortage of fines is observed, a larger sample should be collected to ensure that sufficient sample for the testing of the -0.075 mm fraction is available. It could be useful for such materials to actually screen some material through a 0.425 mm sieve on site to provide about 1 kg of fines in order to reduce the mass of sample that will need to be transported.

5. Each sample must be identified with a label indicating its exact location, date of sampling and depth, with one label inside the sample bag (preferably a relatively thick 40 – 50 µm transparent plastic bag) and a second identical label attached to the cable-tie used to seal the bag.

6. The samples from each leg of the trip should all be sealed in larger bags in batches of 4 or 5 samples.

Logging of Samples: Table 8-1 illustrates by example the manner of logging of each of the sand samples collected.

Table 8-1: Manner of logging sand samples

Date	11 April 2012	11 April 2012
Sample Number	12	13
Location	25 ° 30 ' 14.26" S	25 ° 31 ' 32.54 " S
	18 ° 24 ' 32.78" E	18 ° 33' 18.99 " E
Depth (from – to mm)	400 - 700	200 - 400
Munsell colour as collected	Orange brown	Dark grey
	Dry	Moist
Comments	In borrow pit at worked area. Recent use. No evidence of standing water	Next to Road 4589. Eroded area. Not use for

8.3.2 On-road sampling

Three large bulk samples (50 kg) will be obtained from up to three sections of road in Mozambique, Namibia and South Africa where sand has been used as basecourse. These locations will be advised by the respective roads agencies in these in advance of commencement of the fieldwork.

Visual Pavement Condition Survey: A visual pavement condition survey will be undertake for a distance of 10m on either sand of the sand sample extracted from the pavement. The main features of the pavement condition to be recorded in accordance with TMH9 (1992) are indicated in the Visual Pavement Condition Survey Form presented in Annex C and may be summarized as follows:

(1) General Information
(2) Visual assessment
(3) Structural assessment
(4) Date of construction and traffic carried

8.4 Laboratory Testing

.

(a) Sand samples from open ground – approx. 100 No.

- Sieve analysis (SANS 3001: GR1).
- Hydrometer analysis (as provided-proposed new SANS method).
- Atterberg limits and bar linear shrinkage on both the -0.425 and -0.075 mm fractions (SANS 3001 :GR1 2).
- Cone liquid limit (using BS 1377-2: 1990 (4.3)).
- Apparent relative density on up to 50% of the samples (SANS 3001: AG21).

(b) Sand samples from existing paved roads – Maximum 9 No.

- All tests listed in (a) above.
- MDD/OMC and CBR.

(c) Specialized testing

- On certain selected samples specialised testing will be requested.

Notes:

(1) Testing should follow SANS 3001: GR1 (wet preparation and grading), GR3 (hydrometer), GR10 and GR12 (Atterberg limits and linear shrinkage) and GR30 (compaction characteristics) where available, otherwise TMH 1.

(2) Specialised test methods will be supplied as necessary.

(3) All unused and used material shall be retained until the project has been completed and the Client is satisfied with the report.

Annex 8-A – Sample sites in Mozambique

Site Number	Latitude (° ' " S)	Longitude(° ' " E)	Comments
m1	**26° 51' 03.09"**	**32° 52' 42.44"**	Ponta do Ouro
m2	**26° 51' 01.70"**	**32° 52' 30.76"**	W of Ponta do Ouro
m3	**26° 50' 46.86"**	**32° 51' 13.75"**	Kosi Bay – Ponta do Ouro road
m4	**26° 47' 10.95"**	**32° 48' 38.40"**	Road 201 S of Pedro
m5	**26° 44' 08.45"**	**32° 52' 34.08"**	E of Pedro
m6	**26° 36' 03.69"**	**32° 44' 55.72"**	NE of Camezane
m7	**26° 19' 22.69"**	**32° 35' 53.93"**	Road 202 NW of Bela Vista
m8	**26° 19' 46.65"**	**32° 23' 36.70"**	Road 202 SE of Matias
m9	**26° 16' 40.7"**	**32° 20' 23.98"**	Road 202 N of Matias
m10	**26° 03' 09.39"**	**32° 20' 33.56"**	EN2 SE of Boane
m11	**25° 54' 29.15"**	**32° 39' 14.58"**	N part of Maputo
m12	**25° 44' 43.25"**	**32° 38' 56.42"**	BP next to EN1 W of Marracuene
m13	**25° 47' 12.81"**	**32° 25' 45.74"**	W of Chigogo
m14	**25° 25' 37.36"**	**32° 43' 11.74"**	Left of EN1 NE of Bande
m15	**25° 15' 16.22"**	**32° 52' 15.58"**	In BP N of Palmeira
m16	**25° 03' 31.51"**	**32° 02' 42.54"**	R of EN1 east of Magul
m17	**24° 58' 20.27"**	**33° 32' 24.54"**	Next to EN1 E of Chicumbane
m18	**25° 06' 54.34"**	**33° 44' 03.08"**	Xia Xia
m19	**25° 01' 23.47"**	**33° 47' 29.98"**	ENI Chongoene
m20	**24° 40' 25.54"**	**33° 31' 24.78"**	Chibuto
m21	**24° 41' 52.94"**	**33° 36' 36.60"**	E of Chibuto
m22	**24° 41' 26.06"**	**33° 31' 09.44"**	Chibuto
m23	**24° 39' 55.53"**	**33° 33' 53.67"**	NE of Chibuto
m24	**24° 56' 01.69"**	**33° 49' 40.07"**	E of Pomulene
m25	**24° 46' 45.12"**	**33° 53' 49.63"**	S of Manjacaze
m26	**24° 43' 53.20"**	**33° 51' 04.49"**	E of Muzamane
m27	**24° 49' 53.02"**	**34° 01' 02.04"**	SE of Macupulane
m28	**24° 56' 14.89"**	**34° 00' 49.79"**	NE of Bahane
m29	**24° 54' 53.51"**	**34° 10' 54.12"**	EN1 W of Chidengoele
m30	**24° 18' 05.77"**	**35° 13' 37.97"**	N of Inharrime
m31	**23° 51' 05.38"**	**35° 18' 56.41"**	NW of Maxixe
m32	**23° 38' 59.76"**	**35° 16' 08.38"**	Road 416 W of Morrumbene
m33	**23° 31' 08.02"**	**35° 23' 12.16"**	EN1 near Mabsil
m34	**23° 03' 45.99"**	**35° 16' 06.34"**	EN1 near Unguana
m35	**22° 10' 05.54"**	**34° 43' 02.09"**	Road 423 NW of Muabsa
m36	**22° 08' 55.39"**	**35° 06' 47.73"**	BP near Machengue
m37	**21° 42' 58.83"**	**35° 05' 33.62"**	N of Maimelane
m38	**20° 23' 25.80"**	**33° 55' 13.17"**	Road 427 W of Golega
m39	**19° 27' 36.61"**	**33° 50' 06.48"**	Next to EN1
m40	**19° 12' 06.71"**	**33° 56' 25.82"**	N of Inchope
Where the sands designated above are obviously unsuitable, more suitable sands from as close as possible to the site designated in the table above should be sought. If this is not possible, additional samples from the TRL experiments should be collected to make up the numbers.			

Annex 8-B – Sample sites in Namibia

Site Number	Latitude (° ‘ “ S)	Longitude(° ‘ “ E)	Comments
1	**18° 01‘ 48.86“**	**19° 39‘ 20.08“**	South of Rundu
2	**17° 57‘ 02.15“**	**19° 44‘ 18.93“**	Near Rundu Airport
3	**18° 45‘ 05.03“**	**18° 58‘ 00.26“**	North east of Mururani
4	**17° 58‘ 33.71“**	**20° 28‘ 36.88“**	Near Shitemo
5	**17° 59‘ 43.41“**	**20° 30‘ 11.24“**	Near Shitemo
6	**22° 42‘ 57.90“**	**14° 31‘ 42.34“**	)South of Swakopmund
7	**22° 42‘ 57.90“**	**14° 31‘ 42.34“**	) 3 different sands from this area
8	**22° 42‘ 57.90“**	**14° 31‘ 42.34“**	)
9	**23° 33‘ 53.91“**	**15° 48‘ 26.91“**	South East of Walvis Bay
10	**26° 13‘ 42.81“**	**16° 34‘ 42.19“**	North east of Luderitz
11	**24° 50‘ 15.84“**	**15° 54‘ 18.13“**	South east of Sossusvlei
12	**24° 36‘ 14.72“**	**15° 40‘ 42.38“**	North east of Sossusvlei
13	**25° 45‘ 58.80“**	**19° 12‘ 45.00“**	North east of Koes
14	**25° 38‘ 59.19“**	**19° 24‘ 06.42“**	North east of Koes
15	**27° 02‘ 26.41“**	**19° 34‘ 01.85“**	South of Aroab
16	**26° 59‘ 15.93“**	**19° 33‘ 19.25“**	South of Aroab
17	**26° 08‘ 28.19“**	**19° 32‘ 41.78“**	North of Aroab
18	**25° 55‘ 23.28“**	**19° 08‘ 16.10“**	North east of Koes
19	**25° 55‘ 21.43“**	**19° 08‘ 13.16“**	North east of Koes
20	**24° 51‘ 03.28“**	**18° 48‘ 59.25“**	Gochas
21	**24° 33‘ 39.79“**	**19° 37‘ 25.52“**	On M39 W of Akanous
22	**24° 38‘ 40.7“**	**19° 41‘ 47.81“**	On M39 W of Akanous
23	**24° 08‘ 45.96“**	**18° 54’ 37.58“**	W of Aranos
24	**24° 08‘ 47.82“**	**18° 54‘ 36.58“**	W of Aranos
25	**22° 48‘ 51.92“**	**18° 52‘ 01.23“**	S of Kirschberg
26	**22° 47‘ 07.90“**	**18° 53‘ 23.14“**	S of Kirschberg
27	**21° 51‘ 35.22“**	**19° 43‘ 54.39“**	NE of Gobabis
28	**21° 52‘ 09.88“**	**19° 49‘ 31.91“**	NE of Gobabis
29	**22° 25‘ 46.03“**	**19° 00‘ 21.78“**	Gobabis
30	**18° 31‘ 07.15“**	**17° 04‘ 54.51“**	E of Omupanda
31	**18° 28‘ 03.65“**	**16° 54‘ 27.15“**	E of Omupanda
32	**18° 15‘ 01.33“**	**16° 27‘ 07.49“**	NW of Omithiya
33	**17° 53‘ 53.03“**	**15° 57‘ 45.29“**	Ondangwa
34	**19° 12‘ 53.43“**	**17° 18‘ 23.22“**	NW of Guinas
35	**22° 19‘ 24.01“**	**19° 39‘ 05.99“**	E of Gobabis
36	**22° 19‘ 24.01“**	**19° 39‘ 05.99“**	E of Gobabis
37	**20° 30‘ 41.12“**	**17° 25‘ 21.75“**	N of Okakarara
38	**20° 33‘ 16.09“**	**17° 26‘ 59.46“**	N of Okakarara
39	**20° 49‘ 03.32“**	**17° 46‘ 46.44“**	E of Okumumbonde (white sand in BP)
40	**20° 49‘ 09.23“**	**19° 46‘ 53.58“**	E of Okumumbonde (redder sand outside BP)
41	**21° 32‘ 24.50“**	**17° 33‘ 31.22“**	W of Hochfeld (red sand from road)
42	**21° 24‘ 54.34“**	**18° 00‘ 57.38“**	NE of Hochfeld (red sand from road)
43	**19° 14‘ 21.03“**	**18° 45‘ 43.21“**	W of Maroelaboom – white sand in BP
44	**19° 14‘ 29.63“**	**18° 45‘ 45.07“**	W of Maroelaboom–red dune sand S of road
45	**19° 38‘ 42.18“**	**18° 35‘ 30.45“**	Otjituuo
NB: 5 samples have not been identified – these can be used for any interesting sands observed during the sampling trips or for duplicate samples where significant differences are seen at any sample site. Should these samples not be located, CSIR has large samples of six sands from various areas in the dune-field of N Namibia that could be used as substitutes.			

Annex 8-C – Visual Pavement Condition Survey Form

General information

Road number			Date				
Description			Inspector				
Link information	Start position		Direction	NB	SB	EB	WB
	End position		Number of lanes	1	2	3	4
	Length		Lane number	1	2	3	4

Visual condition assessment

Surface distress	Degree					Extent				
	Slight				Severe	Isolated				Extensive
Aggregate loss	1	2	3	4	5	1	2	3	4	5
Bleeding or flushing	1	2	3	4	5	1	2	3	4	5
Surface texture (coarse = 1, fine = 5)	1	2	3	4	5	1	2	3	4	5
Surface failure	1	2	3	4	5	1	2	3	4	5
Dry/brittle binder (fresh = 1, dry/brittle = 5)	1	2	3	4	5	1	2	3	4	5

Structural distress		Degree					Extent				
		Slight				Severe	Isolated				Extensive
Deformation	Rut	1	2	3	4	5	1	2	3	4	5
	Shear	1	2	3	4	5	1	2	3	4	5
Cracks	Crocodile	1	2	3	4	5	1	2	3	4	5
	Longitudinal	1	2	3	4	5	1	2	3	4	5
	Block	1	2	3	4	5	1	2	3	4	5
	Transverse	1	2	3	4	5	1	2	3	4	5
	Pumping	1	2	3	4	5	1	2	3	4	5
Base disintegration	Potholes	1	2	3	4	5	1	2	3	4	5
	Patching	1	2	3	4	5	1	2	3	4	5
Subgrade	Settlement/undulation	1	2	3	4	5	1	2	3	4	5

General information		Degree					Extent				
		Slight				Severe	Isolated				Extensive
Shoulder condition	Edge-break/erosion	1	2	3	4	5	1	2	3	4	5
	Vegetation	1	2	3	4	5	1	2	3	4	5

Drainage facilities	Very good	Acceptable	Inadequate	Unacceptable	Non existent
Riding quality	Very good	Acceptable	Inadequate	Unacceptable	Very poor
Skid resistance	Very good	Acceptable	Inadequate	Unacceptable	Very poor
Slope	Flat	Rolling	Steep		
Construction	In cut	At grade	Cut-and-fill	On fill	

Date of Construction:	Year:	Estimates traffic (ESAs):	

9. GUIDELINE TABLE OF CONTENTS

9.1 Introduction

In anticipation of Stage 3 of the project which involves the preparation of the Draft Guideline, this section provides an outline of the likely Table of Contents for the consideration of ASANRA and its stakeholders. It must be stressed that this draft Table of Contents is not fixed and is more than likely to change as the drafting of the document commences.

9.2 Draft Table of Contents

1. INTRODUCTION

- 1.1 Background
- 1.2 Purpose and Scope of Guideline
- 1.3 Structure of Guideline

2. GENERAL CHARACTERISTICS AND USE

- 2.1 Introduction
- 2.2 Definition, Formation and Composition
- 2.3 Classification
- 2.4 Distribution
- 2.5 Use in Road Construction

3. PROPERTIES

- 3.1 General
- 3.2 Physical/classification properties
- 3.3 Chemical/mineralogical properties
- 3.4 Mechanical/engineering

4. INVESTIGATIONS AND TESTING

- 4.1 Prospecting for sands
- 4.2 Test methods and Procedures
- 4.3 Sampling Methods and Procedures
- 4.4 Summary of Main Results
- 4.5 Statistical Treatment of Data
- 4.6 Laboratory Tests

5. SPECIFICATION

- 5.1 General
- 5.2 Sand Properties
- 5.3 Current Specifications
- 5.4 New Specifications

ANNEX A – LITERATURE SURVEY REFERENCES

Anderson J.R., Department of Geology, Georgia Perimeter College, Dunwoods, GA 30038, USA. Personal communication.

Acott, SM. 1979. ***Sand stabilization using foamed bitumen***. Proc 3rd Conf Asphalt Pavements for southern Africa. Durban, 1979, pp 155 – 171.

Anon. 1974. **A dictionary of geology**. Harmondsworth, England: Penguin.

Aranovich, LAS and Heyn, AT. 1984***. Performance of low cost pavements in Parana, Brazil***. Proc Int Conf Roads and Development, Paris, 1984, Vol 2, pp 761-766. (Presses Ponts et Chaussees).

Baart D., 1961. **Road Construction in Kalahari Sands and Associated Formations.** Proc. Constr. Engrs. Conf. Ministry of Roads & Road Traffic, Rhodesia, August 1961.

Bagnold, RA. 1941. ***The physics of blown sands and desert dunes***. London; Methuen.

Baillieul, TA. 1975. A reconnaissance survey of the cover sands in the republic of Botswana. **J Sedi Petrology**, Vol 45 (2), pp 494-503.

Bergh, AO, Kleyn, EG and McKay, AH. 2008. ***Preliminary studies on the utilisation of Berea Red Sands for subbase and base construction***. Proc 27th Southern African Transport Conference. Pretoria, 2008, pp 108-124.

Bindra, SP.1987. ***An approach to the development of pavement structures for arid regions of the Middle Eastern countries with special reference to Kuwaiti conditions.*** Indian Highways, Vol 15 (2), pp 102-119.

Bofinger, HE. 1971. ***The Behaviour of Soil cement pavements with Special reference to the Problems of Cracking***. 4th Asian Reg. Conf. on Soil Mechanics and Foundation Engineering, Bangkok, Thailand, July 1971.

Booth, AR. 1977. ***Collapse settlement in compacted soils****.* Pretoria: CSIR Transportek. (CSIR Research Report 324 or Bulletin 13).

Botswana Roads Department, 1992. ***Roads in Botswana***. Gaborone: Botswana Roads Department.

Botswana Roads Department. 1999. ***The Design, Construction and Maintenance of Otta Seals****.* Gaborone: Botswana Roads Department. (Guideline No 1).

Botswana Roads Department. 2000. ***Methods and Procedures for Prospecting for Road Construction Materials****.* Gaborone: Botswana Roads Department. (Guideline No 3).

Botswana Roads Department. 2001. ***The Prevention and Repair of Salt Damage to Roads and Runways****.* Gaborone: Botswana Roads Department. (Guideline No 6).

Botswana Roads Department. 2010. ***The Use of Kgalagadi Sands in Road Construction***. Gaborone: Botswana Roads Department. (Guideline No 11).

Brink, ABA (Editor). 1985*.* ***Engineering Geology of Southern Africa***. Pretoria: Building Publications. (Volume 4).

British Standards Institution. 1990. ***Methods of test for soils for civil engineering purposes***. London: British Standards Institution. (BS 1377).

Carvalho, P. Undated. ***Effective use of sands as a road base under labour-based construction: experiences in Mozambique.***

Carney, JN, Aldiss, DT and Lock, NP. 1994. ***The Geology of Botswana***. Lobatse: Geological Survey Department. (Bulletin 37).

Chauvin, JJ. (undated). ***Les sables: Guide pratique d'utilisation routiere***. Bordeaux: Institut des sciences et des techniques de l'equipement et de l'environnement pour le developpement. (Synthesis).

COLTO. 1998. ***Standard specifications for road and bridge works for state road authorities***. Pretoria: Committee of Land Transport Officials (COLTO).

Cooke, HBS. 1964. ***The Pleistocene Environment in southern Africa***. In: Ecological studies in southern Africa (Edited by DHS Davis) The Hague, Holland: Dr W Junk Publishers.

De Vos, ER. 2007. ***Performance Characterisation of Cement Treated Sand Base Material of Mozambique.*** MSc Thesis, University of Srellenbosch, march 2007.

Dierks, k. 1992. ***Technical Aspects for Appropriate Low-Volume Roads in N***amibia. PhD Thesis, Technical University of berlin, February, 1992.

Dingle, RV, Siesser, WG and Newton, AR. 1983. ***Mesozoic and Tertiary Geology of Southern Africa****.* Rotterdam: A.A. Balkema.

Du Toit, AL. 1954. ***The Geology of South Africa***. Edinburgh: Oliver and Boyd.

Emery, SJ. 1992. ***The prediction of moisture content in untreated pavement layers and an application to design in southern Africa***. Pretoria: CSIR Transportek. (Bulletin 20).

Emery, SJ, Cocks, G and Keeley, R. 2007. ***Transportation Research Record***, 1989 (2), pp 194-200.

Folk, RL. 1954. ***The distinction between grain size and mineral composition in sedimentary rock nomenclature.*** The Journal of Geology, V.62, pp344-359.

Geological Survey of Namibia. 2006. Accessed at http://www.mme.gov.na/gsn/namibiageology.htm on 16/04/2012.

Giffen, JC, Youdale, GP and Walter, PD. 1978. ***Use of non-standard gravels as bases***. Proc 9th ARRB Conference, Part 4, pp 54-61.

Gourley, CS. and Greening, PAK. 1999. ***Performance of Chemically Stabilised Road bases: Results and Recommendations from Studies in Southern Africa.*** TRL Project Report PR/OSC/168/99. Project Record No. R6020.

Guiamba, D. Horak, E and Visser, AT. 2010. ***Comparative studies of non-destructive field testing devices on BSM-emulsion.*** Proc. 29th Annual Southern African Transport Conference and Exhibition (SATC), Pretoria, South Africa.

Henderson, MG. 1988. ***Emulsion stabilized sand base: An alternative to crushed stone***. SAICE Seminar on Cost Effectiveness for Township Planning, Design and Construction, Cape Town, July 1988.

Horta, JC. 1987. ***The design and construction of low volume roads in the northwestern Sahara***. Transport Research Record, 1106, Vol 2, pp 278-290.

Jennings, JE and Knight, K. 1975. ***A guide to construction on or with materials exhibiting additional settlement due to "collapse" of grain structure.*** Proceedings of the 6th African Regional Conference on Soil Mechanics and Foundation Engineering, Durban, September 1975.

Jewell, RJ. 1970. ***Flexible pavement base course materials selection in western Australia***. Civil Engineering Transactions, April 1970, pp 79-84.

Jones, DJ. 1995. ***The use of sand cushioning in road maintenance.*** Proc Annual Transport Convention, Pretoria.

Krumbein, WC and Pettijohn, FJ. 1938. ***Manual of sedimentary petrography***, New York, Appleton-Century.

Krumbein, WC and Sloss, LL. 1963. ***Stratigraphy and Sedimentation***. San Francisco: WH Freeman & Co.

Lancaster, N. 1986***. Grain size characteristics of linear dunes in the southwestern Kalahari***. Journal of Sedimentary Petrology, 56, 395-400.

Lancaster, N. 2000. Eolian Deposits. In: **The Cenozoic of Southern Africa** (Edited by TC Partridge and RR Maud). New York: Oxford University Press, pp 73-87.

Leach, JD. 1960. ***Low cost roads – New Australian developments.*** African Roads and Transport, July/August 1960, pp 7-27.

Lee, IK, Weeks W. and Ingles OK. 1983. ***Geotechnical Engineering***. Pitman Books Ltd., London.

Lees, G. 1964. ***The measurement of Particle Shape and Its Influence in Engineering Materials.*** Journal of the British Granite and Whinstone Federation, Vol. 4, No. 2.

Masch, FD and Denny, KJ. 1965. ***Grain size distribution and its effect on the permeability of unconsolidated sands***. Water Resource Research Journal, Vol 2 (4), pp 665-689.

Main Roads Department. 1975. ***Western Australia Confined Compression Test***. Perth: Main Roads Department, Western Australia. (Test method S17-75).

Main Roads. 2002. ***Selection and use of naturally occurring materials as base and subbase***. Perth: Main Roads Department.

Mainwaring, P. 1968. ***The reconstruction of the Bulawayo to Victoria Falls Road***. The Rhodesian Engineer, Vol 6(2), pp 646-656.

Marais, CP and Freeme, CR. 1977. ***Performance study of asphalt road pavement with bituminous stabilised sand bases***. Trans Res Record, 641, pp 52-61.

Mc Manus, DA. 1982. ***Phi and sediment size analysis***: Discussion. Journal of Sedimentary Research, 52:1011-1014.

Maud, RR and Botha, GA. 2000. ***Deposits of the South Eastern and Southern Coasts.*** In: The Cenozoic of Southern Africa (Edited by TC Partridge and RR Maud). New York: Oxford University Press, pp 19-32.

Mayer, JJ. 1986***. Differential erosion of possible Kalahari aeolian deposits along the Vaal-Orange drainage basin and the upper reaches of the Harts river***. Trans Geol Soc S Afr, 89, pp 401-407.

Metcalf, JB and Wylde, LJ. 1984. ***A re-examination of specification parameters for sandy soil roadbase materials.*** Bull Int Ass Engng Geol, No 30, pp 435-437.

Mgangira, MB. ***Characterisation of some particle properties of Kalahari Sands***. Proc 14th Africa Reg Conf Soil Mech and Geotechnical Engng, Yaounde, Cameroon, Nov 2007, Vol 1, pp141 – 146.

Ministry of Works, Transport and Communications. 1982. ***Botswana Road Design Manual***. Gaborone: Ministry of Works, Transport and Communications.

Ministry of Works, Transport and Communications. 1983. ***Standard Specification for Roads and Bridge Works.*** Gaborone: Ministry of Works, Transport and Communications.

Mitchell, RL. 1982. ***Flexible pavement design in Zimbabwe***. Proc Instn Civ Engrs, Part 1, August 1982, pp 333-354.

Mitchell, RL. 1959. ***Road construction on Aeolian sands.*** Proc 2nd Reg Conf on Soil Mechanics and Foundation Engineering, Lourenco Marques, 1959, pp187-192.

Mockett, LD and Barton, ME. 1990. ***Report on the Engineering Geological Characteristics of sand samples from the Serowe-Orapa Road, Botswana***. Transport and Road Research Laboratory, Crowthorne, Berkshire.

Murphy, HW. 1981. ***The use of non-standard road making materials***. Townsville: Queensland Main Roads Department. (Unpublished report).

National Association of Australian Road Authorities. 1980. ***Pavement materials: Part 2: natural gravel, sand clay and soft and fissile rock***. Sydney: National Association of Australian Road Authorities.

Netterberg, F and Paige-Green, P. 1988. ***Pavement materials for low volume roads in southern Africa: A review*****. Proc Annual Transportation Convention**, Pretoria, July 1988, Vol 2D, pp 2D-1 to 2D-51.

Netterberg, FN. 1998. ***Orapa Kalahari Sand base Experiments: Results of Inspections in 1995 and 1997 and Some Additional Observations.*** Roads Department, Gaborone.

Netterberg, FN. 2012. Personal communication. Pretoria.

NITRR. 1986. ***Standard Methods of Testing Road Construction Materials.*** Pretoria: Department of Transport. (Technical Methods for Highways, TMH 1).

Nogami, JS and Villibor, DF. 1992. ***Use of lateritic fine-grained soils in road pavement base courses.*** Geotechnical and Geological Engineering, Vol 9, pp 167-182.

Overby, C. 1981. ***Tsabong-Makopong Road: km 0-16.0: Construction of a bituminous road 1980-1981.*** Gaborone: Ministry of Works and Communications. (Report 27).

Overby, C. 1982. ***Material and pavement design for sealed low volume roads in Botswana 1974-1981.*** Oslo: Public Roads Administration. (NRRL Report 1042).

Overby, C. 1990. ***Monitoring of sealed low volume roads in Botswana 1980-1989***. Oslo: Public Roads Administration. (NRRL Report 1478).

Paige-Green, P. 1983. ***Sand as a construction material in Australia***. Pretoria: National Institute for Transport and Road Research, CSIR. (Technical Report TS 21/83).

Paige-green, P., Netterberg, FN. and Sampson. LR. (1990). ***The carbonation of chemically stabilized road construction materials: a guide to its identification and treatment.*** DRTT Report DPNT-123, CSIR, Pretoria.

Paige-Green, P and Gerryts, E. 1998***. An innovative solution for township roads in sandy areas***. The Civil Engineering and Building Contractor, May 1998, pp 74- 77.

Paige-Green, P and Overby, C. 2010. ***Aspects regarding the use of local materials in roads in Botswana.*** Proc 11th Congress of IAEG, Sept, 2010, Auckland, pp 4409 -4418.

Paige-Green P and Pinard, M. 2011. ***The Use of a Sedimentological Technique for Assessing the Engineering Performance of Sands in Roads***. Proc 15th Africa Reg Conf Soil Mech and Geotechnical Engng, Maputo, June, 2011, pp 431-438.

Palmer, WT, Viljoen, DP and van der Walt, N. 1992. ***The Compaction of Kalahari Sand at In-situ Moisture Content***. Proc Annual Transport Convention, Pretoria.

Pederson, TA. 1978. ***Low cost road construction techniques in western Australia.*** 2nd Conf Road Engineering Assoc of Asia and Australia, Manilla, Oct 1978, Vol 5, pp 1-13.

Pinard, MI, Obika, B and Motswagole, KJ. 1999. ***Developments in Innovative Low-Volume Road Technology in Botswana.*** Transportation Research Record 1652, Vol 1, pp 68-75.

Presto Products Company. 1991***. Sand Road Case Study: We've Got the Answer for Building Sand Roads***. Appleton, Wisconsin.

Sabita. 1999. ***ETB – The design and use of emulsion-treated bases***. Cape Town: Sabita. (Manual 21).

Sandman, R, Wall, R and Wilson, N. 1974. ***Use of natural materials for pavement construction in South Australia***. Adelaide: Highways Department, South Australia. (Report MS 26).

Schwartz, K, Yates, JRC and Tromp, BE. 1981***. In situ compaction of aeolian Kalahari sands***. Proc 10th Int Conf on Soil Mech and Found Engng, Stockholm, pp 773-776.

Semelink, CJ. 1992. ***The Effect of Shape and Texture of Road Building Material Particles on Their Compactability and Bearing Capacity,*** Report No. PR 91/185, CSIR, Pretoria .

Smit, 1977. ***The geohydrology in the catchment area of the Molopo River in the northern Kalahari (***in Afrikaans). Unpublished PhD Thesis, University of Orange, Free State, Bloemfontein, South Africa.

Strauss, PJ and Hugo, F. 1979. ***Innovations in design and construction of a low volume low cost road on windblown sands***. Transp Res Record, 702, pp 208-214.

Utiyama, H, Nogami, JS, Correa, FC and Vilibor, DF. 1977. ***Pavimentacao Economica: Solo arenoso fino.*** Sao Paulo: Revista Departmento de Estradas de Rodagem. (No 124).

van der Merwe, CP. 1959. ***Stabilization of an aeolian sand.*** **Proc 2nd Reg Conf Africa on Soil Mechanics and Foundation Engineering.** Lourenco Marques (Maputo), Mozambique, pp 199-204.

van Wijk, I, and Carvalho, P. 2002. **Innovative Use of Sands in pavement Layers: Experience in Mozambique.** 2nd World Enginering Congress, Sarawak, malaysis, 22-25 July 2002.

Wentworth, CK. (1922). ***A scale of grade and class terms for clastic sediments,*** J. Geology V. 30, 377-392 (1922).

Weston, D. 1980. ***Compaction for collapsing sand roadbeds***. Proc 7th Reg Conf Africa on Soil Mech and Found Engng, Vol 1, Accra, pp 341-354

Wolmarans, CA and Clifford, JM. 1975. ***An evaluation of the CSIR impact roller***. Proc 6th Reg Conf Africa on Soil Mech and Found Engng, Vol 2, Durban, pp 33-39.

Wooltorton, FLD. (1954). ***The Scientific Basis of Road Design.*** Edward Arnold Ltd. London.

Wylde, LJ. 1979. ***Marginal quality aggregates used in Australia***. Melbourne: ARRB (Report ARR No 97).

Wylde, LJ. 1982. Personal Communication, Adelaide, Australia.