A LABORATORY PROCEDURE USING THE DYNAMIC CONE PENETROMETER FOR ASSESSING THE SUITABILITY OF MATERIALS FOR LOW VOLUME ROADS

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ABSTRACT

In order to minimise the cost of constructing low volume roads (LVRs), optimum use must be made of locally available, naturally occurring materials. However, conflicts often arise between material acceptability, as defined by conventional test methods and specifications, and material suitability in terms of actual engineering performance as a "fitness-for-purpose" road construction material. It is crucial to adopt appropriate test methods and specifications for selecting acceptable construction materials to avoid such conflicts.

This paper presents a laboratory procedure using the Dynamic Cone Penetrometer (DCP) to assess materials' suitability for use in LVRs. This approach enables materials to be selected based on their "fitness-for-purpose". It prevents suitable materials from being rejected based on one or other traditionally specified parameters not being complied with, even though their strength, as measured by the DCP penetration rate (DN value in mm/blow) of the soil, may be adequate. Investigations of the properties of a wide range of locally available materials that have been used successfully in the construction of LVRs have confirmed the validity of the materials evaluation framework.

1. INTRODUCTION

Naturally occurring soils, gravel soil mixtures, and gravels occur extensively in many tropical and sub-tropical climatic zones. Materials typically account for about 35% to 40% of a low volume road (LVR) cost in many countries. Moreover, local materials are a valuable resource as they are relatively cheap to exploit compared, for example, with processed (engineered) materials such as crushed rock, and are often the only source of material available within a reasonable haul distance of the road alignment.

To minimise construction costs and, ultimately, life-cycle costs, maximum use must be made of local materials to achieve affordable upgrading of unpaved roads to paved LVRs. However, the challenge often faced by designers in attempting to use local materials more extensively is that the use of traditional test methods, and the application of traditional specifications, have often resulted in their rejection even though the practice may have shown that they may be "fit-for-purpose" for use and perform successfully within a given LVR environment (Rice and Toole, 2020). This situation highlights the need to find appropriate and reliable test methods to facilitate the selection and more widespread use of local, natural materials to construct LVRs.

Fortunately, there is a wealth of information derived from the back-analysis of the performance of numerous LVRs in a variety of environments in several tropical and sub-tropical countries (Gourley and Greening, 1999; Paige-Green, 1999; Rolt et al., 2017). This has identified many anomalies in the previous understanding of the relationship between material properties and performance and has also questioned many of the accepted paradigms associated with the selection, testing, and specification of materials for incorporation in LVR pavements.

1.1 Aim of Paper

This paper presents a comprehensive evaluation framework for testing and selecting materials based on their ‘fitness-for-purpose”. Extensive research has been carried out on materials testing, evaluation, and performance. However, such work has not previously been drawn together in the manner presented in this paper. This has enabled this new evaluation framework to be developed.

1.2 Scope of Paper

The paper firstly discusses the general requirements of fit-for-purpose materials, followed by the shortcomings of the traditional approaches typically adopted to test and select materials for LVRs. The authors then present a new approach for evaluating the potential suitability of local materials for incorporation in LVR pavements based on a laboratory procedure involving the Dynamic Cone Penetrometer in preference to the more traditional California Bearing Ratio (CBR) test. Finally, factors to be considered for minimising the risk of using locally available, naturally occurring materials are also discussed.

2. MATERIALS TESTING AND SELECTION

The critical properties of a material that exert a significant influence on the performance of a flexible pavement include:

- Shear strength.
- Stiffness (Resilient Modulus).

Both strength and stiffness indicate stability and are generally highly dependent on moisture content and compaction density, as influenced by soil suction and material fabric (Toll, 2012), and stress conditions. In contrast, stiffness, or resistance to deformation (note: stiffness is the rate of loading vs. deformation; deformation includes elastic and plastic stiffness) under load, can change with repeated loading and with weathering or degradation of the material, were it to occur during the pavement's service life.

The primary material properties, other than strength, in terms of CBR, that are commonly considered to influence, rather than control, performance include (COLTO, 1997):

- Particle size distribution (PSD).
- Plasticity Index (PI), or Linear Shrinkage (LS).
- Combinations of PI and PSD, e.g., Plastic Modulus (PM) (Cook et al., 2001).

The above properties all influence the strength or stiffness of the material under different combinations of moisture, density, and traffic loading and are inherent in the strength/stiffness determination. Thus, assessing the influence on pavement performance as affected by various combinations of material properties rather than discrete properties is essential to properly evaluate material for the intended purpose.

2.1 Measurement of Material Properties

The DCP device does not measure any fundamental properties of a material. However, based on investigations carried out by Ayers et al., (1989), it was concluded that:

- The DCP test may be used to estimate the shear strength of a variety of granular materials using the prediction equations developed.
- The single variable equations implicitly account for factors such as moisture and density because a direct, inverse linear relationship exists between the penetration rate (PR) and shear strength.
- Detailed characteristics, such as gradation, maximum aggregate size, density, and void ratio, are not required to predict shear strength from DCP data, although they improve prediction accuracy.
- Using a DCP device in the manner described in the said paper is a viable alternative to detailed in situ test pit investigations; such DCP tests are rapidly conducted and inexpensive.

2.2 Selection of Materials

Traditionally, the selection of naturally occurring granular materials for use in pavement layers is initially by classification tests, which include particle size distribution (grading envelope, maximum particle size), particle durability (soundness), fines plasticity (PI, PM and LS) and swell. In addition, a strength requirement, traditionally derived from the CBR test, is also imposed. An indication of the probable suitability of material is then generally assessed by compliance with specification limits placed on these material properties, which are meant to exclude the most unsatisfactory ones from incorporation in the road pavement structure.

Experience has shown that applying traditional parameters for testing, specifying and selecting materials for incorporation in LVR pavements often gives rise to conflicts between material acceptability, as defined by the specification and material suitability in terms of its actual engineering performance. As a result, satisfactory performance has been obtained from materials that do not meet the specified requirements. Conversely, poor performance has been observed with materials that satisfy the specified requirements (Paige-Green, 1999; Rolt et al., 2017). This suggests that the application of traditional specifications for selecting naturally occurring materials developed mainly for temperate-zone material characteristics modified for LVRs is unreliable (Netterberg and Paige-Green, 1988). In addition, the imposition of multiple property requirements tends to exclude the use of a range of fit-for-purpose materials (Rolt et al., 2017). Such a situation could arise because of:

- The specification of materials' properties is based on index tests that broadly reflect their properties but are not directly related to their performance.
- The use of inappropriate strength tests that are poorly correlated with the strength and stiffness of the material in their in-service state (compacted density and in-situ moisture content).

The above issues give rise to a more significant concern - the efficacy of using an assortment of materials properties, such as grading, plasticity, and CBR, which are not performance-related, as evidenced by the outcome of the back-analysis of many LVR pavements (Rolt et al., 2017). Moreover, the relatively large coefficient of variation (CoV) associated with the related tests (CBR: CoV = 18%, PI: CoV = 74%, Grading: CoV = 31%)

(Lee et al., 1983), and a possible accumulation of errors, especially in poorly resourced laboratories in many tropical/subtropical countries, make it all the more pressing for the use of a more reliable evaluation framework. Such a framework should include a good characterisation test that is more closely linked to structural performance for assessing the suitability of materials for incorporation in LVR pavements.

3. MATERIALS EVALUATION FRAMEWORK

The proposed approach to the evaluation of subgrade/earthworks and pavement layer materials is based on consideration of the following:

- Knowledge of the key engineering properties of the subgrade/earthworks and pavement materials in order to detect those materials with deleterious properties associated with "problem soils", such as excessive swell, erodibility, salinity, dispersiveness or collapse potential. Such properties are obtained from traditional classification, grading, and other appropriate tests on bulk samples obtained from the existing pavement and borrow areas.
- The selection of materials in terms of acceptability for specific use in the subgrade or pavement layers is then based on engineering judgment related to the outcome of the above tests, bearing in mind the preference for local material uses on LVRs.
- Knowledge of the key parameters required in a pavement layer - the material's effective shear strength and stiffness - is a function of the material properties, including grading, plasticity, aggregate hardness, etc. Because of its strong correlation with shear strength (Ayers et al., 1989) and relatively better repeatability than the CBR test (Livneh, 1987), the DN is deemed the more reliable parameter for evaluating materials' suitability described in the evaluation framework below.

3.1 Evaluation of Materials

A subgrade or pavement material's strength is broadly influenced by its basic properties (grading, plasticity, aggregate hardness, etc.). However, the strength of such materials is also influenced by the operating conditions in the pavement and will vary with moisture content, compacted density, and prevailing stress conditions. Therefore, to fully understand how a material is expected to perform under a specific design scenario, and ultimately how fit for a particular purpose it will be, it is necessary to examine how the strength of the material, as influenced by its basic properties, varies with different combinations of moisture content and density and, thereafter, to assess the risk associated with the design assumptions. This can be achieved by adopting a 3-tiered evaluation framework (see Figure 1) as follows:

Stage 1 – Materials screening
This stage's objective is to screen out, through appropriate testing, obviously unsuitable (e.g., highly plastic, oversized) or problematic (e.g., expansive) materials.

Stage 2 – Materials evaluation
This stage aims to evaluate the suitability of materials in terms of their strength, as related to various combinations of moisture and density, for comparison with the design requirement.

Stage 3 – Risk assessment
This stage aims to assess how a material responds to density and moisture content changes to evaluate the implications of such changes on the operational conditions in service.

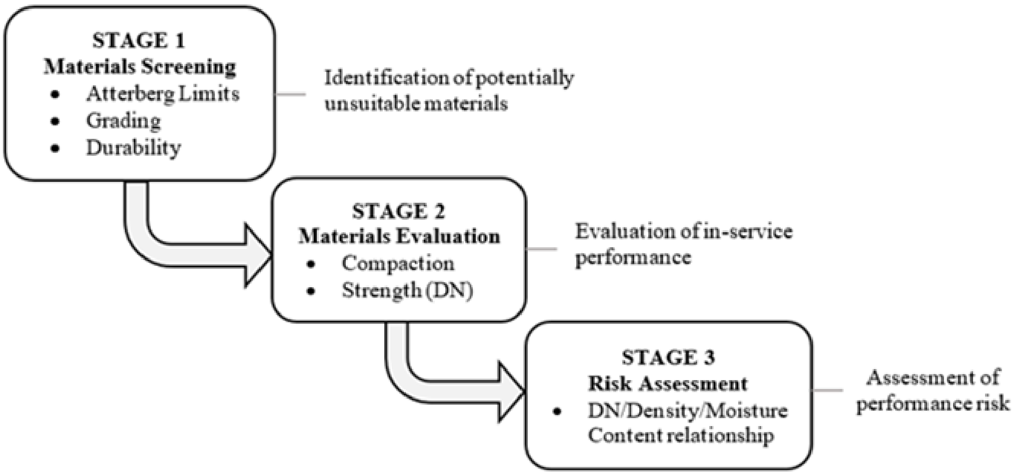

Figure 1: Materials evaluation framework

The various stages of the materials evaluation framework entail undertaking several laboratory tests indicated in Figure 1, following the testing procedures described below.

Stage 1 – Materials Screening
Using appropriate tests, the screening of subgrade or pavement layer materials is first made to detect and eliminate those with deleterious properties associated with "problem soils", such as expansive, erodible, saline, dispersive, etc.

Atterberg limits: The standard tests to determine this parameter, i.e., Plastic Limit (PL), Liquid Limit (LL), Plasticity Index (PI) and Shrinkage Limit (SL), must be carried out to provide a first indication of how a material will react under various moisture conditions, but these tests give little indication of the strength-moisture-density relationship that will be separately investigated in Stage 2. Nonetheless, the PI and LL are useful indices for determining the swelling characteristics of most fine-grained clay soils (Holtz and Gibbs, 1956), whilst the classification of swelling potential of clayey soils can be determined from their LL and PI (Seed et al., 1962).

Grading: The material's Grading Modulus (GM) is also required for excluding overly fine or coarse materials (oversized) from being considered for use in the pavement layers. The following formula (Eq. 1) calculates the GM:

$$GM = [300 - (P2 + P425 + P075)]/100 \tag{1}$$

where P2, P425 and P075 denote the percentages passing through the 2.0 mm, 0.425 mm and 0.075 mm sieve sizes, respectively.

The particle size distribution determination should be based on a wet sieve analysis, with pre-treatment being required for pedogenic materials, such as calcretes and laterites (Netterberg, 1984).

Mineralogical and durability tests: The use of weathered materials of basic igneous origin, such as basalt and dolerite, is potentially problematic, although less so for LVRs with relatively short lives of typically 15 years, as they may decompose in service to various degrees as a result of the alteration of certain primary minerals to secondary clay minerals. Thus, appropriate durability tests (usually involving soaking in ethylene glycol) may need to be carried out following country standards.

Final assessment: The selection of materials in terms of acceptability for a specific use is then based on the results of Stage 1 of the laboratory testing programme, coupled with engineering judgment, bearing in mind the preference for using local materials.

Stage 2 – Materials Evaluation

Once the general acceptability of the material is agreed upon based on the outcome of Stage 1 of the materials testing programme, the material is then subjected to a series of strength tests at three compactive efforts (Light, Intermediate and Heavy) and three moisture contents (Soaked, OMC and 0.75 OMC), i.e., a total of nine combinations of density and moisture content (MC). To achieve relative compaction results of +/- 98%, +/- 95% and +/- 93%, the following three compactive efforts were used (Pinard and Hongve, 2020).

- Light: 2.5 kg rammer, 3 layers, 55 blows/layer
- Intermediate: 4.5 kg rammer, 5 layers, 25 blows/layer
- Heavy: 4.5 kg rammer, 5 layers, 55 blows/layer

The compacted samples should be sealed in a plastic bag for at least 3 days (7 days for pedogenic materials) to enable pore-water pressures and compaction stresses to dissipate and to facilitate moisture equilibration within the sample before undertaking DN laboratory testing. At each combination of density and moisture content, a laboratory DN test is carried out to determine the quasi-shear strength of the soil. The set-up for undertaking the laboratory DN test is illustrated in Figure 2.

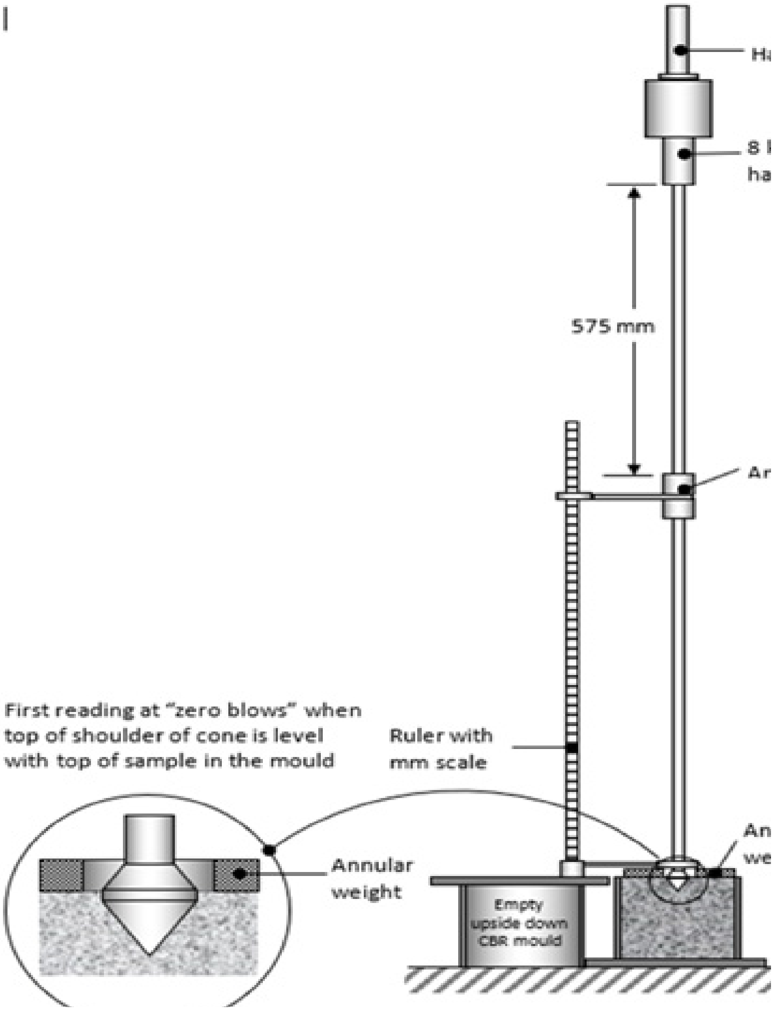

Figure 2: Set-up for laboratory DN test (Pinard and Hongve, 2019)

Figure 3 illustrates the typical outputs of the laboratory DN test programme for two different materials, A and B. The shape and separation of the curves are material dependant and will assist the engineer in undertaking a risk assessment, as explained below. As discussed above, an acceptable DN value (based on the design assumptions) takes account of the key interacting variables that affect material strength. Thus, the DN value implicitly captures acceptable grading and plasticity requirements and does not need to be separately specified when selecting pavement layer materials, thereby reducing the risk of accumulating errors associated with specifying multiple material properties.

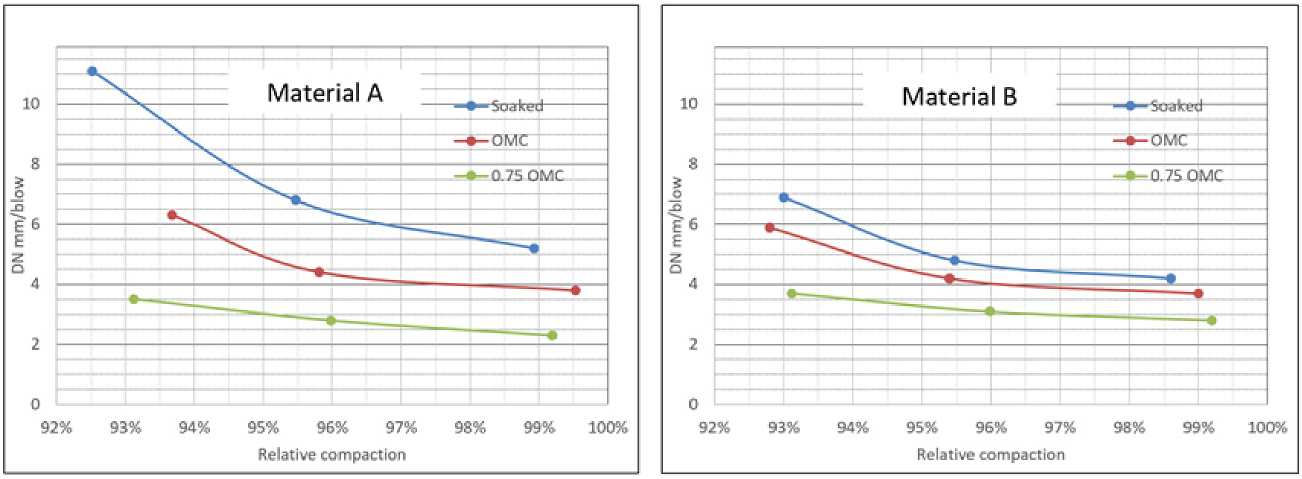

Figure 3: DN/density/moisture relationship for two different materials, A and B

Stage 3 – Risk Assessment

Assessing the risk of failure profile of the material concerning how well suited it is to the design application is an essential aspect of the overall evaluation process. Such risk would be related, in part, to the sensitivity of the material's strength to changes in moisture content and/or density and the implications this could have on pavement performance. This risk can be assessed from the output of Stage 2 of the laboratory testing programme in which the gradient of the curves and the separation between them indicate the following about the particular material:

- The greater the relative vertical separation of the lines, the greater the sensitivity of the material's strength to moisture changes (a function of plasticity), and the greater the likelihood of poor structural performance should the moisture content increase significantly above that assumed for design purposes. To reduce the risk of such an occurrence, a number of measures can be considered, including:
  - Sealing of shoulders to avoid lateral moisture ingress into the pavement's vulnerable outer wheel path areas.
  - Deepening side drains and/or raising embankments to ensure a minimum crown height (vertical distance between the crown of the road and the invert of the side drain) to at least 0.65 m to 0.75 m depending on the longitudinal gradient of the road.
  - Timeously inspecting and re-sealing, e.g., when cracks first develop on the paved surface of the pavement.

- The steeper the slope of the lines in Figure 3, the greater the relative sensitivity of the material's strength to changes in density (a function of particle size distribution and particle shape); and the greater the likelihood of poor performance should the specified density not be achieved during construction. To minimise the risk of such an occurrence, several measures can be considered, including:

- Compacting the subgrade and pavement layers, not to a specified level as is traditionally done but, rather, to the highest uniform level of density possible without incurring material degradation (“compaction to refusal”) (Pinard et al., 2003). This approach will likely produce a significant gain in density, strength, and effective stiffness and a reduction in permeability at minimal additional cost, thereby enhancing the material's overall properties and structural performance.

- Ensuring adherence to the specified pavement layer thickness and minimum compaction requirements by enforcing rigorous quality control measures on site. These tests can be slow, hazardous, of uncertain accuracy, and impractical in situations where there is variation in site materials in the road structure prism along the tested section. The use of the DCP for quality control of compaction operations offers a viable alternative to the traditional methods such as Sand Replacement, core cutter, rubber balloon, and nuclear density gauge (Livneh and Livneh, 2013).

By way of example, using the two diagrams in Figure 3:

- The risk associated with increased moisture content from OMC to soaked is greater for Material A than for Material B because of the relatively larger difference in DN values between OMC and soaked condition for Material A. Therefore, in a dry/moderate environment with good drainage conditions, Material A may be acceptable. In contrast, in a wet environment with a high risk of saturation of the pavement, only Material B would be acceptable.

- The risk associated with not achieving the specified compacted density of the base layer of 98% Mod. AASHTO is insignificant for both materials since those parts of the curves are fairly flat at all moisture contents. However, at lower compacted densities, say 95% Mod. AASHTO, which is typically specified for the subbase, the risks increase since the DN values increase (and effective strength decreases) significantly with a reduction in density from 95% to 94% Mod. AASHTO for both materials at OMC and in the soaked condition. This underscores the importance of achieving the minimum specified compacted densities, particularly at lower compacted densities. It also highlights the potential benefits of compacting to refusal the subgrade and structural pavement layers.

The risk assessment process should also consider several other factors that could significantly influence the structural behaviour of the pavement. These include:

Design considerations: Ideally, the design moisture content should be based on the anticipated in-service, long-term, equilibrium moisture content (EMC), which could be above, at, or below OMC. Thus, the design moisture content must be carefully selected, based on an assessment of the general climatic conditions and, in particular, the micro-climate for the road section under design.

Construction techniques: Generally, it is beneficial to allow the pavement layers to dry below OMC before they are sealed. This will allow the strength gain caused by negative pore-water pressure, i.e., suction (Toll, 2012), to be mobilised soon after compaction, rather than gradually over time, as would occur if the pavement had been sealed at the OMC level.

Vehicle loading and overloading: LVRs are prone to excessive permanent deformation and shear failure due to overloading. A single, excessively loaded axle can cause the pavement to deform severely and fail, particularly if the pavement's moisture content rises and excessive positive pore-water pressures develop. However, this risk can be reduced by allowing the pavement layers to dry back from OMC and designing them as described above. If adequate overload control is unlikely to be achieved in practice, a more substantial pavement structure should be provided, i.e., designing for higher axle loads.

Maintenance: LVRs are particularly vulnerable to inadequate or deferred maintenance due to the extensive use of local, often moisture-sensitive materials for pavement construction. This vulnerability is further exacerbated by the projected climate changes in the coming decades. Thus, the highest priority should be given to timely and adequate maintenance of LVRs to avoid their premature deterioration.

3.2 Validation of Evaluation Framework

The materials evaluation framework described above was developed on the basis of the research evidence emanating from the back-analysis of the in-service performance of a large number of test sections (Gourley and Greening, 1999; Paige-Green, 1999; Rolt et al., 2013; Rolt et al., 2020) located in East, West and Southern Africa. The framework has been successfully applied in several countries in West and Southern Africa (Geddes and Pinard, 2020).

3.3 Impact of Adopting the Materials Evaluation Framework

Material specifications: Provided all materials are assessed as suitable from the outcome of the Stage 1 evaluation procedure discussed above, then the two parameters that need to be specified for the imported materials for the pavement layers are as follows:

- Grading modulus (GM): The inclusion of this parameter as a specification criterion is to exclude any materials that are patently unsuited for use in a pavement layer in terms of their very poor grading and/or very high fines content, e.g., very fine soils that are likely to be plastic soils, or very poorly graded gravels which, in any case, would most probably not satisfy the required DN value. A typical range of values for GM is $1.0 \leq GM \leq 2.25$ (Pinard and Hongve, 2020).

- DN value: The acceptance criterion for a material is the laboratory DN value at a specified minimum compaction density and the anticipated in-service, long-term EMC for the various pavement layers as specified in the DCP-DN catalogue (Pinard and Hongve, 2020).

The DCP-DN catalogue was developed from extensive research carried out in South Africa from the mid-1970s onwards (Paige-Green and van Zyl, 2020) and, more recently, was enhanced under Re-CAP (Pinard and Hongve, 2020). The catalogue stipulates a required laboratory DN value at a specified minimum compaction density and the pavement's anticipated in-service equilibrium moisture content for various design traffic loading classes up to one Million Equivalent Standard Axles, i.e., 1 MESA.

Road Construction Costs: The DCP-DN specifications widen the scope for using local materials and contribute to reduced construction costs by minimising haul distances and material extraction and processing costs. This likelihood was confirmed by a study to determine the cost-effectiveness of the DCP-DN design method compared to other, more traditional, CBR-based LVR design methods (Pinard et al., 2019). The study found that the DCP-DN method was the most cost-effective design option at design traffic loadings up to about 0.7 MESA and across all subgrade strengths and climatic zones.

4. SUMMARY AND CONCLUSIONS

The successful and economical utilisation of local materials in LVR pavements depends on their proper characterisation in terms of their properties and traffic loading, physical environment, and interactions. Unfortunately, a conflict often exists between material acceptability, as defined by conventional test methods and specifications, and material suitability in actual engineering performance. This has led to a need to develop a more reliable, performance-related laboratory materials evaluation framework for selecting and specifying local materials and, ultimately, facilitating their optimised utilisation in the design and construction of LVRs.

The material evaluation framework includes a three-tier evaluation procedure in the laboratory. The materials are initially screened based on classification, mineralogical, and durability tests to eliminate those patently unsuitable for use in the LVR pavement structure. After that, the strength of the material is determined based on its DCP penetration rate in mm/blow, or simply the “DN value”.

The evaluation framework was developed from research carried out over many decades, starting in the mid-1990s, based on the back-analysis of many LVRs and has subsequently been validated through the successful application in several countries in west and Southern Africa. In conjunction with the DCP-DN design method, the evaluation framework's use can significantly reduce the cost of road construction, particularly in rural and remote areas and for low volume traffic roads, through improved utilisation of locally available materials. A real-life example of the application of the Materials Evaluation Framework is presented in an annex to this paper.

5. ACKNOWLEDGEMENTS

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ANNEX A – EXAMPLE OF The APPLICATION OF THE MATERIALS EVALUATION FRAMEWORK

Stage 1 – Materials Screening

Sieving analyses were carried out on samples from test pits on the road and potential borrow pits, as shown in Table A1, to assess the materials' suitability for incorporation into the road pavement. The following results were obtained.

Table A1: Sieve analysis results

Lab #	ID #	Visual Description	Depth m	USCS class.	MC %	LS %	Sieve analysis						PI	SP	GC	PM	GM	Proctor	
							0,075	0,425	2,0	5,0	28,0	50,0						MDD kg/m^3	OMC %
3582	B/P1 sample 1 base	Slightly moist yellowish red clayey gravelly sand	0.5-2.0	SC		7.1	21	38	52	76	100	100	12	251	47	245	1.9	2172	8
3583	B/P1 sample 2 base	Slightly moist yellowish red clayey gravelly sand	0.5-2.0	SC		7.4	16	32	45	64	95	100	13	211	40	204	2.1	2200	7.6
3584	B/P2 sample 3 stock pile	Slightly moist yellowish red clayey gravelly sand	0-2.0	SC		3.33	15	34	52	66	95	100	12	223	41	181	2	2340	5.7
3585	B/P2 sample 4 stock pile	Slightly moist yellowish red clayey gravelly sand	0-2.0	SC		6.67	16	36	55	71	95	100	13	119	42	220	1.9	2170	8.1
3586	B/P 1 sample 5	Slightly moist light grey gravelly sand- clay mixture	-	SC		2.67	43	59	86	93	94	100	19	156	33	807	1.1		
3587	8+000 TP 1 layer 1	Dry strong brown clayey sand	0.2	SC	2.9	5.33	32	82	99	99	100	100	11	435	18	349	0.9	2139	9.4
3588	8+000 TP 1 layer 2	Slightly moist strong brown clayey sand	0.45	SC	7.9	5.33	35	84	98	99	100	100	14	446	16	500	0.8	2139	9.4
3589	3+800 TP2 layer 1	Dry reddish brown clayey gravelly sand	0.1	SC	2.9	2	16	44	58	73	94	100	10	87	37	165	1.8	2195	8.6
3590	3+800 TP2 layer 2	Slightly moist rediish brown clayey sand	0.2	SC	6.6	4	41	87	97	99	100	100	13	348	13	516	0.7	2015	11
3591	3+800 TP2 layer 3	Slightly moist rediish brown sandy clay	0.45	CL	9.5	4.67	55	90	99	100	100	100	12	422	10	654	0.6	1902	13.6
3594	Sand layer 2	Dry yellowish red sand (from pothole	-		1.5														

* Material sample highlighted in yellow was subjected to further testing in Stage 2. The DN-density-moisture relationship for that material is shown in Figure A1.

Stage 2 – Materials Evaluation

The representative laboratory DN value was determined at three different moisture contents and at three compactive efforts as illustrated in Table A2 and Table A3 below:

Table A2: Determination of laboratory DN values for material in soaked condition

Mould no	X8	NO	D3	M5	A1	M4	M1	Z6	Z8
Compactive Effort	Light			Intermediate			Heavy		
Mass of wet sample + mould (kg)	9334	9380	9367	9554	9575	~~9378~~	9789	9813	9804
Mass of mould (kg)	3.000	3.000	3.000	3.000	3.000	~~3.000~~	3.000	3.000	3.000
Mass of wet sample (kg)	6.334	6.380	6.367	6.554	6.575	~~6.378~~	6.789	6.813	6.804
OMC (%)	5.70%								
Mass of dry sample (kg)	5.992	6.036	6.024	6.201	6.220	~~6.034~~	6.423	6.446	6.437
Volume of mould (cm^3)	2780	2780	2780	2780	2780	~~2780~~	2780	2780	2780
Dry density of sample (kg/m3)	2156	2171	2167	2230	2238	~~2171~~	2310	2319	2315
Average Dry density of samples (kg/m3)	2165			2234			2315		
MDD (kg/m3)	2340								
Relative compaction (%)	92.1%	92.8%	92.6%	95.3%	95.6%	~~92.8%~~	98.7%	99.1%	99.0%
Average realtive compaction	92.5%			95.5%			98.9%		
Condition of sample @ testing	Soaked								
Actual MC in centre mould	7.9 %	7.7 %	7.3 %	7.4 %	7.3 %	~~7.6 %~~	6.7 %	6.5 %	6.8 %
Average MC in centre mould	7.6 %			7.4 %			6.7 %		
Best fit DN	11.3	11.0	10.8	7.1	6.7	~~10.6~~	5.4	5.5	5.1
Average Best fit DN	11.0			6.9			5.3		

Table A3: Summary of laboratory DN test results

Compactive effort	Best Fit DN (mm/blow)		
	Soaked	OMC	0.75 OMC
Light	11	6.4	3.6
Intermediate	6.9	4.5	2.9
Heavy	5.3	3.9	2.4

Compactive effort	Dry density (kg/m^3)		
	Soaked	OMC	0.75 OMC
Light	2165	2192	2179
Intermediate	2234	2242	2246
Heavy	2315	2329	2321

MDD	2340 kg/m^3			
		Light	Int	Heavy
Soaked	Relative compaction	92.5 %	95.5 %	98.9 %
	Best Fit DN	11	6.9	5.3
OMC	Relative compaction	93.7 %	95.8 %	99.5 %
	Best Fit DN	6.4	4.5	3.9
0.75 OMC	Relative compaction	93.1 %	96.0 %	99.2 %
	Best Fit DN	3.6	2.9	2.4

Stage 3 – Risk Assessment

The risk of using this particular material under various moisture regimes can then be assessed by plotting the Best fit DN values from Table A3 in a diagram as shown in Figure A1:

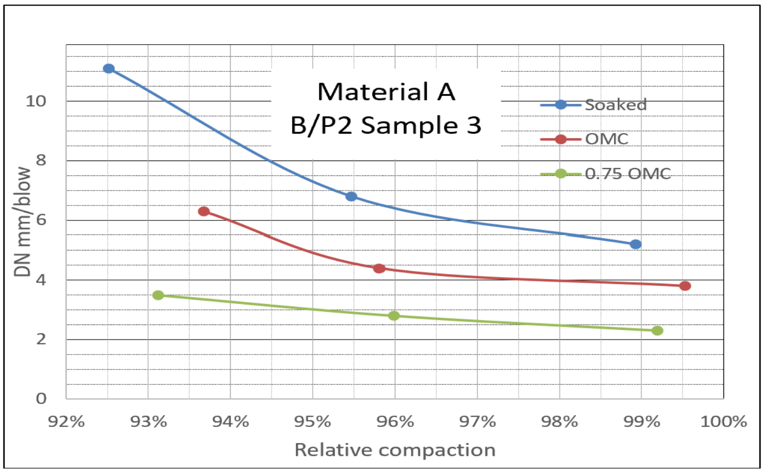

Figure A1: DN/Density/Moisture relationship diagram

If the DN requirement for the particular pavement layer is 4.0 mm/blow, this material will only qualify if:

- the long term EMC is ≈ OMC AND the compacted density is ≥ 97.5%.
- the long term EMC is≈ 0.75 OMC at compacted densities ≥ 93% (lowest acceptable limit).
- the long term intermediate EMC between 0.75 OMC and OMC, acceptable compacted densities can be determined by interpolation between the respective curves.

If there is a risk the material will get soaked in service, it will not qualify for use without modification or stabilisation.