

Potential application of miniature equipment in determining unsaturated fine-grained soil bearing capacity

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ABSTRACT: The determination of soil strength is essential for civil and pavement engineering, traditionally relying on direct shear tests or triaxial tests that are relatively expensive and time-consuming. In Southern Africa, the DCP (Dynamic Cone Penetrometer) is widely used in pavement engineering to evaluate the strength of unbound materials. Around 25% of Mozambique's approximately 30,000 km classified road network is paved mainly with surface dressing, which has their structural pavement layer composed of cement-stabilized or crushed stone. This is a typical pattern across Southern Africa. Due to the scarcity of quality rocks that meet the specifications, as well as cement factories being distanced more than 1,000 km apart, road construction costs present a huge financial overburden to the country. Residual tropical fine-grained soils are often excluded from many pavement design catalogues, anticipating failures as a structural layer. This can be attributed to its historically poor performance in temperate and cold climates, with local guidelines and practices having yet to address this challenge. The exclusion of these soils in pavement design cannot be ignored due to their widespread occurrence. Contemporary laboratory test methods are inappropriate for residual tropical soils as they undergo irreversible structural rearrangement under elevated high temperature requiring huge material quantities for testing and are time-consuming. In response to this, a customized instrument, the "mini-DCP", that resembles the DCP was manufactured suiting the MCT (Miniature Compacted Tropical) technology. It unveiled the potential for its successful application in the selection of fine-grained soils, especially for the upper layers of road pavements, allowing for user-friendly data processing for sensitivity analyses. Furthermore, a new definition of optimum, similar to the optimum of the original proctor compaction test, allowed for a rapid assessment of moisture susceptibility which is paramount in the context of extreme climatic events.

KEYWORDS: Miniature Compacted Tropical; mini-MCV; mini-DCP.

1 INTRODUCTION

Mozambique, despite being located in a tropical/sub-tropical climatic region, has historically neglected naturally occurring materials on justifications revolving around its supposed inadequate capacity and has instead adopted pavement design and implemented solutions that are considered to be less prone to environmental changes, such as crushed stones and cement-stabilized layers. As a consequence, the California Bearing Ratio "CBR" is the only pragmatic test available to assist professionals in pavement design.

Although, CBR has gained popularity in the pavement engineering fraternity, its application is still disconcerting to many. For this reason, other equipment such as the Dynamic Cone Penetrometer (DCP) is used to address some of these shortcomings due to its proven suitability for testing residual tropical fine-grained soils.

DCP, used widely in the world, particularly in Southern Africa, following upon extensive research from mid-1970s, correlated with Heavy Vehicle Simulator in South Africa up to 10 million equivalent 80 kN standard axles with coefficient of correlation $R^2 > 85\%$, and accuracy to performance of pavements, even 33% better, has been reported.

The equipment is widely available in Mozambique and has been used successfully, see Guilamba (2024). CBR on the other hand, has reported statistic CoV of up to 25% for instance, poor repeatability and reproducibility, according to Pinard (2011), that was congruous to Gidigas (2011), introducing ambivalent

results. Those aspects motivated the development and commissioning of a mini-DCP for this investigation.

This paper also presents a nomogram of DCP performance function, portrayed in Figure 4, which was originally calibrated using heavy vehicle simulator data from test sections in South Africa, adapted by the authors to incorporate Köppen-Geiger climatic factors as suggested in the TRH24. The application of the nomogram underscores the moisture sensitivity analysis of materials in an efficient manner, which is paramount in today's context of climate changes and frequent occurring high intensity rainfall.

2 OBJECTIVE

The main objective of this paper is to investigate a potential practical and coherent process to assess applicability of fine-grained soils in structural pavement layers, especially for residual tropical soils, using miniature equipment, mainly the mini-DCP.

3 METHODOLOGY

Four samples of dissimilar soils were classified and the material scalped at 2,0 mm sieve size was used throughout the test program. The soils originated from North (Nangade), Central (Mopeia and Gorongosa) and South (Moamba) Mozambique. The soils were stabilized with Portland Cement in the typical range of 4-6%, if used in the upper layers of pavement structure. The Gorongosa sample was also deliberately incorporated due to its peculiarities. It is a soil consisting of some whitish and

vitreous lustering elements, indicative of muscovite mica, as was later confirmed by XRD (X-Ray Diffractometer) analyses. The samples were characterized using two current methods, comprising of i) Atterberg indicators, soil grading, compaction and ii) Shear resistance by mini-DCP penetration rate DN, expressed in mm/blow or blows/mm, and mini-MCV (mini-Moisture Condition Value), which has the potential to substitute the contemporary moisture content determined through an unsuitable oven-drying process, at high temperatures of 105°C to 110°C as per TMH-1 1986. The mini-moisture condition value “mini-MCV” is well established and has been standardized in Brazil, *DNIT 254/2023-ME*, as a reduced scale tool mimicking the MCV as introduced in the United Kingdom by Parsons (1976). In addition, the mineralogical composition of each sample was determined using a specialized XRD analysis, both on total sample size as well as on the fraction passing <75µm.

A mini-DCP was customized for this research, with characteristics as shown in Figure 1 below:

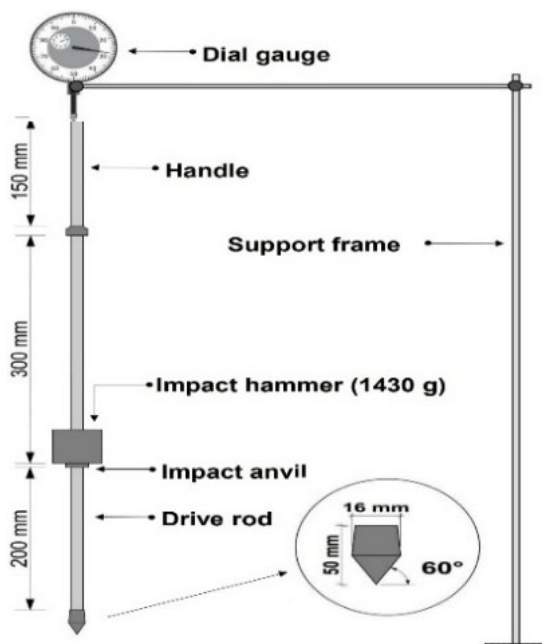


Figure 1. Characteristics of the mini-DCP

The moisture content was calculated using the TMH1 1986 standardized method of oven-drying the soil at 105°C. The mini-MCV is defined as the number of blows to reach refusal density of the specimen in the mini-mould as per Brazil’s norm. The MCV has the potential to quickly indicate the moisture level in the material without subjecting it to high temperatures which inevitably cause irreversible changes to the structure of some tropical/sub-tropical residual soils, Pinard (2011) and Terzaghi (1943).

Table 1. Mineral Composition of Samples, both on Total Samples as well as on the fraction passing sieve 0.075mm

SOIL	MINERAL COMPONENTS								
	Quartz	Plagioclase	Microcline	Kaolinite	Muscovite	Hematite	Anatase	Diopside	Smectite
Nangade (Total Sample)	89,1	0	0	10,6	0	0	0,4	0	0
Nangade (<75 microns)	34,2	0	0	62,6	0	0	3,3	0	0
Gorongosa (Total Sample)	51,3	16,2	25,8	0,5	1,0	0	0	0	5,2
Gorongosa (<75 microns)	23,0	28,1	19,9	9,1	7,9	0	0	0	12,1
Mopeia (Total Sample)	95,1	0	4,4	0,5	0	0	0	0	0
Mopeia (<75 microns)	68,7	0	13,9	16,4	0	0	0	1,0	0
Moamba (Total Sample)	76,8	2,8	5,3	13,6	0	1,5	0	0	0
Moamba (<75 microns)	36,8	3,1	4,3	53,6	0	2,2	0	0	0

Although the degree to which this change occurs cannot be established with precision, it is associated with the mineral constituents of the parent rock. Additionally, the mini-MCV showed a strong correlation with the moisture content w(%), with a coefficient of correlation $R^2 > 90\%$, as shown in Figure-3.

The Cone Penetration Test using the mini-DCP apparatus was carried out for two soil conditions, i) at moulded moisture and ii) after 15h soaking condition. For each of the conditions, 5 sets of specimens with an average of 3 samples per moisture condition, were tested, in analogy to current practice. The mini-DCP penetration readings for each individual blow, as well as the readings of the proctor compaction tests, were recorded. The entire process was repeated after 15h soaking, as was the determination of moisture content of these samples using the traditional oven-drying process.

It is worth noting that the adopted procedure using mini specimens typically uses test samples of about 200 g, only 3-5% of the material necessary when compared to the traditional test protocol for compaction. This is very relevant for both further research and for sensitivity analysis. Macia (2025), discussed in detail the procedure to calculate the representative DN.

The mini-DCP (blows/mm) vs mini MCV (number) chart, for 2 compaction energy, 6 standard drops or 4 each side (6x6 and 4X4) at moulding and 15h soaking is plotted, see Figure 3. Contrary to the proctor compaction chart, an optimum condition is determined based on strength instead of density. Particularly for residual fine-grained soils, if a reasonable presumption is made that both the optimum MCV (from the mini-mould “50x50”mm and from conventional CBR mould “127x152”mm) have similar values, then the design DN can be obtained from conventional CBR mould with moisture condition pre-indicated from the mini-mould. This represents a tremendous time and materials savings in the entire mix design process, as mentioned before. Furthermore, this unveils the possibility for design engineers to analyze the implication of project location within the Köppen Geiger climatic system, the rainfall and drainage conditions, as simulated by soaking time, with congruent DN used as input to the nomogram in Figure 4.

4 RESULTS: ANALYSIS AND DISCUSSION

4.1 Classification

The soils were dry sieved for grading analysis using the full ASTM sieve series. However, Figure 2 depicts the truncated grading analysis at 2,36 mm, for consistency, since the subsequent tests were conducted on material screened at sieve size 2,0mm (from AASTHO series) as per the Brazilian norm. However, for classification purposes, the full samples were thoroughly analyzed according to USCS and AASHTO in addition to the modified compactive effort as shown in Table 2. Except for the Gorongosa soil, all soils passed 100% on sieve size 2,0 mm.

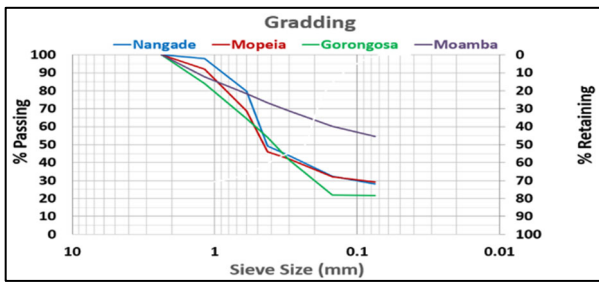


Figure 2. Grading Analysis (truncated at 2,36 mm size)

It is observed that Mopeia and Nangade are quite similar in gradation, but presumably due to their different mineralogy, produced tremendously different test results, as presented in Figure 2.

Table 2. Soil Classification and optimum compaction

Sample	Atterb. Indicators		% passing (sieve in mm)				Classification		Compaction	
	LL	PI	0,075	0,425	2,36	4,75	USCS	AASHTO	MDD (Kg/m ³)	OMC (%)
Nangade	26,6	8,9	28,1	49,3	100	100	SC	A-2-4	2026	6,5
Zero-Mopeia	23,8	11,5	29,0	45,9	99,6	99,9	SC	A-2-6	2179	6,7
Gorongosa	-	-	14,2	35,7	66,1	7,4	SM	A3	2122	7,1
Moamba	31,4	16,3	55,4	73,2	95,3	98,7	CL	A-6	1925	13,0

Moamba soil is much finer than the rest and possesses the highest plasticity index (PI). Paradoxically, Gorongosa is non-plastic, despite its mineral composition, as seen in Table 2.

4.2 Mineral Composition

Quartz mineral is characterized by its low Cation Exchange Capacity “CEC” and was dominant in each of the samples, as shown in Table-1. This low CEC is a characteristic feature of tropical/sub-tropical residual soils. Quartz, in the form of silicates (mainly kaolinite or exceptionally smectite in the case of Gorongosa) or feldspars (in the plagioclase and microcline), is present in the total sample as well as in the portion < 75µm.

The dark red color in the Moamba sample is indicative of the presence of iron-oxide (hematite). This sample is a young laterite exhibiting a lateritic/behavior as per MCT Brazil, although the silica sesquioxide ratio of iron and aluminum “S/R” is >1,2, in accordance with a study conducted by Macia 2025.

4.3 Test Results

The usefulness of the charts provided in Figure-3 is remarkable and deserves elaboration. It appears that easiness to reach at optimum mini-DCP (low mini-MCV of 14,8) during compaction for Nangade and Moamba samples can be attributed to a high kaolinite mineral content of above 50%, as seen in Table 1.

It is observed that gradation in combination with mineralogy and compactive effort are conditioning the specimens with a strong impact in the mini-DCP dry values and values after subsequent soaking. It is interesting to note that cone penetration was sensitive enough to detect such a condition in the mix. However, while gradation has a pronounced effect in densification during compaction and therefore affects the sample strength in dry condition, the mineralogical composition plays an even greater role in maintaining the strength after soaking for a certain period, presumably on account of low CEC of minerals.

Nonetheless, it is notable to observe that Gorongosa specimens revealed relatively high strength values after 15h

soaking, which is attributed to the huge surface area of smectite minerals that were significantly present (5 and 12%), see Table 1. This unexpected result was verified in separate Project Reports that determined a CBR above 90% for 96h laboratory soaked samples. Despite these high strength values, this road section underperformed in service. These high CBR values are believed to be of a transient nature, and have been attributed to a favourable interaction between mineral elements (expansive smectites and non-expansive muscovite and quartz) which may be playing a crucial role in residual compaction, as discussed by Uzan (1985) and supported in plastic equilibrium theory by Terzaghi (1943). This was not taken further since it was outside the scope of the research.

Relative moisture sensitivity among the 4 soils can be anticipated from the slopes in the calibrated charts, which negatively correlated with the moisture-sensitivity. Nangade had the lowest absolute slope of 0,5027, and exhibited the highest sensitivity within the moisture variation range tested. On the other hand, Gorongosa had the highest absolute slope of 2,274, and exhibited the lowest moisture sensitivity, possibly stemming from its wider mineral composition as shown in Table 1.

Contrary to Gorongosa’s premature failure as previously indicated, the country’s experience in incorporating about 5% Portland Cement stabilization on Mopeia and Nangade soils in projects have shown very good performance. There are no records on the utilization of Moamba soils in the upper layers of pavements, presumably due to its fineness or high PI. The exclusion of such a residual soil (with an apparently good DN) in tropical zones was lengthily discussed by Gidigasu (2011), who concluded that the exclusion of these soils might be an over-conservative and un-economical approach.

It is fascinating to see from Figure 3 that, although the Gorongosa sample showed that heavier compactive energy (6x6) indicated a stronger resistance to cone penetration in unsoaked condition, it was not the highly resistant cone penetration after 15h soaking, but effectively the compactive energy (4x4).

The exact soaking time when the shift in tendency occurred could not be established. However, it leads to an understanding that heavier compaction does not necessarily result in a better performance under adverse moisture condition.

Calculation of water content remains unchanged for loose or compacted stages and is determined through a calculation process involving oven-drying of material, irrespective of compaction procedure involved (Modified proctor, for instance). Conversely, MCV is a moisture content value determined in a state of maximum densification (refusal) and is intrinsic to compaction process and equipment. However, it is highlighted that both processes place different mixes in ordinary manner, from driest to wettest in the case of contemporary compaction procedure, and inversely, from wettest to driest in the case of MCV, as depicted in Figure 3.

Incidentally, the adopted procedure of restricting the search for optimum mini-DCP (highest resistance to shear) to visual and sensible moisture-bandwidth that is likely to be implemented in the field has led to elimination of one point (the driest one) in the case of Moamba, portrayed in Figure 3, given its negligible penetration rate after 15h soaking that may be attributed to its fineness. It is hypothesized that the lesser points in conjunction with short range of MCV values scattered the points in Moamba ($R^2 = 0.75$) relatively to the rest of soils ($R^2 > 0.9$).

Notwithstanding the above, MCV intervals cannot be analysed at minute intervals of, say, less than 0.5% equivalent moisture, for reasons as discussed ahead. Otherwise, it simply becomes impractical for field operations.

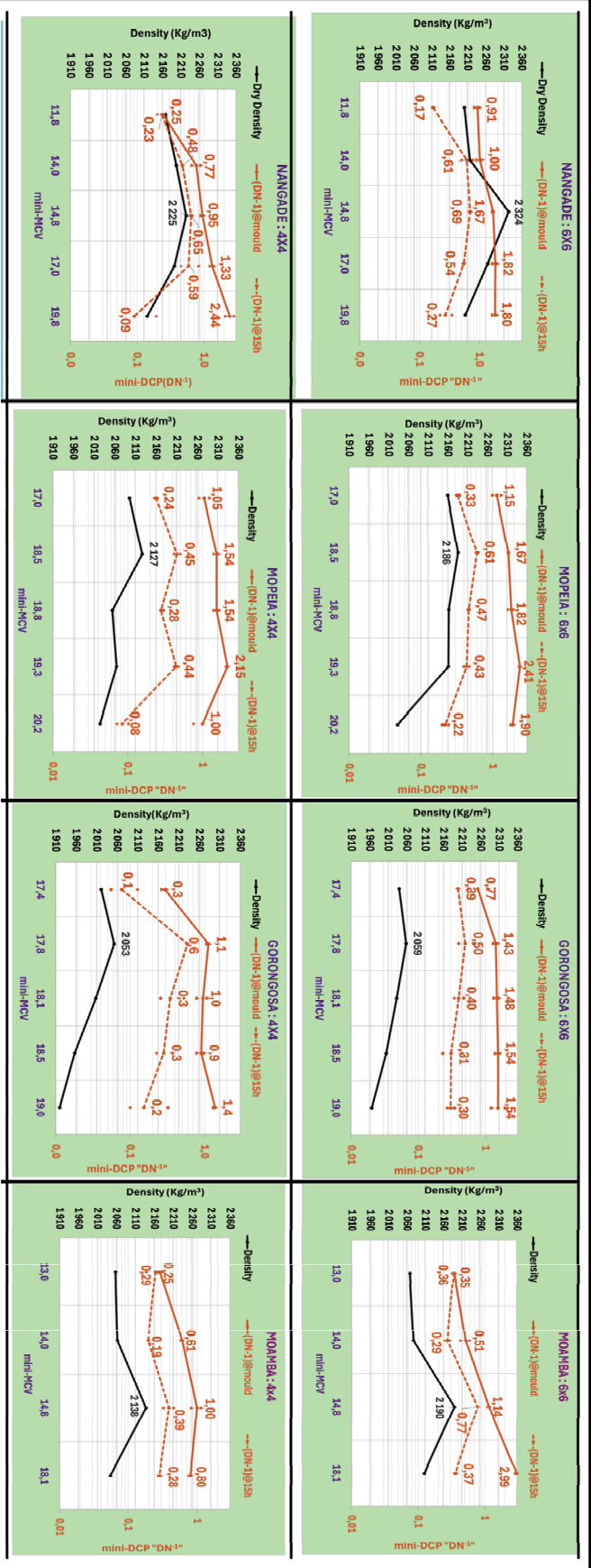


Figure-3a: Super-imposed mini-DCP=DN⁻¹ [Blows/mm], at moulding and after 15h soaking condition, over the mini-Proctor. Of utmost importance is the dashed line, indicative of inherent DCP shear strength of the material conditioned under water for a given time duration (15h soaking in the case). A positive correlation between mini-DCP maximum strength as measured in (blows/mm) and mini-Proctor maximum dry density (kg/m³) is noticed. Nonetheless, strength resistance should override density.

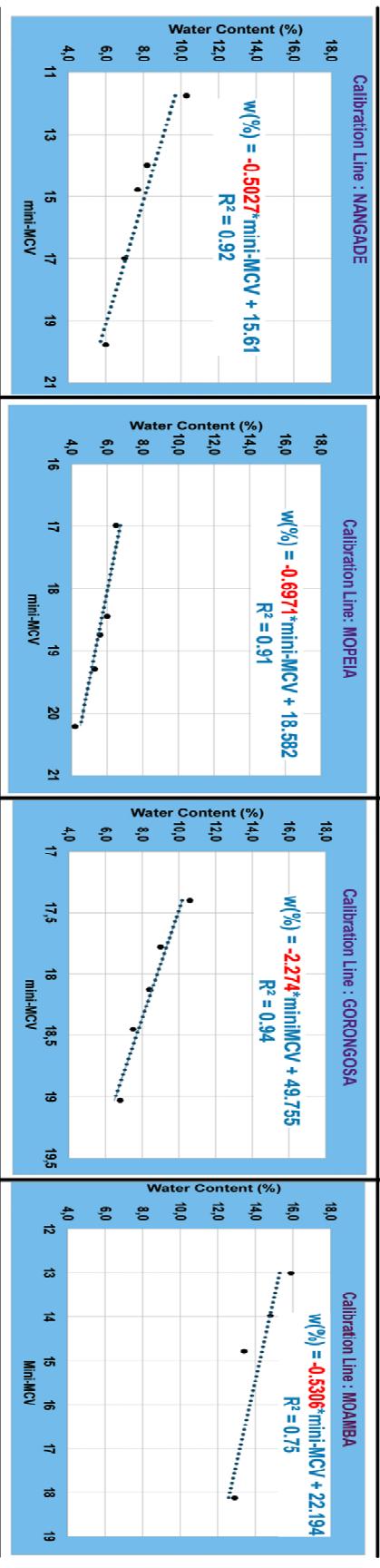


Figure-3b : Calibrated mini-MCV and water content (%) showing good correlation coefficient. This may enable mini-MCV to be referred to instead.

Figure 3. Miniature test results ledger and calibrated mini-MCV.

This Nomogram provides a correlation between i) project location as per Köppen Geiger climatic region, ii) Cover depth, iii) DCP-Penetration rate (either mm/blow or blow/mm) and iii) Traffic (load and bearing capacity).

Notes:

- *Traffic Spectrum* should be converted into loading using appropriate pavement balance Number (BN), see Kleyn 1987; Jordaan 1989 and Jordaan 1994, which varies according to pavement structural composition (for shallower: BN>40 and deeper pavements: BN<40).
- In general, sensitivity analysis to moisture, compaction, layer thickness, etc. as simulated in the mould will be reflected in the cone penetration rate. The rate can be obtained with assistance of mini-DCP (for residual fine-grained materials) or DCP either in real pavement or inside conventional CBR mould, if applicable.
- It is very convenient to use conventional DCP after optimum moisture condition has been identified using mini-DCP, given the enormous reduction (about 97%) of material. However, correlation between mini and conventional mould or site should be verified.

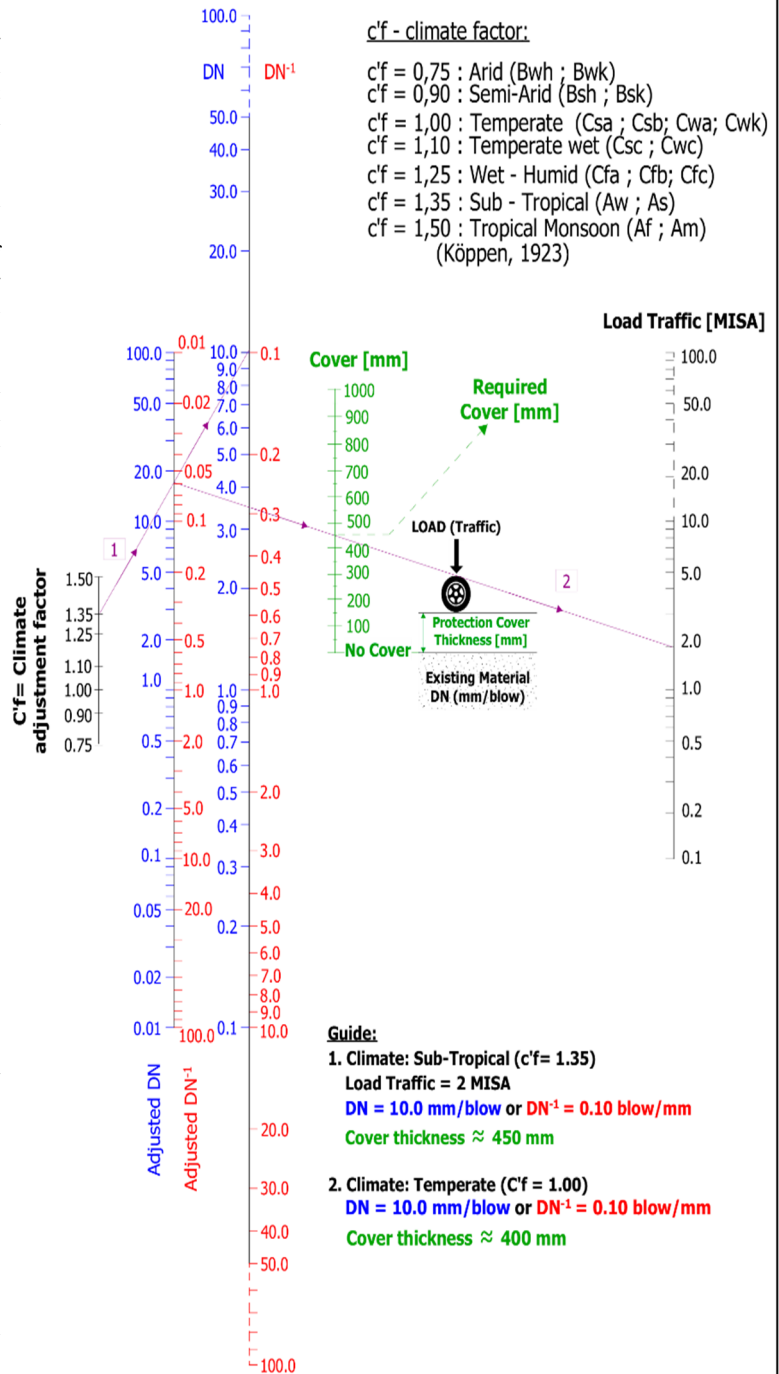
$$\text{COVER} = 194.\log(T) + 457.\log(c'f.DN) - 1285^{(*)}$$

(*) SANRAL, TRH 24 (2024)

$$\text{COVER} = 194.\log(T) - 457.\log(c'f.DN^{-1}) - 1285$$

c'f - climate factor:

- c'f = 0,75 : Arid (Bwh ; Bwk)
 - c'f = 0,90 : Semi-Arid (Bsh ; Bsk)
 - c'f = 1,00 : Temperate (Csa ; Csb; Cwa; Cwk)
 - c'f = 1,10 : Temperate wet (Csc ; Cwc)
 - c'f = 1,25 : Wet - Humid (Cfa ; Cfb; Cfc)
 - c'f = 1,35 : Sub - Tropical (Aw ; As)
 - c'f = 1,50 : Tropical Monsoon (Af ; Am)
- (Köppen, 1923)



Example:

In a component analysis approach, the investigated soils, as characterized by penetration rates derived from figure 3a would require protection cover thickness for a given ambient climate, TRH24 (SANRAL), as under:

Cover Requirement (from DCP-DN After Soaking for 15H)			
Nangade	Mopeia	Gorongosa	Moamba
11	36	75	0

However, additional information may be generated as an alternative to a general climatic factor. considering the actual material performance under soaking conditions, provided that relevant soaking time is adopted and as such, different materials rank differently according to their performance under soaking conditions.

Figure 4. Cover requirements based on dynamic cone penetrometer (after Jordaan 1994) and adapted by the authors for Koppen Geiger climatic factors recommended in TRH24 2024

5 CONCLUSIONS

The development of a miniature Dynamic Cone Penetrometer “mini-DCP” has the potential to function as a practical tool to assess the suitability of fine-grained soils as structural pavement layer, especially for residual tropical climates, which has far reaching implications in the future design, rehabilitation and quality control of unbound materials, especially for residual tropical climates.

Through this work, it was possible to identify and quantify parameters from mini-MCV and mini-DCP, which can be used in a predictive manner to assess the applicability of fine-grained soils, especially those from tropical/sub-tropical climate.

A new concept of optimum condition of the mix based on a direct measurement of strength instead of dry density as contemporarily determined was tested over 4 typical Mozambican soils, with promising results.

It was unequivocally demonstrated that mini-DCP obviates the current timeframe and inadequate practice of oven-drying of samples at high temperatures (105°C-110°C) that is ill-advised for most tropical residual soils. Effectively, relative moisture-sensitivity on tested soils was rapidly quantified in a user-friendly manner with assistance of mini-DCP. Particularly for sandy or silty materials, accuracy in the calculation of optimum mini-MCV may be improved if 2 compactive efforts (e.g. 6x6 and 4x4) are considered. Should the test results be significantly different within the same specimen group when comparing the results of the mini-Proctor compaction and the mini-DCP, additional tests should be performed for confidence in the results and ultimately mini-MCV deduced from mini-DCP results will prevail over mini-Proctor.

In this research, a nomogram tailored to assess the impact of relevant parameters to pavement bearing capacity, such as layer thickness, material quality, moisture and compactive effort and especially regional climate context was compiled from literature review. Engineers are expected to navigate through the foregoing parameters in a pragmatic approach and bring about rationale-based decisions that satisfactorily meet the current engineering demands.

6 RECOMENDATIONS

At Since it is widely recognized that many aspects are involved in soil compaction, such as moisture content, mineralogical composition, compaction process, degree of aggregation, the method and magnitude of compaction energy, etc, it is recommended that both the materials and laboratory conditions imitate field conditions for which the loading capacity was calibrated to avoid difficult correlation problems and deceptive conclusions. It is well established that the compaction process aims at densification of soil particles and that, on its own, it does not change the liquid or solid volumes.

Traditionally, moisture is quantified through an oven-drying process. MCV, on the other hand, is conducted at moulded temperature during compaction and depends mainly upon i) moisture quantity, ii) compaction method (impact over full sample as in the case of miniature equipment or partially impacting per drop as for proctor compaction), iii) number of blows per layer or roller passes that, combined, cause a dispersive or flocculated fabric. Since MCV is process-dependent, changes in its inputs will require a new correlation to be established. Regardless of the DCP equipment scale, it is accepted that MCV remains quite unvaried while the peak value of DN will very likely differ from the miniature to the conventional DCP set-up. When using the mini-DCP, operators will be able to appreciate the significant reduction in the sample size during the pavement design process when incorporating fine grained soils. In similar fashion to CBR, the DCP and its

miniature together with MCV equipment have the potential to evolve into an invaluable tool for the full examination of fine-grained residual soils

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