A Method for Consistent Classification of Materials for Pavement Rehabilitation Design

Technical Memorandum

Final

March, 2007

Authors:

F Jooste

F Long

A Hefer

PREPARED FOR:

Gauteng Department of Public Transport, Roads and Works
Directorate: Design
Private Bag X3
Lynn East, 0039

SABITA
Postnet Suite 56
Private Bag X21
Howard Place
7450

PREPARED BY:

Modelling and Analysis Systems CC.
PO Box 882
Cullinan
1000
(www.modsys1.com)

ACKNOWLEDGEMENTS

The sponsors of this project, Gauteng Department of Public Transport, Roads and Works (represented for this study by Elzbieta Sadzik) and SABITA (represented by Trevor Distin and Piet Myburgh) are gratefully acknowledged. The project has been managed by Les Sampson of the Asphalt Academy.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS I

1 BACKGROUND AND INTRODUCTION 1

1.1 Background 1
1.2 Objective 1
1.3 Context and Scope of this Report 2
1.4 Structure of this Report 2

2 BASIC CONCEPTS 4

2.1 Challenges in Rehabilitation Investigations 5
2.2 Formulation of the Objective 6
2.3 Material Classes for Rehabilitation Design 7
2.4 Vagueness and Subjective Interpretations 8
2.5 Handling Small Samples 8

3 CLASSIFICATION FRAMEWORK 11

3.1 A Fundamental Basis 11
3.2 Guidelines for Test Interpretation 13
3.3 A Holistic Approach 14

4 RECOMMENDED TESTS AND INTERPRETATION OF RESULTS 16

4.1 General Comments On Selected Tests and Interpretation Guidelines 16
4.2 Classification Indicators for Unbound Granular Materials 17
4.3 Classification Indicators for Cement Stabilized Materials 23
4.4 Classification of Bitumen Stabilized Materials 25

5 SYNTHESIS OF AVAILABLE INFORMATION 27

5.1 Method Outline 27
5.2 Certainty Factors For Different Tests 28
5.3 Adjustment for Sample Size 29
5.4 Assessing the Relative Certainty of Evidence 29
5.5 Updating Material Classification for Available Evidence 30
5.6 A Worked Example 31
5.7 Confidence Associated with Assessment 34
5.8 Implementation of Methodology 35

6 SUMMARY AND RECOMMENDATIONS 38

7 REFERENCES 40

APPENDIX A: PROJECT WORK PROPOSAL 42

LIST OF FIGURES

Figure 1: Reliability versus Completeness of Assessment 9
Figure 2: Mohr-Coulomb Material Model 11
Figure 3: Material Composition, Showing Dominance of Friction and Cohesion.................... 12
Figure 4: Examples of Test Rating Systems for Consistent Interpretation of Test Results.................... 13
Figure 5: Interpretation of Grading to Quantify Relative Conformance to Grading.................... 21
Figure 6: Determining Relative Conformance of Evidence to Material Class Limits 30
Figure 7: Grading Analyses for Worked Example.................... 32
Figure 8: Example of C(E) Calculations for FWD Stiffness Sample 33
Figure 9: Illustration of a Materials Classification Report.................... 37

LIST OF TABLES

Table 1: Interpretation of California Bearing Ratio (CBR) 17
Table 2: Interpretation of Percentage Passing 0.075 mm Sieve 17
Table 3: Interpretation of Relative Density..... 17
Table 4: Indicators and Tests for Classification of Unbound Granular Materials 18
Table 5: Interpretation of DCP Penetration Rate 19
Table 6: Interpretation of FWD Backcalculated Stiffness 19
Table 7: Rating of Consistency 19
Table 8: Guidelines for Consistency of Coarse Granular Materials (after SANRAL, 2004) 20
Table 9: Guidelines for Consistency of Cohesive Soils (after SANRAL, 2004)..... 20
Table 10: Rating of Visible Moisture 20
Table 11: Rating of Plasticity Index 20
Table 12: Rating of Relative Moisture Content 21
Table 13: Rating of Grading Assessment 21
Table 14: Rating of Grading Modulus 22
Table 15: Rating of Aggregate Crushing Value (ACV) 22
Table 16: Rating of Number of Fractured Faces 22
Table 17: Rating of Historical Performance (Base Layers) 22
Table 18: Rating of Historical Performance (Subgrade Layers) 23
Table 19: Indicators and Tests for Classification of Cement Stabilized Materials..... 24
Table 20: Interpretation of Cemented Layer Consistency (after SANRAL, 2004) 24
Table 21: Interpretation of DCP Penetration Rate (Cement Stabilized Materials) 24
Table 22: Interpretation of FWD Backcalculated Stiffness (Cement Stabilized Materials)..... 24
Table 23: Rating for Evidence of Active Cement 25
Table 24: Test Rating Values Associated with Different Design Equivalent Material Classes..... 28
Table 25: Recommended Certainty Factors for Different Tests and Indicators 28
Table 26: Recommended Adjustment of CF based on Sample Size 29
Table 27: Example Materials Test Data..... 31
Table 28: Assigned Ratings (based on Natural Gravel Material) 32
Table 29: Worked Example, Summary of Test Data and Certainty Factors..... 33
Table 30: Worked Example, Summary of Certainty Associated with G4, G5 and G6..... 34
Table 31: Relative Confidence of Materials Classification..... 34

1 BACKGROUND AND INTRODUCTION

1.1 BACKGROUND

During a routine pavement rehabilitation investigation, an engineer is typically faced with a wide array of test parameters and condition indicators. These parameters can be quantitative or qualitative, subjectively or objectively determined, and the sample sizes for different indicator types may vary significantly. For example, for a specific pavement layer within a uniform design section, an engineer may be faced with the following set of information:

- Seven Dynamic Cone Penetrometer (DCP) tests;
- Fifty Falling Weight Deflectometer (FWD) deflections;
- Two sets of material descriptions and samples from test pits, together with standard materials test results, including Plasticity Index (PI), grading, California Bearing Ratio (CBR), moisture content and density;
- One subjective visual assessment with a description of observed distresses;
- Fifty semi-subjectively determined backcalculated stiffnesses from FWD tests;
- A general description of the material type from historical records, and
- A general description of the history and past performance of the pavement.

From such a set of information, the engineer has to derive the key assumptions needed to drive the rehabilitation design. The synthesis of the information to arrive at design assumptions is one of the most important and difficult parts of the rehabilitation design process. Apart from basic analytical skill, it also requires considerable experience and knowledge of the main drivers of material behaviour.

It is thus not surprising that engineers often fail to reach a consistent conclusion regarding design inputs such as the material class and its current state. This applies even more so to an ill-defined numerical parameter, like resilient modulus, which is needed for Mechanistic-Empirical (ME) design calculations. Clients often object that tests which were paid for are not properly incorporated in the analysis of layer condition, and design assumptions are sometimes not consistently supported by available evidence.

The authors' involvement in training young engineers has shown that the proper classification and documentation of the material type and its state within the pavement system is one of the most difficult aspects of the design process for young engineers to grasp and master. Coupled to this aspect is the fact that South Africa is at present faced with a shortage of experienced pavement engineers, and so inexperienced practitioners are naturally drawn into the field of pavement rehabilitation design.

Whilst there are guidelines available to guide engineers on the collection of pavement condition data (e.g. TRH12, 1998), these guidelines deal with the rehabilitation design process in general, and do not provide detailed guidelines for interpreting and synthesizing basic test indicators. Young engineers studying these guidelines know *what* to do at each stage of the rehabilitation design process, but not *how* to do it.

It is thus clear that there is a need for a detailed methodology to guide engineers in the interpretation of available pavement condition data, and to synthesize available information so that key design assumptions can be derived in a consistent and rational manner.

1.2 OBJECTIVE

The objective of this document is to provide a method for the consistent assessment of pavement materials using routine tests and indicators. The method was specifically developed for use as part of a knowledge-based design method for pavements that incorporate bitumen stabilized materials, which is described in detail in Jooste and Long (2007). It should be noted, however, that the approach outlined in this document can be of use in any pavement rehabilitation context.

1.3 CONTEXT AND SCOPE OF THIS REPORT

This technical memorandum forms part of Phase 2 of the project aimed at the development of guidelines for the design and use of bitumen stabilized materials. The document specifically pertains to the structural design component of this larger study, as it provides a method for determining the design inputs for the proposed design method for pavements that incorporate bitumen stabilized materials.

The document outlines the general approach and structure for the method. It also provides enough details to facilitate implementation of the method with respect to unbound granular materials and cement stabilized materials. Whilst the general approach can be applied to any material type, the details needed to implement the method for *bitumen stabilized materials* are not yet available. These details are expected to emerge as part of the mix design component of the overall study to develop guidelines for bitumen stabilization.

It is therefore important to note that this document forms part of an ongoing study with broader objectives. Several other components of the larger study are still in progress and are likely to impact on the eventual implementation of the method outlined in this memorandum. The following two components of the ongoing study are of special relevance:

- Knowledge-Based Pavement Design Method: this study forms the main part of the structural design component of the bitumen stabilization guidelines project. The method uses climate, layer thicknesses and materials classes as the inputs to determine the design capacity of a pavement structure. The basic principles and current status of the proposed pavement design method is outlined in Jooste and Long (2007).

- Mix Design Component: this vital element of bitumen stabilization is addressed in a separate study, and is thus not covered by this memorandum. The findings of the mix design component of the study are expected to be published during 2008, and will be used to refine the classification method so that it can also be implemented for bitumen stabilized materials.

It is thus important for readers to note that the method proposed in this document, while believed to be sound in concept, still needs to be expanded and pilot tested. This testing is scheduled to take place during 2007, after which the refined method will be published as part of the finalized guidelines for the design and use of bitumen stabilized materials.

1.4 STRUCTURE OF THIS REPORT

Section 2 presents some of the basic concepts that are used to define and address the material classification problem. This section introduces the three main sources of uncertainty to be dealt with, and shows how these influence pavement rehabilitation design decisions. The main challenges in rehabilitation investigations are highlighted, and the main requirements of a solution to these challenges are outlined.

In Section 3, a general framework for the proposed materials classification method is presented. The three main characteristics of the framework are discussed, namely (i) a fundamental material model; (ii) guidelines for interpretation; and (iii) holistic nature of the approach.

Section 4 provides detailed guidelines on the test types that can be used for the classification of unbound granular materials and cement stabilized materials. Available tests are summarized, and guidelines are provided for interpretation of results. In the case of bitumen stabilized materials, a tentative classification scheme is proposed, with tests and indicators that are likely to be used for these materials proposed.

Section 5 presents a method for synthesizing the outcomes of several test types into a material class. The details of the method are presented and illustrated using a worked example.

Section 6 contains a summary, with recommendations related to the pilot implementation of the proposed classification method. Section 7 provides a list of references.

It should be noted that this report is classified as a technical memorandum, as defined by the documentation guidelines of the Gauteng Department of Public Transport, Roads and Works. As such, the main purpose of the document is to record technical processes and data, and not to present a formal, finished document for general distribution.

2 BASIC CONCEPTS

In this document, we are concerned with the interpretation of information to reach a specific conclusion. This task would be straightforward if it was not for the *uncertainty* which enters at various stages of the interpretation process. Hopgood (2000) classified this uncertainty into three basic forms, which – in the context of this study – can be summarized as follows:

1. Uncertainty in the evidence, or test data;
2. Uncertainty in the relationship between the information and the conclusions drawn from it, and
3. Vagueness in the information or assessment.

These three sources of uncertainty are best understood by means of an example. Consider a situation where an engineer is trying to determine whether an existing asphalt mix at an intersection has enough stability to withstand high intensity loading without the need for an overlay. The engineer locates the as-built data sheets and finds three Marshall Stability values measured on cores taken from the asphalt after compaction. We can now see how uncertainty enters into the interpretation of this data:

> Uncertainty in the Evidence: in the example, the engineer has to rely on information collected during construction. Depending on the situation and the engineer's knowledge thereof, the as-built information may be considered unreliable. Furthermore, only three samples are available. This small sample provides only an estimate of the properties of the actual stability of the asphalt layer.
>
> Uncertainty in Relationships: in this example the engineer uses a test indicator (e.g. Marshall Stability) to estimate how high the stability of the material is. The test may or may not be a good indicator of actual material stability. If it is not an appropriate test, it may give a false indication of stability, and thus we have some doubt (uncertainty) about the appropriateness of the test.
>
> Vagueness in the Information or Assessment: once the engineer evaluates the stability data, an assessment needs to be made on whether the stability is high enough to withstand high intensity traffic. Terms such as "high enough" and "high intensity traffic" inject more uncertainty into the interpretation. If there were 50 fewer heavy vehicles per day over the intersection, would the traffic still be regarded as "high intensity"? Would the stability now be "high enough"? The uncertainty that enters due to vagueness increases significantly when subjective assessments are involved, as in the case of visual assessments.

Whilst there are established techniques for quantifying uncertainty related to samples taken from a population, it can be seen from the above example that the assessment of data to draw a conclusion is often more complex. Sample size is just one of many factors to consider, and minimization of uncertainty in pavement design situations is rarely as simple as just taking more samples. This becomes especially relevant when there is a definite constraint on how much information can be collected.

Using again the above example, consider a situation where the engineer has limited funds available to do more testing. Suppose for the available funding any one of the following can be done: (a) drill twelve cores and subject these to Marshall Stability testing; or (b) drill two cores and do a repetitive simple shear test (believed to be a good indicator of stability) on each one; or (c) drill six cores for Marshall Stability tests, and one core for a repetitive simple shear test. Each of these options will decrease uncertainty, but in a different way. Option (a) would increase sample size and the reliability of our estimate, but we may still be using a poor indicator to estimate the actual stability. Option (b) may provide a better indication of actual stability under traffic, but the indication is compromised by the small sample size. Option (c) is an attempt to balance the two sources of uncertainty.

The option an engineer would choose would depend largely on the engineer's experience and background, and is certain to rely on subjective judgment, which poses new problems when the engineer is inexperienced. Thus the problem of interpreting data to reach a conclusion where uncertainty is involved is not simply constrained to sample sizes. This problem, which Hopgood (2000) refers to as *reasoning with uncertainty*, requires a more holistic view. Perhaps a good start toward such an approach would be to clarify some of the unique challenges related to pavement material evaluations.

2.1 CHALLENGES IN REHABILITATION INVESTIGATIONS

The evaluation of pavement materials as part of rehabilitation investigations poses several unique challenges. These challenges are related to the realities of pavement investigations and pavement design, which includes the following aspects:

Many Sources of Uncertainty: pavement engineering deals with large quantities (i.e. long distances) of natural and thus highly variable materials, which are subject to highly variable loads. The whole science is thus fraught with uncertainty. The many sources of uncertainty create greater risk compared to, say, a bridge pillar design, where the materials (concrete and steel) are manufactured to a relatively high precision, and the direction and magnitude of loading can be determined with high precision.

Risk is Poorly Defined: some engineers have defined risk as likelihood multiplied by consequence (Creagh, 2005; AS/NZS 4360, 1999). While the consequences of the failure of a bridge pillar are easy to conceptualize and perhaps even quantify in terms of cost, the same is not true for pavement design. What is the consequence of 5 per cent more crocodile cracking over a twelve year period, and is it cost-effective to spend an extra R10 million now to prevent it? Several assumptions are needed to answer this question, and many of these – although they can be estimated – are beyond control (e.g. rainfall, overloading, future budgets, etc). Because of this situation, subjective assessment using experience plays a considerable role in pavement design.

Small Sample Sizes: reliance on small samples is part of the current reality of pavement investigations. It is not unusual for a rehabilitation design over 20 km of road, over varying terrain and geological areas to be based on ten or less trial pits. For a shorter uniform subsection, the design is often based on data from one or two trial pits.

All Tests are Indicators: in pavement design situations, the assessment of materials always aims to assess stability and (for some materials) flexibility[♣]. It does so either directly (as in a stability test) or indirectly (as in a grading assessment, which will impact on stability). Because the actual load situation varies, no pavement material test is able to completely quantify long term stability or flexibility. Even a highly sophisticated test, like the repeated load triaxial test, must be performed at a fixed moisture content and stress state which will never correspond completely to the real pavement situation that it aims to assess. Thus all tests provide only a relative indication of the two key properties to be assessed, and some tests do so very poorly.

Interpretation is Vague: pavement rehabilitation investigations are different from acceptance testing. In the latter case, an engineer can compare a test result to an acceptance limit, and interpretation is straightforward (whether the test is an appropriate one or not is not an issue). By contrast, in a pavement rehabilitation investigation, an engineer needs to decide *what is there, and what can be done with it*. A yes or no interpretation does not apply, and a relative interpretation is always needed. This complicates the interpretation of data considerably, especially when conflicting information is involved. It also introduces more subjectivity into the process.

[♣] In this document, the term stability is generally used to denote shear strength, and these terms are used interchangeably depending on the context. Stability and flexibility provide an indication of the resistance to the two main sources of pavement deterioration: deformation (either due to volume change or shear) and cracking (due to fatigue in tension).

These realities present the backdrop against which any methodology for interpretation of pavement condition data must function. Careful consideration of these challenges shows that a suitable approach must incorporate the following elements:

- Clear and rational formulation of the objective;
- Ability to handle vagueness and uncertainty of interpretation, and
- Ability to work with small sample sizes.

Solutions towards addressing these elements are proposed in the following paragraphs.

2.2 FORMULATION OF THE OBJECTIVE

The vagueness and relativity of many pavement materials tests complicates the interpretation of data from these tests considerably. Think, for example, of a grading assessment performed on samples taken from a subbase in a pavement to be rehabilitated. Which grading envelope should be used to assess the material? How does the grading fit any selected envelope, and what does that imply? These questions illustrate the relativity and vagueness of materials evaluation, which can be quite confusing, especially when several test types are involved.

In the authors' experience, this frequently results in a situation where inexperienced engineers simply report test results without performing any systematic interpretation, usually much to the chagrin of clients who pay to have the tests done. This situation can be addressed by formulating a clear objective for the materials assessment process. If an engineer understands what the objective of the analysis is, and how each test result relates to that objective, then a more systematic approach can be taken.

The following seems like a reasonable high level formulation of such an objective:

> *The objective of materials evaluation for rehabilitation design is to obtain a reliable and clear indication of the shear strength, stiffness, and where needed, the flexibility, of the material.*

This formulation seems reasonable, but is not realistic in a routine design situation. For example, how can shear strength be expressed? This depends on the failure theory adopted (e.g. Mohr-Coulomb, Desai etc[♠]), and on the test protocol used. How should the engineer determine stiffness when there are several methods to measure stiffness[♣] and when the current design method does not specify which method should be used? A more practical formulation is clearly needed.

By trying to estimate the shear strength, stiffness or flexibility in absolute terms we present the (often inexperienced) engineer with a very small target, which is also poorly defined. We can address this situation by increasing the size of the target, and by defining it properly. *This can be achieved by grouping materials together in classes, with each class representing a specific type of material (e.g. asphalt, crushed stone, gravel-soil blends, etc) and a similar range of relative shear strength, stiffness and flexibility.*

[♠] For a general reference on failure criteria, including the Mohr-Coulomb and Desai criteria, see: Chen and Baladi (1985) or Jooste and Fernando (1995).

[♣] Stiffness can be backcalculated from surface deflections measured using the Falling Weight Deflectometer (FWD), Deflectograph or Multi-Depth Deflectometer (MDD). It can also be measured using sonar methods, or using laboratory tests such as the resilient modulus test. The rate of loading and load configuration for all these tests differ, and differences between stiffnesses measured with these methods are known to exist and have been documented in some cases. The situation is further complicated by the fact that the South African Mechanistic Design Method (SAMDM) was developed using a combination of these test types. Furthermore, the SAMDM documentation (Theyse et al, 1996) provides no guidelines on how to determine the stiffness to be used in the method.

If there are enough well-defined material classes, and if the basic properties of each class are known with some certainty, then a relative stiffness, shear strength and flexibility can be assigned to each class based on well-established principles of materials behaviour and performance. The objective of materials evaluation for rehabilitation design now becomes much simpler, and can be formulated as follows:

> *The objective of materials evaluation for rehabilitation design is to obtain a reliable and clear indication of the material class. If the material classes are appropriately designated, then each class will imply a certain material type and state and can be used to provide a relative, but consistent indication of shear strength, flexibility and stiffness.*

2.3 MATERIAL CLASSES FOR REHABILITATION DESIGN

The above-noted formulation of the materials assessment objective presents a more rational and attainable goal for engineers to aim for in routine pavement investigations. However, it immediately raises a conceptual issue related to the meaning of different materials classes. For new pavements, or layers that are to be reworked or added to the current pavement, it seems natural to adopt the current classification system for materials as defined in the TRH14 document, which provides guidelines for road construction materials (TRH14, 1985). However, for existing pavement layers that will remain undisturbed in the rehabilitated pavement system, the concept of materials classification is more complex because of the following two issues:

> Material State: In new construction, it is relatively easy to determine a material class. If a material conforms to the specified grading envelope, has the right PI and density, it clearly conforms to a certain class (e.g. G1, C3, etc). However, this becomes more complex if the material has been in service for some time. In this case, the material may conform to the grading and PI specifications of a G1, but it may also exhibit pumping, shoving (which implies de-densification) and a DCP penetration rate that is typical for a G4 material. What class is it now? To answer this, the classification system should take into account the *current state* of the material.
>
> Multiple Samples and Subjective Interpretation: Consider an overlay design on a uniform subsection in which three tests pits were opened. If two of the three test pits indicate the base is a G2 quality material, and the third test suggests the material is a lesser quality G3, which material class should be assumed for design? This question can perhaps be solved in a statistical sense, but conceptually it is more difficult to interpret. After all, considering the subsection as a unit, the base layer is neither a G2 nor a G3, but some combination of the two[♠].

One way to address this complexity in a rehabilitation context would be to adopt a more general classification system using, for example, classes such as “high quality crushed stone”. However, the use of such classes would mean that in many instances different quality materials will be grouped together, thereby decreasing the precision of the design method. Another approach would be to introduce a new materials classification system. However, this is likely to create significant confusion and resistance to implementation.

After consideration of the problem, it was decided to adopt the existing TRH14 classification system, but with an understanding that the obtained materials class will be regarded as the *design equivalent materials class*[♣]. The implications of this term can be defined as follows:

[♠] Material classification is also complicated when conflicting results are obtained. It is not unusual for a materials laboratory to assign a G7 (soil-gravel blend) class to a material based on a single CBR test result, even if the material is in reality a crushed stone that has a grading, PI and DCP penetration rate that meets G1 (high quality crushed stone) specifications or expectations.

[♣] For brevity, the term materials class will generally be used in this document. However, the reader should bear in mind that – in the case of layers in an existing pavement structure – the assigned material class always denotes the design equivalent materials class.

> *When a design equivalent class is assigned to a material, it implies that the material exhibits in-situ shear strength, stiffness and flexibility properties similar to those of a newly constructed material of the same class.*

For example, if a layer in an existing pavement structure is classified as a G2 *design equivalent,* this indicates that the material is considered to exhibit shear strength, stiffness and flexibility properties that are similar to those of a newly constructed G2 material. Since materials to which *design equivalent* classes are assigned have been in service for some time, the raw material would conform to (or exceed) the specifications for the class, as stated in TRH14, in almost all instances.

The TRH14 classification system is regarded as being highly suitable for rehabilitation design, as the behaviour and performance patterns of each material class is known with some certainty. The system is also relatively precise, and provides a higher resolution classification than other systems such as the AASHTO soil classification system (AASHTO, 1978; Spangler and Handy, 1982)[♣].

2.4 VAGUENESS AND SUBJECTIVE INTERPRETATIONS

Vagueness and subjectivity are unavoidable characteristics of pavement materials investigation. Some materials assessment tests, like grading analyses, do not even have a quantified outcome. For some tests that do have a quantified outcome, the outcome needs to be interpreted before it becomes meaningful. For example, a moisture content of 6 per cent becomes meaningful only if it is interpreted in terms of optimum moisture content. Other tests, like PI, are easy to interpret, but not all engineers understand the implications of a certain PI for design. To handle vagueness and uncertainty of interpretation, the following needs to be implemented:

> Fundamental Understanding: Engineers should have a fundamental understanding of the factors that influence shear strength, stiffness and flexibility. This understanding should explain which test parameters are meaningful and how they relate to these three aspects.
>
> Holistic Approach: Engineers should understand that currently no single test provides a complete description of shear strength, stiffness and flexibility. Some tests are good indicators of these aspects, others are not. By incorporating as many as possible meaningful tests in the evaluation of a material, a more reliable and complete assessment is obtained.
>
> Interpretation Guidelines are Needed: To reduce the subjectivity of interpretation, more precise guidelines are needed to guide the interpretation of tests. These guidelines should serve as a means to translate a test outcome to a quantified indicator for shear strength, stiffness or flexibility.

A framework for addressing the above noted requirements is presented in Section 3.

2.5 HANDLING SMALL SAMPLES

Samples are typically interpreted by analyzing the sample average and standard deviation, and obtaining confidence interval estimates from the sample statistics. Established statistical theory exists for sample sizes that are medium (e.g. three to ten observations) to large (e.g. thirty or more observations). In pavement rehabilitation design, however, it is not unusual to have only one or two observations for a certain parameter (e.g. moisture content) within a uniform subsection.

Pavement systems and individual pavement layers exhibit a high variability in almost all important parameters (e.g. surface deflection, layer thickness and density, etc.). This is due to the fact that almost all pavement materials comprise natural (as opposed to manufactured) materials which are constructed

---

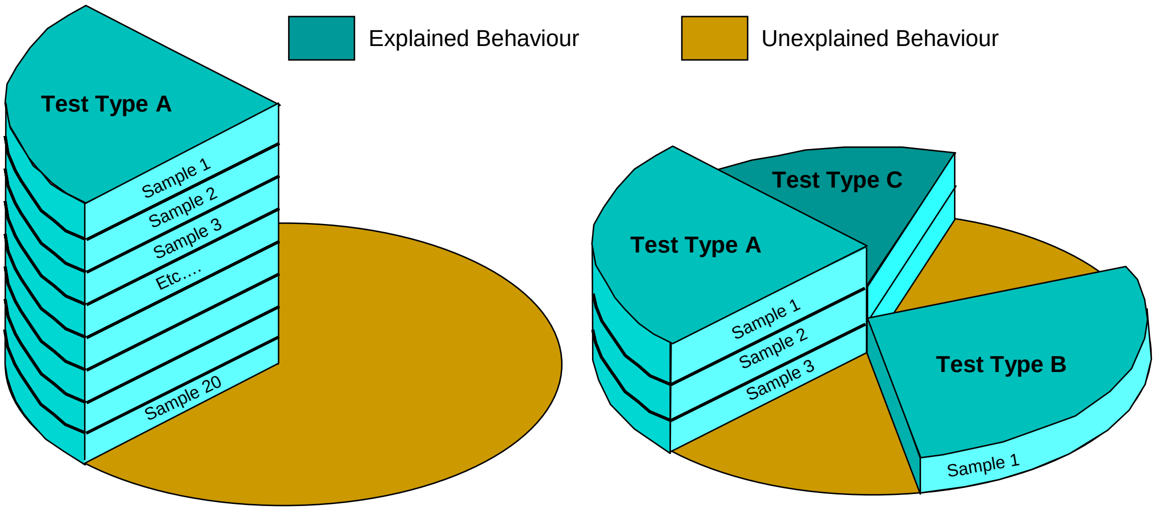
[♣] For example, the grading indicators allowed for the A-1 class in the AASHTO classification system are such that a G1, G2, G3 or G4 material (as defined in TRH14, 1985) would classify as an A-1 material. The system also does not differentiate the material type (e.g. crushed stone or gravel).

on a large scale using coarse and inexact construction methods. The pavement system is furthermore impacted on by highly variable parameters like traffic loading and environment.

Given the large variability inherent in pavement systems and materials, any rigorous statistical approach would advocate relatively large sample sizes to obtain accurate estimates of population parameters such as the mean and confidence limits. In cases where a rigorous statistical approach was followed (Jordaan and Van As, 1994), the recommended sampling intervals or sample sizes prove to be very expensive, and only appropriate for non-destructive testing devices like the Deflectograph which measure at near continuous intervals. It is almost certain that the rigorous application of sampling theory to obtain sampling intervals for destructive tests like the DCP and test pits would prove to be impractical and too expensive.

One factor which mitigates the effect of small samples is the fact that a holistic pavement evaluation does not – or should not – rely on only one parameter to drive the assessment. When several different indicators are used in a systematic and comprehensive evaluation of the situation, the sample size of the overall evidence set effectively increases. For example, it can be argued that an information set consisting of 10 deflections, two test pits and five DCP tests is better than one that consists of 100 deflections alone.

An important aspect of this situation is that in pavement evaluation, all tests are indicators. No test provides a complete description of fundamental information needed for design. As such, each test provides a single piece of the material evaluation puzzle. It can thus be argued that, in a holistic evaluation approach, what is needed is not more of the same piece, but many different pieces, as is illustrated in Figure 1. This figure illustrates the balance that needs to be struck between a more reliable assessment of a small part of the behaviour to be explained, and a less reliable assessment of a large part of the behaviour to be explained.



Situation 1: Reliable estimation of one indicator

Situation 2: Three indicators, but less reliable estimation each

Figure 1: Reliability versus Completeness of Assessment

Given the fact that most test parameters provide incomplete information, a viable approach would be to regard each observation as an additional piece of evidence, and then use this evidence to adjust the opinion about the likelihood of an outcome or situation (e.g. the type and state of a material). This approach can be applied even when there is only a single observation of a certain type. Admittedly, we will not have much confidence in our opinion if it is based only on one observation for a specific type of evidence. However, when we systematically add other evidence (i.e. other test parameters) to our assessment, then our confidence can increase significantly.

The approach of using observations to update the likelihood of a certain occurrence or situation being applicable has been used with good effect in areas where subjective opinion and small samples provide the only basis for estimation. An example of this approach is Bayesian updating, in which the probability of a certain hypothesis being true or false is updated sequentially by adding available evidence (Hopgood, 2001). In this study, a derivation of Bayesian updating, called Certainty Theory, was adopted to address the problem of classifying material using evidence constructed from small samples. This approach will be described in detail in Section 5.

3 CLASSIFICATION FRAMEWORK

The previous section outlined the basic concepts related to the interpretation of test data. Vagueness, uncertainty and subjectivity were highlighted as some of the characteristics of the material assessment task that present specific challenges. It was also noted that, to address these challenges systematically, a sound materials assessment method should: (a) start from a sound fundamental basis; (b) contain very specific guidelines for interpreting test data; and (c) be holistic and comprehensive.

This section outlines a framework for the systematic interpretation of several materials tests, with the objective to obtain a rational and consistent classification of a material. The discussion is presented in three main subsections which respectively address the three requirements noted above.

3.1 A FUNDAMENTAL BASIS

To provide a sound basis for the materials classification method developed as part of this study, a model of pavement material behaviour was first adopted. The assumed model is shown in Figure 2, and represents the material as a conglomerate of course particles, fine particles, binder and air voids. The material model adopted is the well-known Mohr-Coulomb model, which generally applies to composite materials consisting of a combination of loose aggregate and binder. A schematic representation of this material is shown in Figure 2. This model applies to almost all pavement engineering materials except clay and silt and manufactured materials such as geotextiles, with the important distinction that the composition of the mastic differs significantly for different materials.

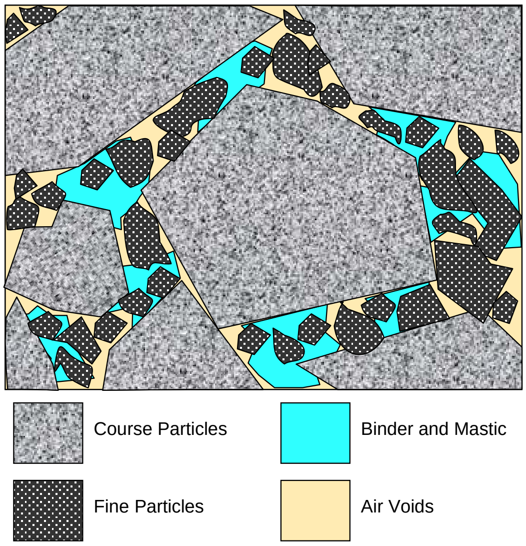


Figure 2: Mohr-Coulomb Material Model

The material model shown in Figure 2 can be used to explain the components that determine the strength and stiffness of the material. There are two components that determine the material's shear strength:

- The cohesive strength, which is determined mainly by the mastic (consisting of the mixed binder and fine material), and

- The strength provided by inter-particle friction, and mobilized when compressive stresses force the fine and coarse particles together.

The cohesive and frictional strength components determine not only the shear strength, but also the stiffness and tensile strength. When the material is in compression, the stiffness and shear strength is primarily determined by a combination of the cohesive and frictional elements. When the material works in tension, particles are not pushed together and the stiffness and tensile strength are determined mainly by the cohesive element (i.e. the mastic).

The materials that are most resistant to shear and tensile failure are those in which there is a good balance between the strength provided by the cohesive and frictional elements. However, some materials tend to be dominated either by the frictional or cohesive element, as illustrated in Figure 3.

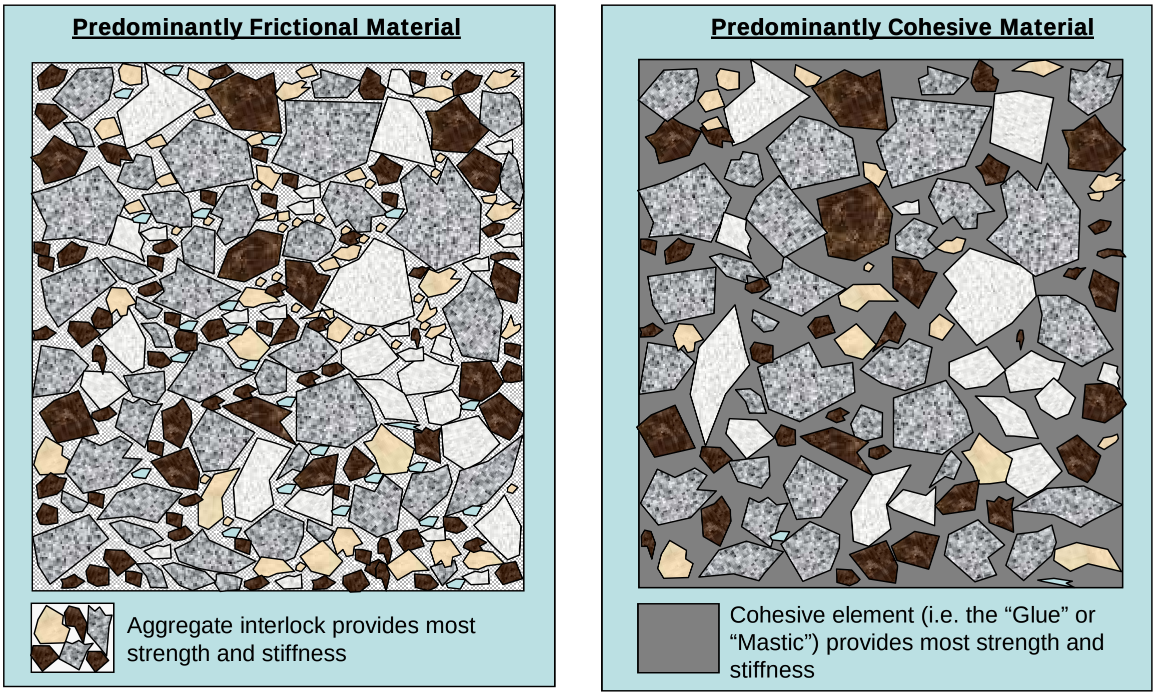


Figure 3: **Material Composition, Showing Dominance of Friction and Cohesion**

It is clear from the composition of these materials that the relative role that the frictional or cohesive component plays in determining the strength and stiffness depends almost entirely on the state of the mastic. In the case of asphalt, for example, the mastic consists of the binder and filler combination. At high temperatures, the visco-elastic binder softens. When the material is loaded in this condition, load is transferred directly to the coarse aggregate matrix, and shear strength will thus derive almost completely from the frictional component. A similar effect is observed in crushed stone and natural gravel, where excess water will destroy the suction forces that bind the fine particles together into a mastic, thereby significantly reducing the cohesive strength or stiffness component.

A clear understanding of the role of cohesion and friction in determining the strength and stiffness of pavement materials is important, as most test indicators provide an assessment of one or both of these elements. Thus some tests, like the Plasticity Index (PI), relate only to the cohesive element, while others, like a grading analysis, relate to the shear strength element. A fundamental understanding of what is measured by a specific test can provide the key to a rational and useful interpretation of the test’s results.

The above definition and discussion of the Mohr-Coulomb model, and the cohesive and frictional components that drive this model, are used in Section 4 to classify the various materials tests, and to guide their interpretation.

3.2 GUIDELINES FOR TEST INTERPRETATION

Many engineering tests are well established and form part of material specifications. Where such tests also provide a numerical output, the interpretation of the test is relatively straightforward. One such example is the PI, which is represented by a number, and which is included in the specification of several material types. It is thus relatively easy to build a scale of interpretation of PI results.

Other tests are less precise, and more detailed guidelines are needed to guide engineers in interpreting the test result. One such example is the material grading, which is generally evaluated by means of a visual assessment of a particle size distribution plot. To use this assessment for comparing and classifying materials, the assessment needs to be quantified in some way. This quantification can be guided by a proper understanding of what the test measures, and by experience of the range of typical outcomes (representing materials with good to poor shear strength and stiffness).

A key element of the framework as proposed in this study is thus the figures or tables used to convert a standard test result to a *rating* which can be used directly for materials classification. Coupled with this is the range of values, for each test rating, which are expected to be measured in each material class. For this classification system, the rating of each test result was designed to correspond with the material classes, as will be explained in more detail in Section 4.

Examples of the rating systems developed for the interpretation of PI and moisture content are shown in Figure 4. It should be noted that these rating systems are at this stage based on available specifications, and will be calibrated and refined as part of the pilot implementation planned for 2007. Section 4 documents the rating systems for all the tests that were selected for use in the proposed materials classification system.

Material Type	**Plasticity Index Measured on Fraction Passing 0.425 mm Sieve**									
Crushed stone	< 4	4 and 5	6 and 7	8 to 10	> 10					
Natural gravel			< 5	5 and 6	6 to 10	10 to 12	> 12			
Gravel-soil						< 11	11 or 12	13 to 15	> 15	
Sand, Silty Sand, Silt, Clay							< 12	12 to 14	14 to 20	> 20
PI Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Material Type	**Moisture Content as Percentage of Optimum**									
Crushed stone	< 60	60 to 65	66 to 80	81 to 90	91 to 100	> 100				
Natural gravel			< 65	65 to 70	71 to 80	81 to 100	> 100			
Gravel-soil						< 80	80 to 90	91 to 100	> 100	
Sand, Silty Sand, Silt, Clay							< 90	90 to 100	101 to 120	> 120
Relative Moisture Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Figure 4: Examples of Test Rating Systems for Consistent Interpretation of Test Results

The examples shown in Figure 4 apply to unbound materials and thus the test rating corresponds directly to the design equivalent materials class, which can range from a G1 to a G10. The meaning of the design equivalent class, as defined in Section 2.3, is important when the rating systems are interpreted. For example, Figure 4 shows that, for this proposed interpretation, a crushed stone material with a PI greater than 12 would be assigned a PI rating of 6. Since the PI rating is designed to coincide with the TRH14 material classes, the material is regarded as being the design equivalent of a G6. This means that, based on the PI only, the material is more comparable to a G6 (a soil-gravel blend) than a graded crushed stone.

It should be clear from this example that the system is not clinical and precise, but relies to a large extent on experience and subjective interpretation. However, the system ensures that a proper and consistent interpretation is performed. It also normalizes the test result across different material types so that test results can be quantified and combined. This is a vital aspect of the proposed system, since the system is highly dependent on the availability of several *different* test indicators to obtain a balanced and reliable result. This aspect was introduced in Section 2.5, and is further expanded on in the following subsection.

3.3 A HOLISTIC APPROACH

A vital aspect of the proposed system is that it provides a framework for the rational synthesis of several different test indicators. In fact, the outcome of the assessment becomes more reliable as more test indicators are added to the assessment. This is because each test typically explains only a small part of the cohesive or frictional elements of material behaviour. More complex tests, like triaxial shear tests, may evaluate these two elements together, but will do so only for a specific moisture or binder content. The use of other indicators will still be needed to determine how the material will behave if the moisture state or binder content changes.

Since each test provides only a partial explanation of the material's behaviour, the reliability of the assessment can be greatly increased by increasing the sample size, and by adding more indicators (i.e. test types) to the assessment. The proposed system is therefore strongly biased towards a holistic assessment, which works best when a comprehensive range of test indicators are used.

Several methods have been developed to enable decision making or system control based on uncertain and vague information, and some of these methods are outlined in Hopgood (2001). The approach developed for this study is based mainly on Certainty Theory (Shortliffe and Buchanan, 1975; Hopgood, 2001) but also incorporates some aspects of Fuzzy Logic (Zadeh, 1975; Hopgood, 2001).

Certainty Theory is adapted from Bayesian Updating (Hopgood, 2001), and has been implemented in expert systems that assist in the diagnosis of infectious diseases (Shortliffe, 1976). Certainty theory in essence provides the framework from which hypotheses can be tested using vague and uncertain evidence. The following features of Certainty Theory are especially useful in the context of pavement materials classification:

- Several pieces of independent evidence can be combined to test the certainty that a given hypothesis is true;
- The method provides a consistent outcome, irrespective of the order in which the available evidence is evaluated;
- If there is uncertainty about evidence (either due to vagueness or sample size), then this can be explicitly incorporated in the assessment.

Certainty Theory is somewhat similar to Bayesian Updating in that evidence is used sequentially to make an assessment. However, in the case of Certainty Theory, the hypothesis to be tested is associated with a certainty value instead of a formal statistical probability. The method works as follows (Hopgood, 2001):

1. If H is the hypothesis to be tested, then the certainty that the hypothesis is true is designated as C(H), which has a value of 1.0 if H is known to be true, 0.0 if H is unknown and -1.0 if H is known to be false. In the context of the present study, H could for example be the hypothesis that the base layer is a G1 design equivalent.

2. The value of C(H) is determined by applying rules which are based on experience or domain knowledge. Each rule has a certainty factor (CF) associated with it, to reflect the level of certainty in the available evidence, or in the knowledge on which the rule is based. A typical rule may be:

   If [PI < 4] then [Material is a G1 design equivalent] With Certainty CF

3. The certainty factor of a rule, CF, is modified to reflect the level of certainty in the evidence. This gives the modified certainty factor CF', calculated simply as:

   $CF' = CF \times C(E)$ ....*(Equation 4.1)*

   Where C(E) is a number between 0 and 1, indicating that the evidence in support of the hypothesis is either completely absent (C(E) = 0.0) or known to be present with absolute certainty (C(E) = 1.0).

4. To get C(H|E), which is the updated certainty that the hypothesis H is true, given the evidence E, the following composite function is applied (Hopgood, 2001):

   <u>If $C(H) \geq 0$ and $CF' \geq 0$ then</u>: $C(H|E) = C(H) + [CF' \times (1-C(H))]$................................*(Equation 4.2)*

   <u>If $C(H) \leq 0$ and $CF' \leq 0$ then</u>: $C(H|E) = C(H) + [CF' \times (1+C(H))]$.............................*(Equation 4.3)*

   <u>If C(H) and CF' have opposite signs, then:</u>

   $$C(H|E) = \frac{C(H) + CF'}{1 - min(|C(H)|, |CF'|)}$$ ....*(Equation 4.4)*

In the application of the above methodology for material classification, the certainty factor CF associated with a specific test can be assigned based on domain knowledge and experience. If the test is known to be a good overall indicator of cohesion, frictional resistance or both, then CF will tend to be higher. CF can also be adjusted based on the sample size and range of sampled values. For small sample sizes, CF can be lowered to reflect decreased confidence in the available evidence.

The steps and equations outlined above provide a general method for consistently evaluating the certainty that a hypothesis is true, given uncertain and vague rules and evidence. A generalized and simplified example of the method's application for materials classification is outlined below:

1. We want to test the hypothesis H that the material for which we have information is a graded natural gravel (G4). To do this, we formulate the following rules:

   If [Material is Natural Gravel] and [PI < 4] then [Material is a G4 design equivalent] with CF = 0.4

   If [Grading conforms to G4 Envelope] then [Material is a G4 design equivalent] with CF = 0.3

2. We now obtain samples and measure the PI and grading. The certainty factors can be adjusted based on the sample size.

3. We start with the first available evidence (PI test). At this stage C(H) = 0. Since CF = 0.4 for the first rule concerning PI, we use Equation 4.1 and 4.2 to calculate the updated certainty for the hypothesis that the material is a G4 (C(H|E).

4. The updated certainty C(H|E) becomes the new starting certainty C(H) for the second rule which interprets the grading. We again apply Equation 4.2 to calculate the new value for C(H|E).

This process can be applied for each material class to obtain a relative indication of how much the available test data point to each class. In such an application, the calculations are simple, but the repeated application of rules to different material classes can be cumbersome. However, as will be shown in the detailed description of the method in Section 6, this process can easily be programmed into a spreadsheet or other software application. A worked example is included in Section 5.6.

4 RECOMMENDED TESTS AND INTERPRETATION OF RESULTS

Section 3 outlined a general framework for materials classification and presented a general method to address the most important needs for such a framework. A fundamental material model was presented, and it was highlighted that most materials tests provide an indication of cohesion and/or friction resistance, which constitute the two determining components of shear strength and stiffness.

In this section, pavement and material tests that can be used for material classification are discussed. The objective of this section is to present the available tests and indicators, together with a method for rating or interpreting the test outcome, specifically so that the rated outcome can be used in a combined assessment. The method for *combining* the assessments from various tests is detailed in Section 5. The discussion of available test types is grouped according to the following three key material types: (a) unbound granular materials; (b) cement stabilized layers; and (c) bitumen stabilized materials.

4.1 GENERAL COMMENTS ON SELECTED TESTS AND INTERPRETATION GUIDELINES

The tests presented in the following paragraphs mostly consist of routine pavement assessment tests. As such, the relation between the various tests and material behaviour and performance is well-established[♣], and many of the tests form part of current materials guidelines or specifications. A detailed discussion of each test, with validation of its relevance is considered to be outside of the scope of this study. However, some explanation and references are provided for some tests or indicators, especially for those tests that do not normally form part of standard specifications.

For tests that provide a quantified outcome that is easy to interpret, guidelines for interpreting the outcome are provided. For tests that do not provide a quantified outcome, or for which the interpretation is more complex (e.g. depending on material type), a *rating system* is proposed. The rating system was designed to correspond directly with the TRH14 classification system. Thus, the rating scale for unbound granular materials ranges from 1 to 10, with a rating of 1 corresponding to a G1 design equivalent material class. Apart from the association between the rating and material class, the rating also provides a numerical value that can be used to determine sample statistics. This is a vital aspect of the material classification system, since a proper synthesis of information only becomes possible when test indicators can be consistently quantified.

It should be noted that the proposed interpretation guidelines and rating systems were derived based on available guidelines and specifications such as TRH14. However, the interpretation guidelines are not intended to be a duplication of existing specifications. In many instances the guidelines or rating system had to be adjusted to suit the objective of this study, which is material classification. Some deviation from existing guidelines or specifications should thus be expected.

It will be noted that in some instances the interpretation guidelines point to more than one material class for a given indicator range. For example, a CBR value of 82 per cent may indicate a G2, G3 or G4 material. In such instances, the indicator merely serves to disqualify other material classes. In other instances, ranges of values are associated with different material classes. These ranges may overlap, meaning that a test outcome may again point to more than one material class. This assignment is by design, and explicitly indicates that the outcome points to more than one possible material class. To further refine the material classification, more tests will need to be considered, and the method for doing this is detailed in Section 5.

[♣] It is acknowledged that the ability of some routine tests to quantify shear strength has been doubted in recent years by some researchers. Examples of such tests include the California Bearing Ratio (CBR) and the Unconfined Compressive Strength (UCS) test. The reader should bear in mind, however, that a key principle of the proposed system is to make an assessment based on a combined evaluation of several test types. As such, even partially useful tests may assist in some way to make a more reliable classification. This aspect is discussed in more detail in Sections 2.5 and 3.3.

In some tables, the following abbreviations are used:

CS	=	Crushed Stone;
NG	=	Natural Gravel;
GS	=	Gravel-Soil Blend

4.2 CLASSIFICATION INDICATORS FOR UNBOUND GRANULAR MATERIALS

Guidelines for the interpretation of the test results are provided in the tables that follow. A summary of the tests and indicators that can be used to classify unbound granular materials are presented in Table 4.

Table 1: Interpretation of California Bearing Ratio (CBR)

Test Density	Soaked CBR (%)	Possible Design Equivalent Material Class
98 % Mod. AASHTO or In-Situ Density	>100	G1
	80 to 99	G2, G3 or G4
95 % Mod. AASHTO or In-Situ Density	45 to 79	G5
93 % Mod. AASHTO or In-Situ Density	25 to 44	G6
	15 to 24	G7
90 % Mod. AASHTO or In-Situ Density	10 to 14	G8
	7 to 9	G9
	< 7	G10

Note: Interpretation ranges are based mainly on TRH14 guidelines

Table 2: Interpretation of Percentage Passing 0.075 mm Sieve

Percentage Passing 0.075 mm Sieve	Possible Design Equivalent Material Class
4 to 12	G1, G2 or G3
5 to 15	G4
13 to 20	G5
15 to 25	G6
25 to 30	G7
30 to 40	G8
40 to 50	G9
> 50	G10

For the interpretation of the Percentage Passing the 0.075 mm Sieve, some results may point to more than one material class. For example, for 18 percent passing, the material class could be either a G5 or G6. In such instances, the highest material class that matches the measured values should be assigned.

Table 3: Interpretation of Relative Density

Relative Density	Possible Design Equivalent Material Class
≥ 1.02	G1
1.00 to 1.01	G2
0.98 to 0.99	G3, G4
0.95 to 0.97	G5
0.93 to 0.94	G6, G7
< 0.93	G8,G9,G10

Table 4: Indicators and Tests for Classification of Unbound Granular Materials

Test or Indicator	Relevance for Material Classification	Interpret. or Rating	Comments
Soaked CBR	When soaked, tests mainly the frictional strength component of shear strength.	Table 1	Test relevance and interpretation is based on TRH14 specifications.
Percent passing 0.075 mm Sieve (Fines)	Impacts on the density that can be achieved, and on the bearing strength of the material. As such, relates mainly to frictional component of shear strength.	Table 2	Ideal range is 6 to 10 per cent. At less than 4 % fines, density is difficult to achieve. Shear strength reduces when fines exceed roughly 13 % (Hefer and Scullion, 2002; Gray, 1962).
Relative Density	Relates to the density of packing of particles, and hence to the potential to develop frictional resistance.	Table 3	Test relevance and interpretation is based on TRH14 specifications.
DCP Penetration	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity	Table 5	Test relevance and interpretation is based on experience and ranges published Kleyn (1984).
FWD Stiffness	Provides a direct but relative indication of the stiffness under dynamic loading. Likely to be highly correlated to shear strength at small strains for most materials.	Table 6	Test relevance and interpretation ranges based on experience in southern Africa.
Consistency Rating	Provides a rough indication of material density and stiffness.	Table 7 to 9	Rating based on material consistency evaluation from test pits.
Plasticity Index Rating	Determines the influence of water on shear strength. For a fixed maximum aggregate size, shear strength is greatly reduced with an increase in PI.	Table 11	Rating is based on TRH14. Test relevance and main effects related to shear strength are reported in Hefer and Scullion (2002); and in Gray (1962).
Visible and Measured Moisture Content	The relative moisture content is the measured moisture content, relative to the optimum moisture content for the material. It provides an indication of the degree of saturation and the relative cohesive strength.	Table 10 and Table 12	Rating is based on experience, and on specifications reported by Hefer and Scullion (2002). These include the specifications of New South Wales (1997) and Queensland (1999).
Grading Assessment Rating	Rating quantifies the conformance of the material grading to applicable specifications. Good conformance to grading indicates increased frictional resistance.	Table 13	Rating requires that the relative conformance to the appropriate grading be quantified. This value is then used to obtain an overall rating for grading based on material type.
Rating for Grading Modulus	Rating quantifies the relative amount of fines in the material. As such, it influences the ability of the material to develop interlock between coarse particles.	Table 14	Rating is based on TRH14 and on Colto (1998) specifications.
Rating for Aggregate Crushing Value (ACV)	The ACV is believed to provide an indicator of aggregate strength and soundness. Lower strength and poor durability will indicate reduced long term shear strength.	Table 15	Rating is based on TRH14 and on Colto (1998) specifications.
Number of Fractured Faces	The number of fractured faces on the minus 0.475 mm sieve fraction serves as an indication of angularity and surface friction. This impacts directly on stiffness and shear strength.	Table 16	Rating is based on TRH14 and on Colto (1998) specifications. Relation between the angularity and texture of particles and the shear strength and stiffness is discussed in Hefer and Scullion (2002).
Historical Performance	The historical performance for the base and subgrade can be isolated with some confidence using past traffic and observed condition.	Table 17	Based on experience and existing guidelines (e.g. TRH12, 1998).

Table 5: Interpretation of DCP Penetration Rate

Penetration Rate (mm/blow)	Possible Design Equivalent Material Class
< 1.40	G1
1.40 to 1.79	G2
1.80 to 1.99	G3
2.00 to 3.69	G4
3.70 to 5.69	G5
5.7 to 9.09	G6
9.1 to 13.99	G7
14.00 to 18.99	G8
19.00 to 25.00	G9
> 25.00	G10

Note: To quantify a DCP refusal result, a penetration rate value of -1 is recommended to denote refusal.

Table 6: Interpretation of FWD Backcalculated Stiffness

Backcalculated Stiffness (MPa)	Possible Design Equivalent Material Class
> 600	G1
500 to 600	G2
400 to 499	G3
300 to 399	G4
200 to 299	G5
150 to 199	G6
100 to 149	G7
70 to 99	G8
50 to 69	G9
0 to 49	G10

Table 7 provides a rating system for the evaluation of consistency. It is recommended that the consistency description be based on the definitions as provided in the latest M1 Manual (SANRAL, 2004). The definition of various consistency descriptions is shown for coarse granular materials and cohesive soils in Table 8 and Table 9, respectively.

Table 7: Rating of Consistency

Material Type	**Consistency Description**									
Crushed Stone	V.Dense	Dense	Med. Dense	Loose	V.Loose					
Natural Gravel			V.Dense	Dense	Med. Dense	Loose	V. Loose			
Gravel-Soil					V.Dense	Dense	Med. Dense	Loose	V. Loose	
Sand, Silty Sand, Silt, Clay						V.Stiff	Stiff	Firm	Soft	V. Soft
Consistency Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 8: Guidelines for Consistency of Coarse Granular Materials (after SANRAL, 2004)

Consistency	Description of Layer Condition
Very Loose	Very easily excavated with spade. Crumbles very easily when scraped with geological pick.
Loose	Small resistance to penetration by sharp end of geological pick.
Medium Dense	Considerable resistance to penetration by sharp end of geological pick.
Dense	Very high resistance to penetration of sharp end; and requires blows of geological pick for excavation.
Very Dense	Very high resistance to repeated blows of geological pick; and requires power tools for excavation.

Table 9: Guidelines for Consistency of Cohesive Soils (after SANRAL, 2004)

Consistency	Description of Layer Condition
Very Soft	Geological pick head can easily be pushed in to the shaft of handle; easily moulded by fingers.
Soft	Easily penetrated by thumb; sharp end of geological pick can be pushed in 30 to 40 mm; moulded with some pressure.
Firm	Indented by thumb with effort; sharp end of geological pick can be pushed in up to 10 mm; very difficult to mould with fingers; can just be penetrated with an ordinary hand spade.
Stiff	Penetrated by thumb nail; slight indentation produced by pushing geological pick point into soil; cannot be moulded by fingers; requires hand pick for excavation.
Very Stiff	Indented by thumb nail with difficulty; slight indentation produced by blow of geological pick point; requires power tools for excavation.

Table 10: Rating of Visible Moisture

Material Type	Moisture Content Description									
Crushed Stone	Dry	Slightly Moist	Moist	Very Moist	Wet					
Natural Gravel		Dry	Slightly Moist	Moist	Very Moist	Wet				
Gravel-Soil					Dry	Slightly Moist	Moist	Very Moist	Wet	
Sand, Silty Sand, Silt, Clay						Dry	Slightly Moist	Moist	Very Moist	Wet
Visible Moisture Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 11: Rating of Plasticity Index

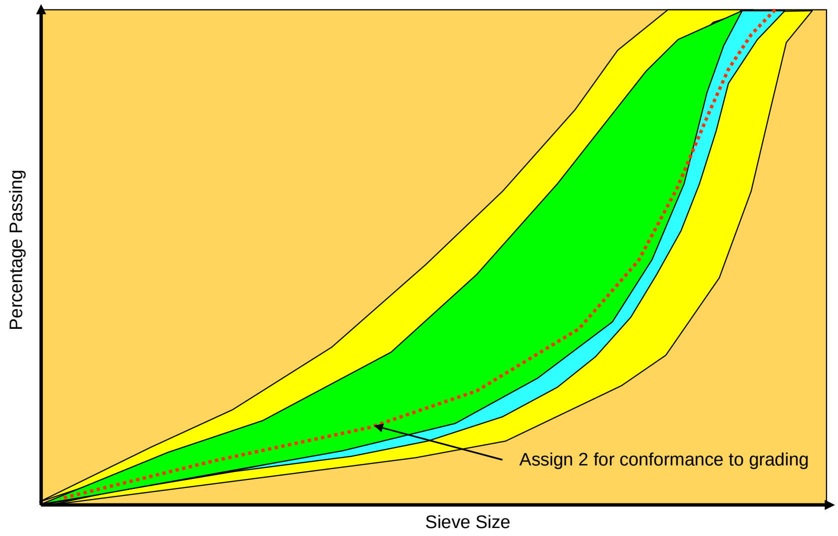
Material Type	Plasticity Index Measured on Fraction Passing 0.425 mm Sieve									
Crushed stone	< 4	4 and 5	6 and 7	8 to 10	> 10					
Natural gravel			< 5	5 and 6	6 to 10	10 to 12	> 12			
Gravel-soil						< 11	11 or 12	13 to 15	> 15	
Sand, Silty Sand, Silt, Clay							< 12	12 to 14	14 to 20	> 20
PI Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 12: Rating of Relative Moisture Content

Material Type	Moisture Content as Percentage of Optimum									
Crushed stone	< 60	60 to 65	66 to 80	81 to 90	91 to 100	> 100				
Natural gravel			< 65	65 to 70	71 to 80	81 to 100	> 100			
Gravel-soil						< 80	80 to 90	91 to 100	> 100	
Sand, Silty Sand, Silt, Clay							< 90	90 to 100	101 to 120	> 120
Relative Moisture Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

The rating for grading assessment requires first that the relative conformance of the material to the appropriate grading envelope be determined. For this assessment, a score of 1 to 4 is assigned, where 1 denotes full compliance to the grading envelope, and 4 denotes a significant deviation from the envelope. Figure 5 can be used as a guide to determine the relative conformance to the grading envelope.

Once the conformance to the grading envelope has been quantified, an overall rating for grading can be assigned using the rating system shown in Table 13. This system assigns an overall grading rating from 1 to 10, based on the material type and the quantified conformance to grading.



1	Inside Grading Envelope
2	Just coarse of envelope, but follows envelope closely (well-graded)
3	Fine of envelope, or significantly coarse of envelope
4	Significant deviation from specified envelope

Figure 5: Interpretation of Grading to Quantify Relative Conformance to Grading

Table 13: Rating of Grading Assessment

Material Type	Conformance to Grading Envelope									
CS (use TRH 14 G1to G3 Spec)	1	2	3	4						
NG (use TRH 14 G4 Spec)				1	2	3	4			
GS (use TRH 14 G4 Spec)					1	2	3	4		
Grading Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 14: Rating of Grading Modulus

Material Type	Grading Modulus									
Natural Gravel				2.6 to 2.0	2.5 to 1.5	2.7 to 1.2	< 1.2			
Gravel-Sand Blend						2.5 to 1.2	2.7 to 0.75	2.7 to 0.75	2.7 to 0.75	< 0.75
GM Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

For the interpretation of Grading Modulus (GM), some results may point to more than one rating. For example, for natural gravel a GM value of 2.3 can have a rating of 4, 5 or 6. In such instances, the highest rating that matches the measured value should be assigned.

Table 15: Rating of Aggregate Crushing Value (ACV)

Material Type	ACV									
Crushed Stone	<28	28 or 29	30	>30						
Natural Gravel			<29	29 or 30	>30					
ACV Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 16: Rating of Number of Fractured Faces

Material Type	Number of Fractured Faces of +4.75 mm Material									
Crushed Stone	All Faces	2	1	<1						
Natural Gravel			2	1	<1					
Fractured Faces Rating	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Table 17: Rating of Historical Performance (Base Layers)

Condition Description (select one matching closest)	**Traffic Accommodated to Date (mesa)**				
	<0.5	**0.5 to 1**	**1 to 3**	**3 to 10**	**>10**
No visible rutting, deformation, pumping or potholes, surfacing mostly intact. Minor patching only.	Difficult to assess		2	1	1
Less than 8 mm narrow rutting in wheelpath, minor pumping and traffic-related cracking. Minor patching.	Difficult to assess	4	3	2	1
8 to 12 mm narrow rutting in wheelpath, some deformation, shoving and/or pumping. Frequent patching noted.	7	5	4	3	Difficult to assess
More than 12 mm narrow rutting in wheelpath, severe and frequent shoving, pumping and/or deformation. Frequent patching.	9	7	5	Difficult to assess	

Note: Assessment is only valid if there are no surfacing related problems (e.g. stripping, brittleness, rutting) which may have caused a rapid deterioration in the base layer. Also, assessment is not valid if an overlay or surface seal was recently placed.

Table 18: Rating of Historical Performance (Subgrade Layers)

Condition Description (select one matching closest)	Traffic Accommodated to Date (mesa)				
	<0.5	0.5 to 1	1 to 3	3 to 10	>10
No wide, subgrade related rutting visible	Difficult to assess		7	6	5
Suspect some subgrade deformation occurred, as shown by wide, subgrade related rutting (<10 mm depth), and slight undulation and/or subgrade related failures	Difficult to assess		8	7	6
Strong evidence of subgrade related rutting (>10 mm depth) and/or severe undulations or definite signs of subgrade related failures	10	9	8	Difficult to assess	

Note: Assessment is only valid if an overlay or surface seal was not recently placed.

4.3 CLASSIFICATION INDICATORS FOR CEMENT STABILIZED MATERIALS

A summary of the tests and indicators that can be used to classify cement stabilised materials is presented in Table 19. Guidelines for the interpretation of the test results are provided in the tables that follow.

The classification of cement stabilized materials is more complex than for unbound granular materials, since the state of the material can vary significantly depending on the degree of cementation still present in the material, and on the deterioration owing to past traffic. Determining whether the layer is still in a cemented state is a key aspect of the material classification, and this was taken into account in the design of test interpretation guidelines.

As in the case of unbound granular materials, guidelines for interpretation of test results are provided. For some tests or indicators, a rating scheme is proposed to enable test indicators to be consistently quantified. The rating scheme was designed so that the following relationship between the test rating and material classes apply:

Rating 1: Indicates condition similar to recently constructed C1, C2 or C3 material.

Rating 2: Indicates condition similar to recently constructed C4 material.

Rating 3: Indicates material is either ineffectively stabilized, or deteriorated to an equivalent granular state.

Materials for which the rating from various tests averages to 3 should be regarded as unbound granular material, and the classification guidelines for unbound granular materials should be applied in such cases.

Table 19: Indicators and Tests for Classification of Cement Stabilized Materials

Test or Indicator	Relevance for Material Classification	Interpretation or Rating	Comments
Consistency Rating	Provides a rough indication of the degree of cementation of the material.	Table 20	Rating based on material consistency evaluation from test pits. Rating system is based on the SANRAL M1 Manual (SANRAL, 2004).
DCP Penetration	Indicator for overall shear strength. Sensitive to density, moisture content, particle strength, grading and plasticity.	Table 21	Test relevance and interpretation is based on experience and ranges published by Kleyn (1984).
FWD Stiffness	Provides a direct but relative indication of the stiffness under dynamic loading. Likely to be highly correlated to shear strength at small strains for most materials.	Table 22	Test relevance and interpretation ranges based on experience in southern Africa.
Evidence of Active Cement	Quantifies the confidence that material is acting as a cohesive, cement stabilized layer	Table 24	None

Table 20: Interpretation of Cemented Layer Consistency (after SANRAL, 2004)

Material Condition	Rating
Hand-held specimen can be broken with hammer head with single firm blow. Similar appearance to concrete.	1
Firm blows of sharp geological pick point on a hand-held specimen show indentations of 1 mm to 3 mm. Grains cannot be dislodged with a knife blade.	1
Material crumbles under firm blows of sharp geological pick point. Grains can be dislodged with some difficulty under a knife blade.	2
Cannot be crumbled between strong fingers. Some material can be crumbled by strong pressure between thumb and hard surface. Disintegrates under light blows of a hammer head to a friable state.	2
Some material can be crumbled by strong pressure between fingers and thumb. Disintegrates under a knife blade to a friable state.	3

Table 21: Interpretation of DCP Penetration Rate (Cement Stabilized Materials)

Penetration Rate (mm/blow)	Rating
< 1.50	1
1.5 to 3	2
> 3	3

Note: To quantify a DCP refusal result, a penetration rate value of -1 is recommended to denote refusal.

Table 22: Interpretation of FWD Backcalculated Stiffness (Cement Stabilized Materials)

Backcalculated Stiffness (MPa)	Rating
>1200	1
500 to 1200	2
< 500	3

Table 23: Rating for Evidence of Active Cement

Available Evidence	Rating
Clearly visible in material colour and consistency. Clear indication of active cement, based on chemical tests.	1
No cementation visible, slight indication of active cement, based on chemical tests.	2
No indication of active cement, either in material colour and consistency or from chemical tests.	3

4.4 CLASSIFICATION OF BITUMEN STABILIZED MATERIALS

It was noted in Section 1 that the classification method presented in this document forms part of a larger study aimed at the development for guidelines for the design and use of bitumen stabilized materials. A critical component of this larger project is a study aimed at the development of suitable tests and indicators for the design of bitumen stabilized materials. In particular, the study will aim to develop test protocols and evaluation criteria to use in the design of bitumen stabilized materials. It is hoped that these tests will address the assessment of shear strength, stiffness, flexibility, curing and durability.

Since the development of tests and acceptance criteria for bitumen stabilized materials is still underway, detailed guidelines for the classification of these materials are not yet available. At this stage, the following guidelines and tests are tentatively proposed for the classification of bitumen stabilized materials[♣]:

> Source Material Class: Bitumen stabilized materials are believed to be highly dependent on the quality of the source material (Jooste and Long, 2007). The classification of the stabilized material would therefore rely to a large extent on the classification of the material before stabilization. The design equivalent material class of the unstabilized source material (typically G1 to G10) is therefore expected to be a primary determinant in the classification of bitumen stabilized materials.
>
> Tests for Overall Shear Strength: Bitumen stabilized materials, as typically used in South Africa, involve relatively low binder contents. The observed long term field performance of these materials (Jooste and Long, 2007) suggests that these materials act in a manner similar to dense crushed stone (i.e. stress dependent, Mohr-Coulomb type behaviour). As such, the evaluation of the frictional resistance is a key aspect of the classification of bitumen stabilized materials. A study is currently being conducted to develop a test protocol for assessing the shear strength of bitumen stabilized materials. This test, or a simplified indicator based on the test, would be a key element of the classification of bitumen stabilized materials.
>
> Test for Appropriate Cohesion: Although bitumen stabilized materials are believed to act in a manner similar to dense crushed stone, it is believed that these materials typically have a relatively high cohesive strength compared to unstabilized crushed stone. An assessment of the cohesive strength by means of standard tests such as the Indirect Tensile Strength (ITS) or the Unconfined Compressive Strength (UCS) should therefore be considered. However, it is critical that the assessment of these criteria should be performed by means of *a lower and higher limit.* The lower limit should be used to ensure that the material has a minimum required cohesive strength, while the upper limit should ensure that the material is not over-stabilized, thereby turning it into a brittle material as opposed to a frictional Mohr-Coulomb type material. Materials that cannot meet both the upper and lower limits for cohesive strength indicators should be redesigned by adjustment of the source material grading or source material constitution.

[♣] The reader should note that the classification method presented in this report was developed in support of a design method for pavements that involve bitumen stabilized materials. In this context, the classification of bitumen stabilized materials is mostly concerned with *new materials, or materials yet to be constructed (as opposed to existing bitumen stabilized layers)*. As such, the classification method for bitumen stabilized materials will necessarily rely to a large extent on the quality of the existing layers that will be recycled using bitumen stabilization.

At this stage, the following tentative classification scheme is proposed for bitumen stabilized materials:

> Class BSM1: This material should be designed to have high shear strength, and would typically be used as a base layer for design traffic applications of more than 6 million equivalent standard axles (mesa). For this class of material, the source material would typically be a well graded crushed stone or reclaimed asphalt pavement (RAP).
>
> Class BSM2: This material should be designed to have moderately high shear strength, and would typically be used as a base layer for design traffic applications of less than 6 mesa. For this class of material, the source material would typically be a graded natural gravel or RAP.
>
> Class BSM3: This material will typically consist of soil-gravel stabilized with higher bitumen contents. As a base layer, the material would only be suitable for design traffic applications of less than 1 mesa.

It is expected that guidelines for the test types and interpretation limits to be used for classification of bitumen stabilized materials will become available during 2008. At that time, these tests and interpretation limits can be implemented in the framework and method presented in this document.

5 SYNTHESIS OF AVAILABLE INFORMATION

In the previous section, the tests that can be used for material classification were presented, and guidelines for interpretation and quantifying test results were provided. In this section, a method for combining test results to obtain an overall classification is presented. The method is based on Certainty Theory, as discussed in Section 3.3, but with some important modifications to suit the present context.

5.1 METHOD OUTLINE

As noted in Section 3.3, the Certainty Theory approach involves an assessment of how well the available evidence suits a given hypothesis. In the present context, the evidence would be available test data, and the hypothesis to evaluate would be that the material conforms to a specific material class. The method involves the following steps:

Step 1: For each of the available material tests, determine and report the 90th percentile, median and 10th percentile values from the available observations. For those tests for which a rating system is provided in Section 4, use the ratings at each observation to determine the required statistics. Where there is only one observation available, simply report the observation as the median value.

Step 2: Determine the certainty factor associated with each of the available tests (i.e. CF as defined in Section 3.3). This certainty reflects the confidence that we have in each test to provide an accurate indication of the in-situ shear strength and stiffness of the material. Details related to this step are provided in Section 5.2.

Step 3: Adjust the relative certainty determined in Step 2 to take account of sample size. This adjustment decreases the confidence for smaller sample sizes. Details related to this step are provided in Section 5.3.

Step 4: Select a likely material class (e.g. G4) for the layer in question. We will now determine how well the available test data conform to this class.

Step 5: For each of the available tests, determine the expected range of values for the selected material. For example, if the material in question is a G4, and the test is the soaked CBR, we will use Table 1 to obtain the expected range of CBR values for a G4 (i.e. 80 to 99 per cent, from Table 1). For tests that involve a rating system, as defined in Section 4, the rating values corresponding to different material classes are shown in Table 24.

Step 6: For each test, determine how much the 90th percentile to 10th percentile range overlaps with the expected range of values for the material. This provides the relative certainty that the test data pointing to the material class in question is indeed present (i.e. factor *C(E)*) as defined in Section 3.3). Details of how to perform this calculation are provided in Section 5.4.

Step 7: For each test, use the certainty factor CF from steps 2 and 3 and the certainty of evidence C(E) from step 6, to update the certainty that the material tested conforms to the class selected in step 4. This calculation then provides the relative certainty that the material belongs to the selected class, given the available evidence (i.e. C(H|E) as defined in Section 3.3). Details on these calculations are provided in Section 5.5.

Step 8: Repeat steps 4 to 7 for each likely material class. For example, if we are performing a classification for an unbound granular base, we may evaluate the certainty associated with classes G1 to G5.

Step 9: Select the material with the highest certainty given the available evidence. This material class is assigned to the layer in question. Properly document the evidence and calculations.

Table 24: Test Rating Values Associated with Different Design Equivalent Material Classes

Material Type	Design Equivalent	Test Rating Range
Crushed Stone	G1	0.5 to 1.5
	G2	1.5 to 2.5
	G3	2.5 to 3.5
Natural Gravel	G4	3.5 to 4.5
	G5	4.5 to 5.5
	G6	5.5 to 6.5
Gravel-Soil and Cohesive Soils (Silt and Clay)	G7	6.5 to 7.5
	G8	7.5 to 8.5
	G9	8.5 to 9.5
	G10	9.5 to 10.5
Cement Stabilized	C3	0.5 to 1.5
	C4	1.5 to 2.5
Bitumen Stabilized	BSM1	0.5 to 1.5
	BSM2	1.5 to 2.5
	BSM3	2.5 to 3.5

5.2 CERTAINTY FACTORS FOR DIFFERENT TESTS

It was noted in Section 3 that most pavement materials tests provide only a partial indication of the shear strength and stiffness of a material, and that this characteristic of pavement materials assessment could be addressed by implementing a holistic approach that relies on a broad range of indicators.

To explicitly take account of the fact that all tests provide only a relative indication of the shear strength and stiffness, a certainty factor is assigned to each test indicator. This certainty factor represents the factor CF as defined in Section 3.3. In essence, CF represents our subjective confidence in the ability of a test to serve as an accurate indicator for material strength and stiffness. The value of CF can range from 0 to 1, with a value of 1 indicating absolute confidence in a test or indicator (a highly unlikely assignment).

Table 25 provides suggested certainty factors for the tests and indicators discussed in Section 4. The ratings shown in this table are based on a subjective assessment of the completeness and appropriateness of each test or indicator. Engineers can adjust these values to take account of experience or specific project situations, but the assumed values should be reported to clients. If the assumed values deviate substantially from those suggested in Table 25, the assumed values should ideally be motivated in the assessment report.

Table 25: Recommended Certainty Factors for Different Tests and Indicators

Test or Indicator	Certainty Factor
Soaked CBR	0.4
% Passing 0.075 mm Sieve (Fines)	0.3
Relative Density	0.3
DCP Penetration	0.4
FWD Stiffness	0.3
Consistency Rating	0.2
Plasticity Index Rating	0.4
Measured Moisture Content Rating	0.3
Grading Assessment Rating	0.4
Visible Moisture Content Rating	0.2
Rating for Grading Modulus	0.2
Rating for Aggregate Crushing Value (ACV)	0.3
Number of Fractured Faces	0.3
Historical Performance	0.4
Rating for Evidence of Active Cement	0.3

5.3 ADJUSTMENT FOR SAMPLE SIZE

The problems related to small sample sizes was discussed in detail in Section 2.5, where it was noted that sample sizes consisting of one or two observations are not uncommon in pavement condition assessments. To take account of this, it is recommended that the Certainty Factor (CF) associated with each test be adjusted to take account of the sample size. Table 26 shows the recommended adjustment factors based on sample size. These factors are applied by multiplying the factor from Table 26 with the CF factor for the test from Table 25.

Table 26: Recommended Adjustment of CF based on Sample Size

Sample Size (number of observations)	Adjustment Factor
1	0.2
2	0.3
3	0.6
4 to 6	0.7
6 or greater	1.0

5.4 ASSESSING THE RELATIVE CERTAINTY OF EVIDENCE

The problem related to vagueness and uncertainty of test data was discussed in Section 2. In the present context, uncertainty is introduced because of the incompleteness of most tests, and by the fact that we are using a sampling estimate. The incompleteness of tests is taken into account by the assignment of a certainty factor (CF) to each test, as explained in Section 5.2. However, we still need to account for the fact that we are using a small sample to estimate the state of a material, and for the variation observed in the test results.

To illustrate the problem, consider a scenario where we have 5 CBR tests for a selected layer. For this small sample, the 10th percentile, median and 90th percentile CBR values are 16, 24 and 40, respectively. If we want to test how well the CBR conforms to a G6 material, we first determine the CBR range associated with a G6 from Table 1, and obtain a CBR range of 25 to 44 per cent.

One way to assess whether the material is a G6 is to simply use the 10th percentile value, based on the assumption that this will give us a suitably conservative estimate. However, this approach over-simplifies the problem, because it gives us a simple yes or no answer, implying that the material is either definitely a G6 or not at all. This over-simplifies the assessment, as the results we have clearly show that the material is at least *somewhat like a G6*, based on the CBR values.

A more rational, albeit less exact, approach is clearly needed. Specifically, the approach should be able to handle vagueness. Rather than giving a yes or no answer, it should indicate whether the material conforms to a G6 in less restrictive terms. An assessment phrased as “somewhat like a G6”, “a lot like a G6” or “not at all like a G6” would be more appropriate.

To accommodate such vagueness, aspects of Fuzzy Logic (Zadeh, 1975) were incorporated to give a relative assessment of how well the test data conforms to a given material class. The proposed method for achieving this is illustrated in Figure 6. The figure shows the CBR limits associated with material classes G7, G6 and G5. Also shown is a triangle which is determined as follows: left bottom corner is the 10th percentile value, top corner is the median value and right bottom corner is the 90th percentile value.

The triangle represents the available evidence in a relative manner. The height of the triangle is given a fixed value of 1.0. We can now calculate the total area of the triangle and the portion of the triangle that falls within the G6 class. The relative area that overlaps with the G6 class gives us a relative indication of how strongly the CBR evidence points to a G6 class. In the context of the certainty theory methodology, we assume that the relative area that overlaps with the material class in question, gives us the factor C(E) as defined in Section 3.3.

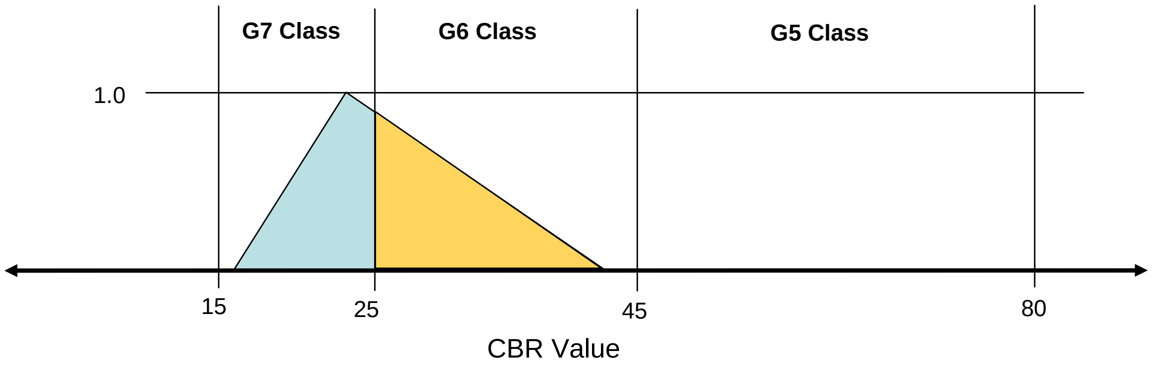


Figure 6: **Determining Relative Conformance of Evidence to Material Class Limits**

5.5 UPDATING MATERIAL CLASSIFICATION FOR AVAILABLE EVIDENCE

It should be kept in mind that the objective of the assessment is to determine the certainty associated with the hypothesis that the material that was tested conforms to the selected material class. Using the example from the preceding subsection, the material selected for evaluation is a G6, and we want to obtain the relative certainty that the material is indeed a G6. As defined in Section 3.3, the certainty for this hypothesis is C(H), which is initially zero, but which will increase when we consider tests for which the results conform partly to the range expected for a G6 material.

The certainty factors for the different tests, combined with the adjustment for sample size, provide the certainty factor CF associated with each test. The comparison of the test results with the expected limits for the materials class in question (as shown in Figure 6 and discussed in Section 5.4) provides us with the certainty that evidence is present, C(E). We now have all the factors needed to calculate an updated certainty for the hypothesis that the material tested conforms to the selected material class, i.e. C(H|E) as defined by Equations 4.1 to 4.4.

In the present context, the calculation of C(H|E) will mostly involve repeated application of Equation 4.2. Initially, C(H) is zero. We then calculate CF’ using Equation 4.1, and then C(H|E) using Equation 4.2. We then move on to the next test type, which will have a new CF and C(E) associated with it. We again calculate CF’. For the new test type, the certainty C(H) is set equal to C(H|E) determined from the previous test type. We again use C(H) and CF’ in Equation 4.1 to calculate the new C(H|E). This process is repeated for each test type to obtain an overall certainty that the material conforms to the selected class.

Once we have the overall certainty that the material conforms to the selected class, we select the next likely class and repeat the process using the same set of information. In some instances, this evaluation may require that the conformance to five or more classes be evaluated. Although this seems cumbersome, the calculations are simple and the process can easily be automated using a spreadsheet macro or a computer program.

5.6 A WORKED EXAMPLE

The following paragraphs illustrate the application of the method described in Sections 5.1 to 5.5. This example uses data from an actual pavement rehabilitation investigation, but slightly adjusted to clearly illustrate the concepts of the method. The example involves an assessment of an upper subbase layer for the eastbound lane of a planned rehabilitation project 18 km long.

Based on the condition of the road, the construction history and the deflection patterns, the road was designated as a single uniform design section that will receive a uniform treatment throughout. All available results are therefore assessed together. The available information consists of the following:

- Materials test data from nine test pits. Available test data include: material description, relative density, moisture content, DCP penetration, grading analyses, CBR and PI.
- 173 FWD deflections with backcalculated stiffnesses for all layers.

Table 27 summarizes some of the test indicators for the subbase. The grading analyses for the subbase are summarized in Figure 7. In the test pits, the base was described as a dense weathered dolerite in all instances.

Table 27: Example Materials Test Data

Station (Km)	**Relative Density**	**CBR (%)**	**% Passing 0.075 mm Sieve**	**Moisture as % of Optimum**	**GM**	**PI**	**DCP Penetration (mm/blow)**
1.5	1.03	70	11	70	2.34	9	1.8
2.7	0.87	24	4	108	2.7	10	4.8
4.3	0.94	64	5	91	2.67	9	-1
4.9	1	66	6	96	2.65	7	-1
7.9	1	70	13	67	2.17	8	-1
9.2	1	100	3	75	2.68	8	-1
12.5	1	90	12	63	2.24	5	2.4
14.3	0.98	80	6	72	2.59	8	1.4
17.5	0.94	N/R	10	48	2.24	6	-1
10th Percentile:	**0.93**	**52**	3.8	**60**	**2.2**	**6**	**-1.0**
Median Value:	**1.00**	**70**	6.0	**72**	**2.6**	**8**	**-1.0**
90th Percentile:	**1.01**	**93**	12.2	**98**	**2.7**	**9**	**2.9**
No. Observations	**9**	**8**	9	**9**	**9**	**9**	**9**

Note: For DCP penetration, a value of -1 indicates refusal. N/R indicates no result was obtained.

The backcalculated stiffnesses for the subbase were as follows:

- 10^{th} Percentile = 189 MPa
- Median = 466 MPa
- 90^{th} Percentile = 581 MPa

For most of the available tests, the results can be directly evaluated by means of the interpretation guidelines provided in Section 4. However, for the consistency, grading, GM, PI and moisture evaluations, the test results first have to be converted to a rating, in order to facilitate a numerical evaluation of results. The ratings assigned for these indicators are summarized in Table 28.

Once all the tests have been quantified, we can summarize the available tests, their certainty factors and their sample statistics. For this example, the certainty factors from Table 25 were adopted. Since the sample size exceeds six for all tests, the adjustment factor for sample size (from Table 26) is 1.0 in all cases. The available test data and certainty factors are summarized in Table 29.

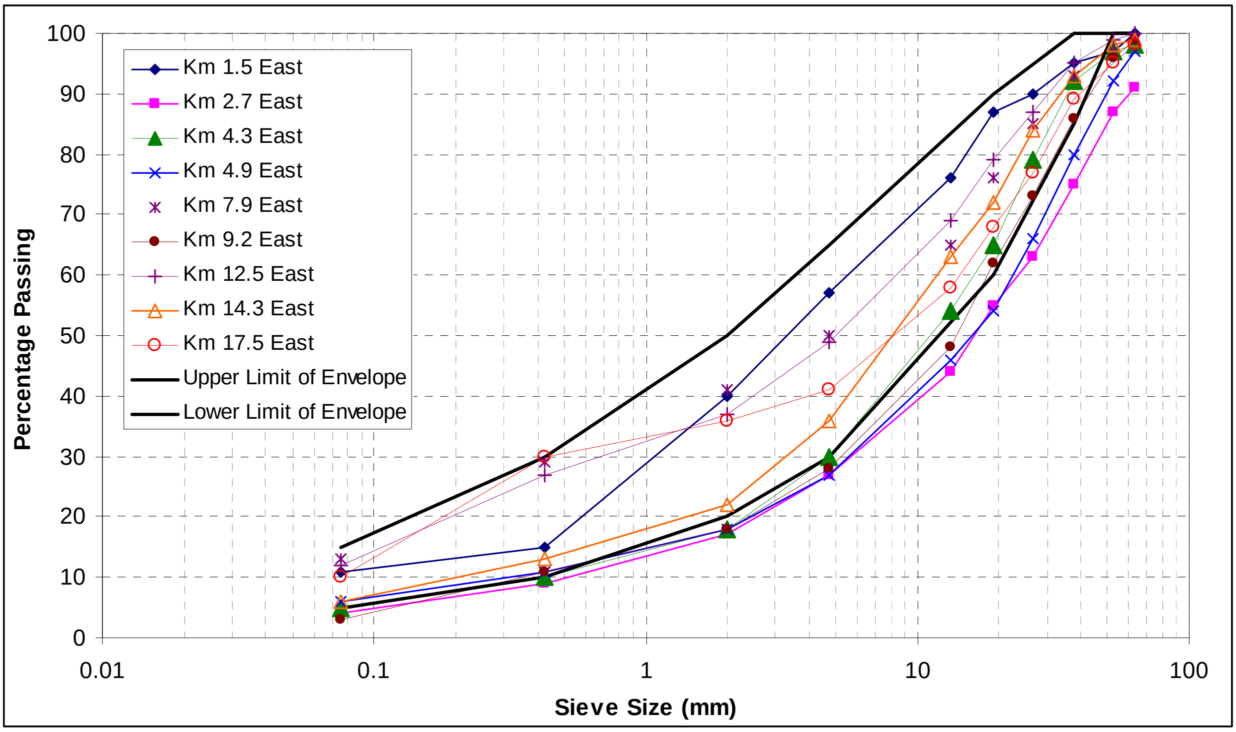


Figure 7: Grading Analyses for Worked Example

Table 28: Assigned Ratings (based on Natural Gravel Material)

Station (Km)	**Consistency** (Table 8)	**Grading Analysis** (Figure 5 and Table 13)	**Moisture as % of Optimum** (Table 12)	**GM** (Table 14)	**PI** (Table 11)
1.5	4	4	4	4	5
2.7	4	6	7	6	5
4.3	4	5	6	6	5
4.9	4	5	6	6	5
7.9	4	4	4	4	5
9.2	4	5	5	6	5
12.5	4	4	3	4	4
14.3	4	4	5	4	5
17.5	4	5	3	4	5
10th Percentile:	**4**	**4**	**3**	**4**	**5**
Median Value:	**4**	**5**	**5**	**4**	**5**
90th Percentile:	**4**	**5**	**6**	**6**	**5**
No. Observations	**9**	**9**	**9**	**9**	**9**

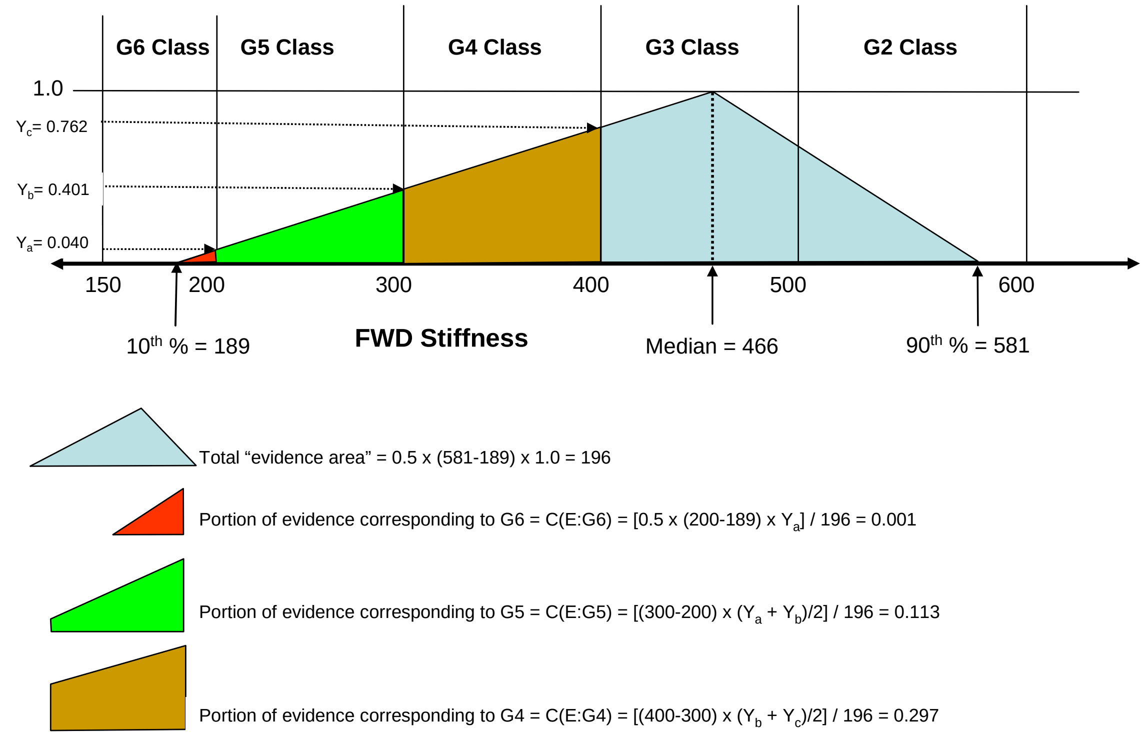
Note: Tables shown in column headers are the rating tables in Section 3 that were used to obtain the rating value.

Table 29: Worked Example, Summary of Test Data and Certainty Factors

Test	CF$_1$	CF$_2$	10th %	Median	90th%	C(E) G4	C(E) G5	C(E) G6
DCP Penetration	0.4	0.4	-1.0	-1.0	2.9	0.05	0.00	0.00
FWD Stiffnesses	0.3	0.3	189	466	581	0.30	0.11	0.00
Consistency Rating	0.2	0.2	4	4	4	1.0	0.0	0.0
PI Rating	0.4	0.4	5	5	5	0.0	1.0	0.0
Grading Rating	0.4	0.4	4	5	5	0.25	0.75	0.0
Moisture Rating	0.3	0.3	3	5	6	0.33	0.54	0.08
GM Rating	0.2	0.2	4	4	6	0.44	0.50	0.06
% Passing 0.075 mm	0.3	0.3	3.8	6.0	12.2	0.92	0.0	0.0
CBR	0.4	0.4	52	70	93	0.18	0.79	0.0
Relative Density	0.3	0.3	0.93	1.00	1.01	0.20	0.21	0.02
Column	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*

In Table 29, CF$_1$ is the certainty factor related to the test type (Table 25), and CF$_2$ is simply CF$_1$ adjusted to take account of sample size. In this case, CF$_2$ is equal to CF$_1$ because the sample size is greater than 6 in all cases. Columns 6, 7 and 8 represent the relative certainty that the test evidence points to a G4, G5 or G6 design equivalent material class, respectively.

The factors C(E) are determined using the method described in Section 5.4. Figure 8 shows an example of the detailed calculation of C(E) for FWD Stiffness. This calculation relies on the FWD Stiffness limits recommended in Table 6, and on the sample statistics shown highlighted for FWD stiffness in Table 29.



Total “evidence area” = 0.5 x (581-189) x 1.0 = 196

Portion of evidence corresponding to G6 = C(E:G6) = [0.5 x (200-189) x Y_a] / 196 = 0.001

Portion of evidence corresponding to G5 = C(E:G5) = [(300-200) x (Y_a + Y_b)/2] / 196 = 0.113

Portion of evidence corresponding to G4 = C(E:G4) = [(400-300) x (Y_b + Y_c)/2] / 196 = 0.297

Figure 8: Example of C(E) Calculations for FWD Stiffness Sample

Table 30 shows the final adjusted certainty factors (CF') for a G4, G5 and G6 material, and also the cumulative certainty that the material is a G4, G5 or G6 (i.e. C(H|E)). The final cumulative certainty for these three material classes is shown in the bottom row. The classification method shows that most of the evidence points to the material being a G5 design equivalent, and some evidence also points to a G4 design equivalent. There is comparatively little information to suggest that the material is a G6 design equivalent.

Table 30: Worked Example, Summary of Certainty Associated with G4, G5 and G6

Test	CF' (G4)	CF' (G5)	CF' (G6)	C(H-G4|E)	C(H-G5|E)	C(H-G6|E)
DCP Penetration	0.02	0.00	0.00	0.02	0.00	0.00
FWD Stiffnesses	0.09	0.03	0.00	0.11	0.03	0.00
Consistency Rating	0.20	0.00	0.00	0.29	0.03	0.00
PI Rating	0.00	0.40	0.00	0.29	0.42	0.00
Grading Rating	0.10	0.30	0.00	0.36	0.59	0.00
Moisture Rating	0.10	0.16	0.03	0.42	0.66	0.02
GM Rating	0.09	0.10	0.01	0.47	0.69	0.04
% Passing 0.075 mm	0.28	0.00	0.00	0.62	0.69	0.04
CBR	0.07	0.32	0.00	0.65	0.79	0.04
Relative Density	0.06	0.06	0.01	0.67	0.80	0.04
Final Assessment of Relative Certainty for				**G4 = 0.67**	**G5 = 0.80**	**G6 = 0.04**

Note: CF' calculated with Equation 4.1

C(H-G4/G5/G6|E) calculated with Equation 4.2, 4.3 or 4.4

5.7 CONFIDENCE ASSOCIATED WITH ASSESSMENT

For the example discussed in the preceding subsection, a fairly confident assessment of the most likely material class could be made. This is because there were enough test types, and the sample sizes were high enough. This strength of confidence in the assessment is indicated by the relatively high certainty (C(H-G5|E) = 0.8) that the material is a G5 design equivalent. If we only had DCP and FWD data available, our assessment would have stopped at row three of Table 30, and our assessment would have pointed to a G4, with a relative certainty of only 0.11.

The strength of confidence in our assessment is thus quantified by the certainty of the assessment, and this is an indirect indicator of the reliability of any design which is based on this assessment. Table 31 provides some guidelines to assess the confidence associated with the material classification.

Table 31: Relative Confidence of Materials Classification

Final Value of C(H|E)	Confidence in Classification
< 0.3	Very low confidence. It is strongly recommended that more data be gathered to enable a more confident assessment to be made.
0.3 to 0.5	Low confidence. Suitable only for situations where the existing pavement condition and age is such that structural rehabilitation will not be considered or is very unlikely.
0.5 to 0.7	Medium. Suitable or situations where the existing pavement condition and age is such that structural rehabilitation is unlikely, or for which the condition and/or other factors predetermines the treatment type.
> 0.7	High. This is the minimum recommended certainty for situations where structural rehabilitation is likely, and for which the rehabilitation design will rely completely on the quality and state of existing pavement layers.

5.8 IMPLEMENTATION OF METHODOLOGY

The preceding subsections outlined the method for synthesizing results from different materials tests to obtain a rational and consistent classification of a material being evaluated. The assigned design equivalent material class is a critical component of a rehabilitation design, as it determines the manner in which the material will perform under loading.

In the context of rehabilitation design, the assigned material class can be used to determine typical stiffness and shear strength values that can be expected of the material. This addresses a critical shortcoming of the current South African Mechanistic Empirical Design (SAMDM) method, namely the subjective determination of layer stiffnesses used for design. In the current SAMDM, designers determine the layer stiffness values based on published ranges, or by using backcalculated stiffnesses. Both these approaches allow considerable leeway in the selection of design stiffness, and this often results in the manipulation of design calculations.

The method developed in this study presents a holistic and consistent approach to determining a design equivalent material class which is indicative of the material in its current state within the pavement system. The assignment of the design equivalent class is based on measured data and a systematic approach, and this removes much of the subjectivity that normally enters into a mechanistic-empirical pavement design.

Following this approach, the proposed design method for pavements that incorporate bitumen stabilized layers relies only on the design equivalent material class and the thickness of the layer (Jooste and Long, 2007). This direct reliance on assigned material class removes almost all subjectivity from the design process and strengthens the link between (a) the measured material quality and condition in the field; and (b) the pavement design which is dependent on these factors.

In the proposed method for bitumen stabilized pavements, the design equivalent material class is used to determine the factors that are used to determine the Effective Long Term Stiffness (ELTS) of the material. The calculation of the ELTS relies on established principles of pavement behaviour, such as (Jooste and Long, 2007):

- Stress-stiffening of coarse granular materials, and stress-softening of subgrade materials;
- Influence of support stiffness on fatigue and deterioration of overlying layers; and
- Influence of layer thickness in determining fatigue propagation in cement stabilized layers.

These principles, amongst others, were used to develop a method for calculating a Pavement Number (PN), which is calculated as the sum of the product between the ELTS and layer thickness for all layers. An empirical relationship was developed between the PN and the structural capacity of several Long Term Pavement Performance (LTPP) evaluation sections, as well as several pavements that had been tested using the Heavy Vehicle Simulator. Details of this relationship, and of the method for calculating PN is provided in Jooste and Long (2007). This document also provides guidance of the typical stiffness and behaviour properties of the various design equivalent material classes.

The following **practical considerations and recommendations** should be considered in the implementation of the proposed method:

Reliance on Laboratory Tests: It should be clear from the preceding discussions that the proposed material classification method relies heavily on laboratory tests, which in turn require the opening of test pits. While the method can be applied using only non-destructive tests (e.g. backcalculated stiffnesses from the FWD or other deflection devices), the relative certainty associated with the assessment will be low.

This reliance of the classification method on laboratory tests is by design, and emphasizes the authors' belief that materials assessment is the core component of pavement rehabilitation design. Whilst non-destructive tests are highly cost effective and informative, they do not at this stage allow a complete assessment of shear strength or stiffness. Furthermore, these methods invariably rely on the experience and subjective approach of the engineer. The method proposed in this study counteracts this effect, and reduces the design risk, especially for inexperienced engineers.

Since this feature of the proposed method is sure to have cost implications, it is recommended that the issue be clarified with roads agencies, to ensure a congruency between the proposed method and the approach to materials testing and evaluation that is adopted by roads agencies.

Adjustments Based on Experience: Section 4 presents guidelines for the interpretation of routine tests, and Table 4 proposed certainty factors for the various tests and indicators. Whilst these guidelines are believed to be sound and appropriate for most design situations, some circumstances may require a deviation from these guidelines. Experienced and expert practitioners, in particular, may be aware of special circumstances that warrant adjustment of the interpretation guidelines or certainty factors. The proposed method was designed to easily accommodate this. However, in such situations it is recommended that the designer present a brief motivation to the client, to explain any adjustments made to the interpretation of tests or to the certainty factors of tests.

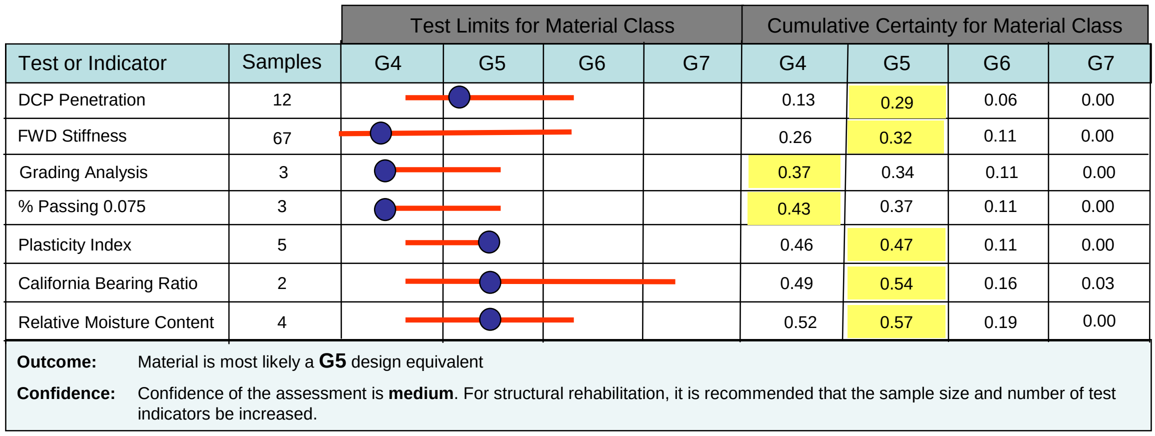
It is recommended that the proposed tests and interpretation guidelines be submitted to experienced practitioners who are willing to participate in the refinement and improvement of the proposed method. This should ideally be done as part of the pilot testing of the proposed methodology.

Confidence Associated with the Assessment: The proposed method can be used irrespective of the number of tests considered, or of the order in which the tests are assessed. However, if only one or two indicator types are used, the confidence associated with the assessment will decrease significantly. The relative confidence of the assessment should be assessed and evaluated in the light of the design situation, to determine if more testing is needed to enable a more confident assessment to be made. Table 31 provides some guidelines to assess the confidence of the material classification, but it is recommended that this aspect be refined as part of the pilot implementation process.

Documentation of Classification Procedure: It is believed that the proposed method provides engineers with a tool to consistently classify pavement materials for purposes of rehabilitation design. However, there is a danger that engineers will implement the method as a black box, thereby detracting from the ability of the method to de-mystify the process of synthesizing data from several test types. A crucial aspect associated with the method of implementation is thus the manner in which the assessment is documented and presented to clients. It is recommended that a well-designed report format be adopted, to clearly show the impact of each test result on the overall assessment. Figure 9 shows an example of such a report format.

Synthesis Calculations: The synthesis procedure outlined in this section involves repeated application of a few simple formulas. Whilst the process is relatively straightforward, it can be cumbersome if many potential material classes need to be considered. It is thus recommended that software be developed to aid engineers in the application of the methodology. This software should ideally be made available to practitioners during 2007 to enable proper testing and refinement of the method as part of the pilot testing phase.

Expansion of the Framework: The method developed in this study can be easily expanded to include more tests and indicators in addition to those presented in Section 4. A critical assessment of the tests presented in Section 4 should form part of the pilot testing phase, specifically to identify more tests or indicators that could be incorporated in the assessment. This applies in particular to the assessment of bitumen stabilized materials, as the appropriate tests and indicators for classification of these materials are yet to be finalized.



		Test Limits for Material Class				Cumulative Certainty for Material Class			
Test or Indicator	Samples	G4	G5	G6	G7	G4	G5	G6	G7
DCP Penetration	12					0.13	0.29	0.06	0.00
FWD Stiffness	67					0.26	0.32	0.11	0.00
Grading Analysis	3					0.37	0.34	0.11	0.00
% Passing 0.075	3					0.43	0.37	0.11	0.00
Plasticity Index	5					0.46	0.47	0.11	0.00
California Bearing Ratio	2					0.49	0.54	0.16	0.03
Relative Moisture Content	4					0.52	0.57	0.19	0.00

Outcome: Material is most likely a **G5** design equivalent

Confidence: Confidence of the assessment is **medium**. For structural rehabilitation, it is recommended that the sample size and number of test indicators be increased.

Figure 9: Illustration of a Materials Classification Report

6 SUMMARY AND RECOMMENDATIONS

This technical memorandum documents a method for consistent classification of materials for pavement rehabilitation design. The method is general in its approach, but was specifically developed for use in a knowledge-based design method for pavements that incorporate bitumen stabilized layers.

A general problem statement was provided and discussed, and it was pointed out that pavement material assessments involve three types of uncertainty which greatly complicate the interpretation of test data. These three types of uncertainty involved are: (i) uncertainty in the evidence, or test data; (ii) uncertain relationships between test parameters and material behaviour and performance; and (iii) vagueness in the information or test outcome.

The method developed in this study was designed to effectively counteract the uncertainty involved in materials assessment. It does so by working from a fundamental model of material behaviour, and by adopting a framework that can handle vagueness and uncertainty. A key aspect of the approach is that it is able to incorporate any number of test indicators as part of the classification process, provided that each test result can be consistently quantified. The method encourages a holistic approach, in which the materials assessment is based on several different tests and indicators.

The test types that can be used to classify unbound granular materials and cement stabilized materials were summarized, and guidelines were provided for interpreting results. In the case of bitumen stabilized materials, a tentative classification scheme was proposed, and tests indicators that are likely to be used for these materials were proposed.

A method for synthesizing the outcomes of several test types into a material class was presented. The method incorporates elements of Certainty Theory and Fuzzy Logic, and can easily be programmed into a spreadsheet or other software application. A detailed example was provided to clarify the method and its calculations. It was highlighted that although the proposed method can be programmed into a software package, it is important that the calculations be presented in a manner that clarifies the available test data and how these influence decisions.

Recommendations:

- While the proposed classification method incorporates non-destructive tests, it also relies heavily on information obtained directly or indirectly from test pits. Since this feature of the proposed method is sure to have cost implications, it is recommended that the issue be clarified with roads agencies, to ensure a congruency between the proposed method and the philosophy toward materials testing and evaluation that is adopted by roads agencies.

- Guidelines for the interpretation of routine tests were proposed, as were certainty factors for the various tests and indicators. Whilst these guidelines are believed to be sound and appropriate for most design situations, some circumstances may require a deviation from these guidelines. It is recommended that the proposed tests and interpretation guidelines be submitted to experienced practitioners who are willing to participate in the refinement and improvement of the proposed method. This should ideally be done as part of the pilot testing of the proposed methodology.

- A crucial aspect related to implementation of the proposed method is the manner in which the assessment is documented and presented to clients. It is recommended that a well-designed report format be designed as part of the pilot testing phase, to clearly show the impact of each test result on the overall assessment. The format of the output should be discussed with clients to ensure that the results are presented as clearly and informatively as possible.

- The synthesis procedure outlined in this document involves repeated application of a few simple formulas. Whilst the process is relatively straightforward, it can be cumbersome if many potential material classes need to be considered. It is thus recommended that software be developed to aid engineers in the application of the methodology. This software should ideally be made available to practitioners during 2007 to enable proper testing and refinement of the method as part of the pilot testing phase.

- The method developed in this study can be easily expanded to include more tests and indicators in addition to those presented in this document. A critical assessment of the tests presented in this memorandum should form part of the pilot testing phase, specifically to identify more tests or indicators that could be incorporated in the assessment. This applies in particular to the assessment of bitumen stabilized materials, as the appropriate tests and indicators for classification of these materials are yet to be finalized.

7 REFERENCES

AASHTO. 1978. **Standard Specifications for Transportation Materials and Methods of Sampling and Testing**. AASHTO Designation: M145-73, 12th Edition, Washington, D.C.

Australia/New Zealand Standards. 1999. **AS/NZS 4360. Risk Management**. Standards Australia. (Web Reference, 19 March 2007: www.standards.com.au/catalogue/script/Details.asp?DocN=stds000023835).

CHEN, W.F. and Baladi, G.Y. 1985. **Soil Plasticity, Theory and Implementation**. Developments in Geotechnical Engineering, Vol 38, Elsevier, New York, N.Y.

COLTO. 1998. **Standard Specifications for Road and Bridge Works for State Authorities**. Committee of Land Transport Officials, Halfway House, South Africa.

CREAGH, M. 2005. Risk Assessment for Unbound Granular Materials and Pavement Performance, Geotechnical Engineering, PMG. Paper prepared for the **Roads System and Engineering Technology Forum.** Queensland, Australia, August, 2005.

GRAY, J.E. 1962, Characteristics of Graded Base Course Aggregates Determined by Triaxial Tests. **National Crushed Stone Association, Engineering Bulletin No. 12**, National Crushed Stone Association, Washington, D.C.

HEFER, A and Scullion, T. 2002. **Materials, Specifications, and Construction Techniques for Heavy Duty Flexible Bases: Literature Review and Status Report on Experimental Sections**. Texas Transportation Institute, The Texas A&M University System, College Station, Texas (Report 0-4358-1), October, 2002 (Resubmitted: July 2005).

HOPGOOD, A.A. 2001. **Intelligent Systems for Engineers and Scientists**. Second Edition. New York, CRC Press, 2001.

JOOSTE, F.J. and Fernando, E.G. 1995. **Development of a Procedure for the Structural Evaluation of Superheavy Load Routes**. Texas Transportation Institute, The Texas A&M University System, College Station, Texas (Report 1335-3F), November, 1995.

JOOSTE, F.J. and Long, F.M. 2007. **A Knowledge Based Structural Design Method for Pavements Incorporating Bitumen Stabilized Materials**. SABITA / Gauteng Department of Transport, Roads and Works, Pretoria, 2007 (Gautrans DTRPW Report Number CSIR/BE/IE/ER/2007/0004/B).

JORDAAN, G.J. and Van As, C.S. 1994. Pavement Evaluation: Test Frequency Requirements for Deflection Bowl Parameters. **Proceedings of the 6th Conference on Asphalt Pavements in Southern Africa** (CAPSA), Cape Town, 1994.

KLEYN, E.G. 1984. **Aspects of Pavement Evaluation and Design as Determined with the Aid of the Dynamic Cone Penetrometer** . (In Afrikaans). Pretoria: Transvaal Roads Department, Materials Branch, May, 1984 (Report L6/84).

Roads and Traffic Authority of New South Wales. 2001. **RTA Conditions of Contract and Quality Assurance Specifications, Rev 2001**. Roads and Traffic Authority of New South Wales (web reference: http://www.rta.nsw.gov.au).

SANRAL. 2004. **Geotechnical and Materials Investigations, Design and Documentation**. South African National Roads Agency Limited. Pretoria, South Africa (M1 Materials Manual).

SHORTLIFFE, E.H. and Buchanan, B.G. 1975. A Model of Inexact Reasoning in Medicine. **Mathematical Biosciences**, Vol 23, pp. 351 to 379, 1975.

SHORTLIFFE, E.H. 1976. **Computer-Based Medical Consultations**. MYCIN, Elsevier, 1976.

SPANGLER, M.G. and Handy, R.L. 1982. **Soil Engineering**, 4th Edition, Harper & Row, New York.

Standard Specifications Roads, 3rd Edition, Queensland, Department Main Roads. Web reference **http://www.mainroads.qld.gov.au**.

THEYSE, H.L. , De Beer, M. and Rust, F.C. 1996. **Overview of the South African Mechanistic Pavement Design Analysis Method**. Paper Number 961294 Presented at the 75th Annual Transportation Research Board Meeting, January 7 to 11, 1996, Washington, D.C.

TRH12. 1998. **Flexible Pavement Rehabilitation Investigation and Design**. Committee of State Road Authorities. Pretoria, South Africa. (Technical Recommendations for Highways Series, TRH 12).

TRH14. 1985. **Guidelines for Road Construction Materials**. Committee of State Road Authorities. Pretoria, South Africa. (Technical Recommendations for Highways Series, TRH 14).

ZADEH, L.A. 1975. Fuzzy Logic and Approximate Reasoning. **Synthese**, Vol 30, pp. 407 to 428, 1975.

APPENDIX A: PROJECT WORK PROPOSAL

Project Proposal Number: PP/2005/09/d

Version: 1.0

Updating Bituminous Stabilized Materials Guidelines, Phase 2: Development and Calibration of Structural Design Procedure

Submitted by: **Dr Fenella Long, MAS**

Name	Company	Contact details
Dr Fenella Long	MAS	(083) 399 0090, flong@modsys1.com
Dr Wynand Steyn	Transportek, CSIR	(012) 841 2634, wsteyn@csir.co.za

1. TERMS OF REFERENCE

This proposal forms part of a larger study proposal, entitled "*Compilation of a Bituminous Stabilized Materials Guideline Document for Foamed and Emulsified Bitumen Treated Materials*" (Proposal Number PP/2005/09). As such, the tasks and methodology defined in this proposal comprise a sub-task of a larger project and should be viewed as such. The background, project objectives, expected benefits and implementation plans are described in detail in proposal PP/2005/09, and will not be restated here. Briefly, the project pertains to the updating of the TG2 and TG(X) guidelines, which are intended to guide and assist practitioners in the selection and design of pavements and materials that incorporate bituminous stabilization consisting of bitumen emulsion or foamed bitumen. The objectives of the larger project are to improve or redesign the modules relating to the mix design and structural design, to ensure that the guidelines reflect the latest best practice as well as all available research and field performance data. The overriding objective is to compile a complete guideline document incorporating the mix and structural design and construction guidelines.

The first phase of the project was an inception study with two components, mix and structural design. An objective of the inception study was to plan further testing and development activities needed for the thorough revision of the TG2 and TG(X) guidelines. It was recommended that in Phase 2 of the project the mix design and structural design guidelines be developed and reviewed, and in Phase 3 the guideline document be compiled.

This proposal pertains to the structural design component of Phase 2 of the larger project, which comprises the development of the structural design guidelines. The development of the mix design guidelines is detailed in a companion proposal (PP/2006/03/c). The two components of Phase 2 should be executed in parallel.

2. PROJECT OBJECTIVES

This structural design guideline development project has three objectives:

1) To expand the LTPP database compiled during the Inception Study to a sufficient level to enable the development of classification based design guidelines.
2) Develop and populate a classification based design matrix.
3) Peer review of the recommended design guidelines.

3. METHODOLOGY

The methodology proposed in the following paragraphs is in accordance with the framework for a structural design method as documented in the Structural Design Inception Study Reports:

- Long F.M., Jooste F.J. and Jenkins K.J., Updating Bituminous Stabilized Materials Guidelines: Inception Study, Summary Report, February 2006, DRAFT.
- Long F.M., and Jooste F.J., Updating Bituminous Stabilized Materials Guidelines: Structural Design Inception Study, Technical Memorandum, February 2006, DRAFT.

This development of the structural design guidelines for a Bituminous Materials Guideline will comprise of the following tasks:

Task 1: Update LTPP Summaries with Recently Available Information
At the time of the inception study some information on the LTPP sections studied was not available (e.g. the SANRAL 2005 network survey and the current condition). In this task, this information will be accessed and the LTPP summaries updated. It may not be possible to obtain actual performance data on the current condition, however, and in those cases the clients or relevant engineers will be contacted to obtain a subjective opinion of the current condition.

Task 2: Peer Review of LTPP and HVS summaries
Since the LTPP and HVS summaries developed in the Inception Study will form the empirical base for the structural design methodology, it is essential that these summaries be accurate and appropriate. This task therefore involves a peer review of the LTPP and HVS summaries developed in the Inception Study. The project engineers, resident engineers and clients originally involved in the design and construction of each section will be contacted to:

- Validate and/or correct the information contained in the LTPP summaries, and
- Expand the summaries to include practical hints and tips that ensured successful construction.

The peer review will also be performed on any additional LTPP summaries compiled in Task 5.

Task 3: Develop Material Classification Method
This task involves developing a robust, appropriate method for a classification based design method. The following specific subtasks are involved:

- Study and select model for determining the appropriate material class from several indicators.
- Develop and test the selected model.
- Identify and contact practitioners, and hold workshop to select classification parameters and ranges.

This task will be executed in conjunction with the mix design project team, as the mix design output will form important inputs into the material classification system. However, the theoretical framework of the method can be developed prior to the availability of the recommended mix design method with the associated tests and classification limits. The method will then be refined in Task 7 when the mix design results are available and any additional LTPP data have been collected.

Task 4: Develop Structural Design Matrix/Method
In this task the design matrix will be populated with the available data. This requires:

- An in-depth study of the available LTPP and HVS data.
- Formulation of the structure of the design matrix.
- Assignment of the pavement structures to the design matrix.
- Interpolation of new structures using mechanistic principles for unpopulated areas within the design matrix.

Task 5: Expand LTPP Database
In this task, the database of LTPP pavements developed in the Inception Study will be expanded to address the deficiencies identified in the Inception Study and from the previous task. At this stage it

is envisaged that an additional 10 to 16 sections will need to be included, however this will be finalised only after completion of Task 4.

The data gathered in this task will include the following, where applicable:

- Identification and assessment of failed pavements;
- Additional foamed bitumen pavements;
- Pavements with natural gravel subbases (particularly with thick recycled bases);
- Pavements on poor quality subgrades;
- Foam pavements constructed on stabilised subbases, and
- BSM pavements constructed as part of a newly constructed road.

The data will be obtained by three means. Firstly, analysis of existing as-built records, available behaviour and performance data and traffic assessments in line with the methodology used to prepare LTPP summaries in the Inception Study. Secondly, some sections will require field measurements, as discussed in the next task. Thirdly, some sections, such as the sections on poor quality subgrades will be developed by interpolating between, or extrapolating from, existing structures using mechanistic principles.

Task 6: Collect Additional Field Data

This task involves the collection of field data from in-service pavements. This is only required for pavement types where no data are already available, and will be limited to the collection of essential data in an effort to limit the total project cost. Some or all of the following data will be collected:

- Testpits and material tests
- Deflection measurements (FWD)
- Visual condition
- Rutting measurements
- DCP tests
- Roughness measurements
- Core extraction

The data will be used to compile LTPP summaries for the sections in line with the summaries prepared in the Inception Study.

Task 7: Refine Material Classification and Design Method

The material classification and design method developed in Tasks 3 and 4 will be refined with the data collected in Tasks 5 and 6 and on inclusion of the recommended mix design method selected in the companion Phase 2 project. This task can therefore only begin when the mix design method is finalised.

The populated design matrix will also be refined and validated through liaison with identified expert practitioners.

Task 8: Simple Methodology for Designing Structures not Included in the Design Matrix (optional)

In this task, the method used to design the non-validated structures in the design matrix will be expanded and documented. This will be done by formalising the method and inputs used and defining the inputs required. This method should only be used by experienced practitioners, and could be included in the final BSM guideline as an appendix. Note that this task involves the use of mechanistic principles, and not the mechanistic-empirical method. As such, transfer functions will not be used.

This task is optional.

Task 9: Strategy for On-going Population of the Design Matrix

This task involves the development of a strategy to facilitate the on-going population of the design matrix as data on more pavements become available, or as updated data on pavements included in the design matrix become available. This involves determining a strategy for alerting practitioners and road authorities to the need for more data, and the compilation of a detailed list of both the required and desired data.

Task 10: Documentation

The project findings will be detailed in a technical memorandum, which will serve as a backup to the guidelines to be presented in the guideline document. The findings will also be summarized in a project summary report.

4. DELIVERABLES

The deliverables for this project will consist of a technical memorandum, a project summary report and a detailed presentation to the project funders. The project documentation will contain the following information:

- Expanded LTPP summaries;
- Description of method selected for material classification from several indicators;
- Populated design matrix;
- Method for designing structures not explicitly included in design matrix (optional), and
- Strategy for obtaining new data on pavements as it becomes available.

The project documentation will be structured according to the Gautrans Documentation Guidelines so that raw data and technical discussions are limited to the technical memorandum, while the project summary report will concisely summarize key observations and recommendations.

5. SKILLS DEVELOPMENT

The skills development part of this project will involve the use and associated mentoring of a Gautrans technician or young engineer in the project work, particularly in Tasks 5 and 6 as outlined in the Methodology section. The skills imparted will be:

- Data retrieval
- Analysis of retrieved data
- Exposure to project documentation, such as as-built records, design reports and Pavement Management Systems
- Basic reporting

The cost of employment of the mentee will be carried by Gautrans as part of their normal salary. The cost of the mentoring by the project team is included in the Project Cost section of this proposal.

6. PROJECT PLAN

6.1. Project Team / Personnel

The project team will consist of Dr Fritz Jooste, Dr Fenella Long and Sanet Jooste of MAS with Prof. Kim Jenkins acting in an advisory role. Details of the project team are summarized below.

Table 1. Project Team

Name	Organisation	Contact details	Hourly Rate
Dr Fritz Jooste (FJ)	MAS	(082) 578 5628, fritzj@modsys1.com	R 500
Dr Fenella Long (FL)	MAS	(083) 399 0090, flong@modsys1.com	R 450
Sanet Jooste (SJ)	MAS	(072) 266 1726, sanetj@modsys1.com	R 420
Professor Kim Jenkins (KJ)	SANRAL Chair	(082) 920 7859, kjenkins@sun.ac.za	R 500

The development of the mix design guidelines will be championed by Professor Kim Jenkins. The output from the mix design tests are an input into the structural design guidelines, and therefore the mix design and structural design teams will work in tandem to ensure the mix and structural design guidelines are aligned.

6.2. Project Costs

Detailed costs are only provided for Phase 2: Structural Design Procedure Development. These costs are detailed in Table 2. The cost of Task 6 is a range, which depends on the number of field sites from which field data will be collected. The number of sections will be finalised after the completion of Task 4 and in consultation with the clients. The work will be done by Fritz Jooste, Fenella Long and Sanet Jooste. Two workshops with experienced practitioners will be held during the project. The costs shown include the time cost of the project team, but do not include the cost of holding the workshops. The Project Manager's costs are <u>not</u> included in this proposal, but are listed in the master proposal.

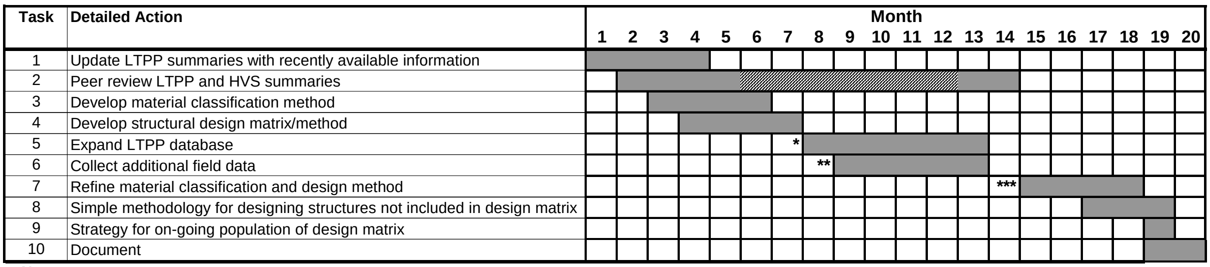
Table 2. Project Costs for Structural Design Procedure Development

Task Type	Task	Detailed Action	Cost Minimum - Maximum	Cost Minimum - Maximum
Data gathering tasks	1	Update LTPP summaries with recently available information		
	2	Peer review LTPP and HVS summaries		
	5	Expand LTPP database		
	6	Collect additional field data (3 to 10 sites at R 50 000 per site)		
Development tasks	3	Develop material classification method		
	4	Develop structural design matrix/method		
	7	Refine material classificaiton and design method		
	8*	Simple methodology for designing structures not included in design matrix		
Reporting tasks	9	Strategy for on-going population of design matrix		
	10	Document		
Other		Skills development mentoring		
		Liaison, meetings and presentation to Funders		
		Direct Costs (Travel, documentation, etc.)		
Sub Total				
Value Added Tax (14 %)				
Total				

* This task is optional

6.3. Time Line

The Gantt chart is shown in Figure 1. The project will take 12 months to complete, however the start of some tasks is dependant on the completion of previous tasks and the Mix Design study. The estimates shown in Figure 1 are based on sufficient information coming from Part 1 of the applicable Mix Design Tasks (see Phase 2 Mix Design Proposal). Should this not be the case, the completion of the tasks shown will be delayed.



Task	Detailed Action	Month 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Update LTPP summaries with recently available information	▨	▨	▨	▨																
2	Peer review LTPP and HVS summaries		▨	▨	▨	▨	▧	▧	▧	▧	▧	▧	▧	▨	▨						
3	Develop material classification method			▨	▨	▨	▨														
4	Develop structural design matrix/method				▨	▨	▨	▨													
5	Expand LTPP database							*	▨	▨	▨	▨	▨	▨							
6	Collect additional field data								**	▨	▨	▨	▨	▨							
7	Refine material classification and design method														***	▨	▨	▨	▨		
8	Simple methodology for designing structures not included in design matrix																	▨	▨		
9	Strategy for on-going population of design matrix																			▨	
10	Document																			▨	▨

Notes

* Scope is subject to output of Tasks 3 and 4

** Start and scope of task is subject to output of Task 5

*** Start and scope of taks is subject to output of Tasks 5 & 6 and the Mix Design study

Figure 1. Gantt Chart