OPTIMUM DESIGN OF SUSTAINABLE SEALED LOW VOLUME ROADS USING THE DYNAMIC CONE PENETROMETER (DCP)

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ABSTRACT

Sustainable upgrading of unsealed roads to a low volume sealed standard is best accomplished by maximising the use of the in situ materials within the prevailing road environment. Over the years and under traffic loading, unsealed roads achieve a significant degree of subgrade compaction, localised weak areas tend to become strengthened and an accumulation of residual gravel wearing course provides a sound support or foundation for the new road. Optimising the use of these conditions usually results in a reduction in the need to import large quantities of virgin material. Appropriate testing with the simple DCP test device can be used to assess the in situ conditions including material quality and moisture regimes along the road alignment. This information can be used to identify uniform sections; the in situ layer strength diagrams of each of these sections can then be analysed with respect to the estimated traffic to determine the layer quality and thicknesses for a sustainable design. Estimation of the expected traffic can often be a problem in such situations and guidelines to assist in this regard are presented. Data from various road sections in southern Africa are used to support the discussion.

INTRODUCTION

The length of unsealed roads in all developing and many developed countries generally far exceeds that of the sealed road network. Unsealed roads are, however, unsustainable in the long term as they require repeated replacement of the gravel wearing surface. Experience in many countries has shown that the best wearing course gravels have either been depleted or are no longer available. The lack of availability of suitable gravel may be a function of either economics or for environmental reasons. Other aspects such as the need for regular grader maintenance, the generation of dust and the erosion of materials into water courses may also mitigate against the continued use of unsealed roads. The most beneficial solution to these problems is usually to reconstruct the roads with a bituminous surfacing.

Sustainable upgrading of unsealed roads to a low volume sealed road standard is, however, best accomplished by maximising the use of the in situ materials within the prevailing road environment. Over the years and under traffic loading and wetting and drying cycles, the unsealed road would have achieved a significant degree of subgrade compaction, localised weak areas would have been strengthened and an accumulation of residual gravel wearing course over the years would provide a sound support or foundation for the new road. Optimising the use of these conditions usually results in a reduced need to import large quantities of virgin material.

Even then, in order to ensure that the proposed paved road is cost effective and can compete with the life-cycle costs of the unpaved alternative, the overall cost of upgrading to the sealed standard must be kept as low as possible. By making optimal use of the in situ conditions and minimising the quantity of imported material required, a reduction in the construction cost has an immediate impact on the life-cycle costs of the pavement, provided that the maintenance needs for this new road are not significantly higher than a conventional pavement structure.

This paper describes a technique, using a Dynamic Cone Penetrometer (DCP), to characterise the in situ road conditions of an existing unpaved road and to design a sustainable and optimal sealed pavement structure that will minimise life-cycle costs. A flow chart illustrating the DCP design process is shown in Figure 1.

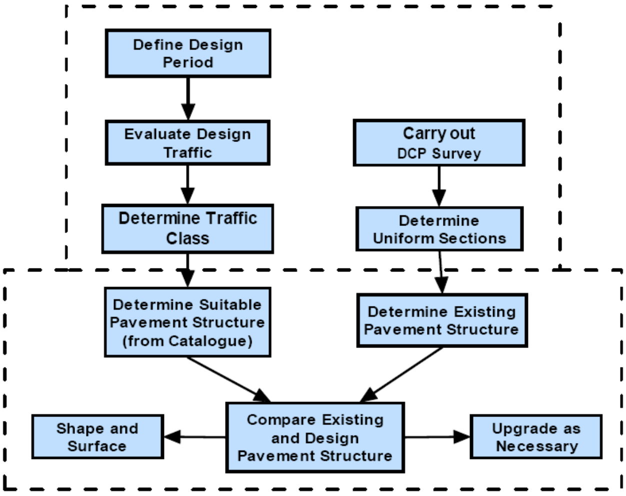

Figure 1: Flow chart of DCP pavement design process

THE DCP TEST

The Dynamic Cone Penetrometer (DCP) is a simple yet robust piece of equipment that can characterise the ground conditions in and beneath an unsealed road quickly and with an accuracy appropriate to the requirements of the design procedure discussed in this paper.

Since its development in the 1950s (Scala 1956) the apparatus and its use and interpretation of results has increased significantly (Paige-Green & Du Plessis 2009). The result is that the DCP is used extensively, for many road projects, including the rehabilitation design of even heavily trafficked roads (COLTO 1997). Although its use for the design of light pavement structures was first proposed in 1987 (Kleyn & Van Zyl 1987), its implementation was minimal and very little has been published on its use. Paige-Green (2011) reported on his personal experience with its use and presented a slightly refined technology for its implementation. This generated some interest in its wider use and the identification of some shortcomings. These are addressed in this paper.

The DCP equipment consists of a steel cone (20 mm diameter with a 60º angle) that is driven into the ground under a fixed energy (an 8 kg mass falling through 575 mm). The rate of penetration into the gravel or soil material (DN in mm/blow) has been found to be a reasonably good predictor of the California Bearing Ratio (CBR) at the prevailing in situ moisture and density conditions using the following equations (Kleyn 1984) shown diagrammatically in Figure 2:

$$\text{If DN} > 2 \text{ mm/blow} \qquad \text{CBR} = 410 \times \text{DN}^{-1.27} \tag{1}$$

$$\text{If DN} < 2 \text{ mm/blow} \qquad \text{CBR} = (66.66 \times \text{DN}^2) - (330 \times \text{DN}) + 563.33 \tag{2}$$

The first equation is generally more applicable to lower traffic roads with in situ CBR values up to about 150%.

Of major significance is the fact that the DCP test assesses the material conditions at their in situ density and moisture content. Both of these need to be taken into consideration when interpreting the results of the DCP survey. Tables to convert DCP penetration rates into in situ CBR values (in terms of the South African G-class materials classification system) for unsealed road wearing courses and subgrades as well as sealed low volume road structural layers and subgrades have been developed and published elsewhere (Paige-Green 2011).

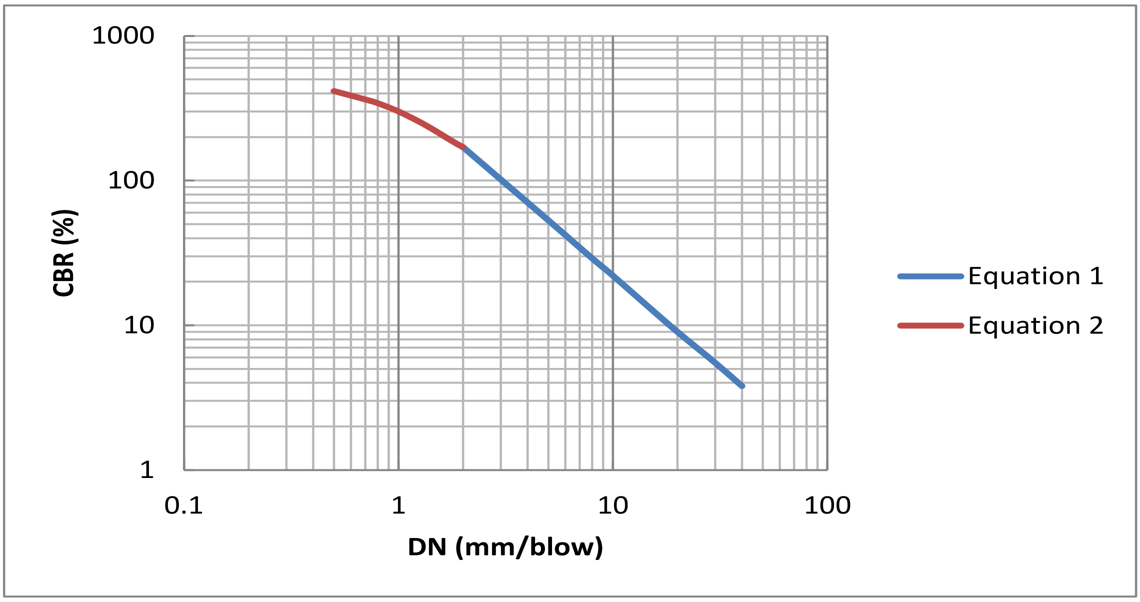

Figure 2: LSD for various traffic categories

As the DCP penetration rate (DN) and the CBR values are essentially interchangeable, either of these can be used in the pavement design process discussed in this paper. However, in order to simplify discussion and to avoid excessive repetition, only the DN value will be discussed. It should, however, be noted that the derived CBR value has been used to develop many of the layer strength diagrams (LSD) discussed in the paper and the in situ CBR can be determined from any DN value presented in the paper using Equation 1 above.

THE DESIGN PROCESS FOR LVR PAVEMENTS

The design fundamentals of low volume road pavements should not differ from any other pavement type. The standard procedures for appraising the pavement design loading, design strategy and analysis period must be followed (COLTO 1996). It should, however, be noted that aspects such as traffic characterisation may entail considerably more work as discussed in the following section.

The actual design method will still require that the pavement structure (bearing capacity) must be appropriate for the estimated traffic that will be carried over the life of the road.

Apart from the pavement bearing capacity and the traffic, other design aspects are not considered any further in this paper.

TRAFFIC

Accurate quantification of the traffic that the road will carry is essential. The authors, however, consider this to be a much bigger problem on lightly trafficked roads than on more highly trafficked roads. The main reason for this is that the small heavy vehicle counts normally obtained on such roads are dramatically affected by any intermittent or temporary (often seasonal) increases in traffic arising from the development of new infrastructure along the road, seasonal agricultural traffic, intermittent mining traffic, etc. A sudden but small increase in heavy traffic can have a severe effect on the estimation of the overall cumulative standard axle estimation.

It is thus vitally important that traffic counts capture all of the traffic using the road – this may require 24 hour counts, often during various seasons and at different times of the local commercial cycles, and should include axle weight surveys where necessary. Many better quality unsealed roads attract overloaded vehicles that avoid higher standard roads in order to minimise the possibility of being caught and prosecuted for overloading. Indeed, the possibility that unsealed roads may attract such traffic after sealing should also be assessed.

The traffic counts need to be converted to cumulative standard axles (in terms of 80 kN axle loadings), which will be used for classification of pavement structures within the design 'catalogues' or 'Layer Strength Diagrams' that will form the basis of the DCP design method.

Research (Kleyn & Savage 1982) has shown that, for balanced pavements (Paige-Green & du Plessis 2009), the exponent (n) used to calculate the equivalency factor F ($F= (P/80)^n$) can differ significantly from that normally used (i.e. 4.2 based on the AASHO road test). Recent studies (Paige-Green & Overby 2010) have shown that roads on deep and strong subgrades can have n-exponents as low as between 1 and 2. This obviously has a major impact on determining a realistic cumulative axle count for the pavement design and will often reduce the estimated number of standard axles being carried significantly.

Once the traffic has been categorised a layer strength diagram (LSD) for that traffic can be developed. This can be established from existing pavement design catalogues, although this is not really any more cost-effective than conventional pavement design as it would be based on traditional designs. Typically, a series of catalogues or layer strength diagrams should be developed for specific roads, based on in situ moisture conditions (not soaked conditions, using the conventional CBR, assuming that the drainage standards are appropriate and drains are correctly maintained) and preferably making use of information collected from existing low volume roads in an area, such that the in situ conditions can be related to known performance.

Typical LSD's, in terms of DN values, that have been developed are shown (for different traffic categories from 10 000 (LE0.01) to 1 million (LE1) standard axles) in Figure 3. These are based on the results of extensive work in South Africa and have been found to be applicable to a number of low volume paved roads in Malawi.

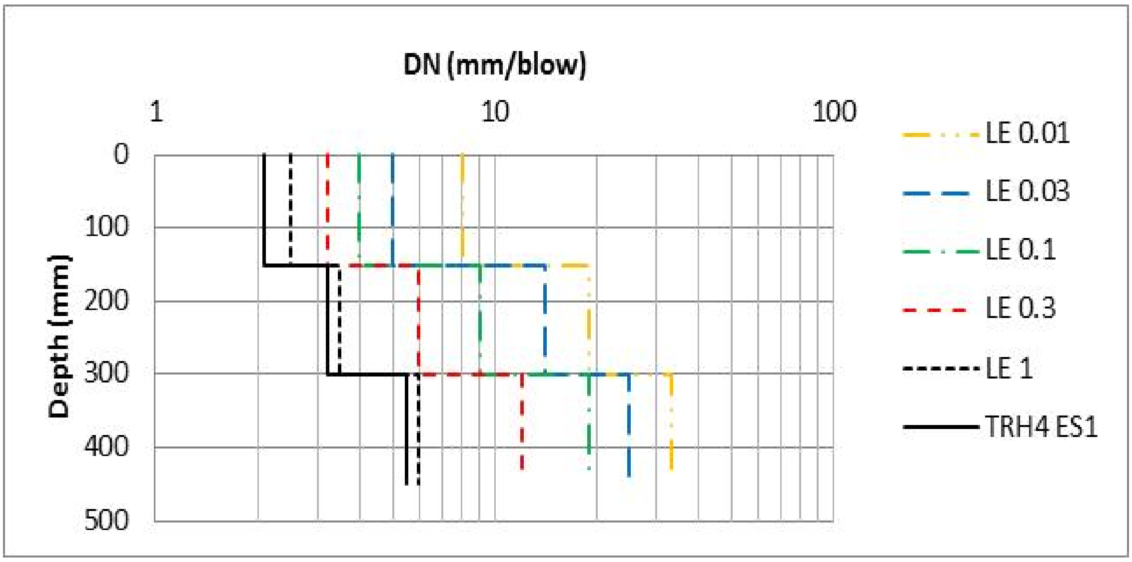

Figure 3: LSD for various traffic categories

The same chart developed in terms of in situ CBR is shown in Figure 4.

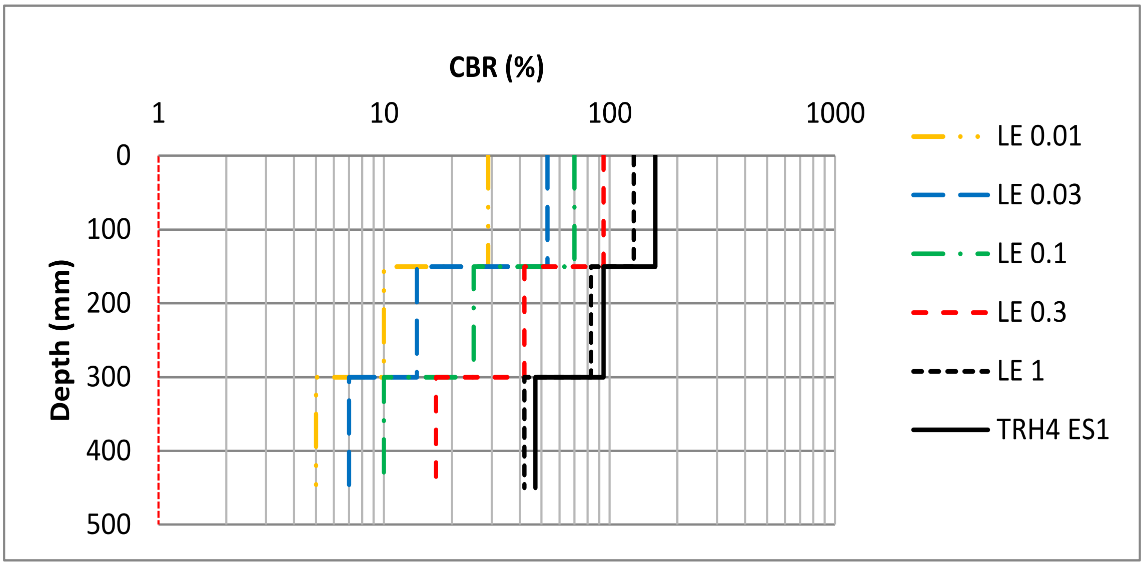

Figure 4: LSD (in terms of in situ CBR) for various traffic categories

The LSD diagrams presented have relatively high in situ penetration rates with base DN values between 3.2 and 8 (equivalent in situ CBR of between 29 and 80%) for roads carrying up to 300 000 standard axles. These have, however, been derived from the back-analysis of a number of successful low volume road structures in southern Africa where DN values of the base course up to 11 have provided an adequate service for periods up to 30 years (Paige-Green 1991; Pinard 2011).

DCP SURVEY

For an old unsealed road that has carried many heavy vehicles over its service life, the underlying in situ material is often highly compacted giving strong support over considerable depth (deep pavements usually with a well-balanced structure) (Paige-Green & Du Plessis 2009). This deep pavement structure should be retained and used to greatest benefit in the new pavement structure. In order to determine the condition of these materials beneath the proposed pavement structure, a DCP survey should be carried out. This will normally consist of a DCP test (to 800 mm depth) at a spacing of between 100 and 500 m depending on the typical material types, variability, drainage conditions, etc. When in doubt, or in the absence of data regarding the in situ conditions, the smallest spacing should be used.

It is imperative that an estimate of the in situ moisture condition is made at the time of DCP testing. This should assess the moisture condition in and beneath the unsealed road in terms of whether it is at the expected in-service moisture condition (outer wheel track) or much wetter or much drier. Based on this assessment, a statistical estimate of the likely strength in the final road pavement will be made.

As many DCP tests as possible should be carried out during the survey and it is suggested that at least 20 test results should be available for each uniform section. This will ensure some statistical reliability.

ANALYSIS OF DCP SURVEY AND PAVEMENT DESIGN

The DCP data should be analysed in a number of ways as follows:

Initially the total number of blows required to reach a depth of 800 mm (DSN_{800}) should be determined and plotted using a cumulative sum technique (Botswana Ministry of Works, Transport & Communications 2000) to identify any general trends regarding the variability of the pavement support (Figure 5). This will typically identify changes in underlying material types, transitions from cut to fill or variable soil moisture conditions. The example in Figure 4 shows a uniform section up to km 22 with a hard material at a depth of less than 200 mm but from km 23 onwards the DCP data showed that hard material occurs at depths of more than 300 mm and even deeper than 800 mm.

The weighted average DCP penetration rates over the top 150 mm of the structure and the underlying 150 mm (i.e. from 150 to 300 mm) should be determined and also plotted using a cumulative sum (cu-sum) technique to identify homogeneity of the upper layers of lack thereof (Figure 6). The trend shown in Figure 4 is repeated for the layer between 150 and 300 mm but the upper 150 mm layer which consists mainly of old wearing courses shows an additional change between km 18 and 23 where the existing wearing course material is significantly stronger than the other two sections.

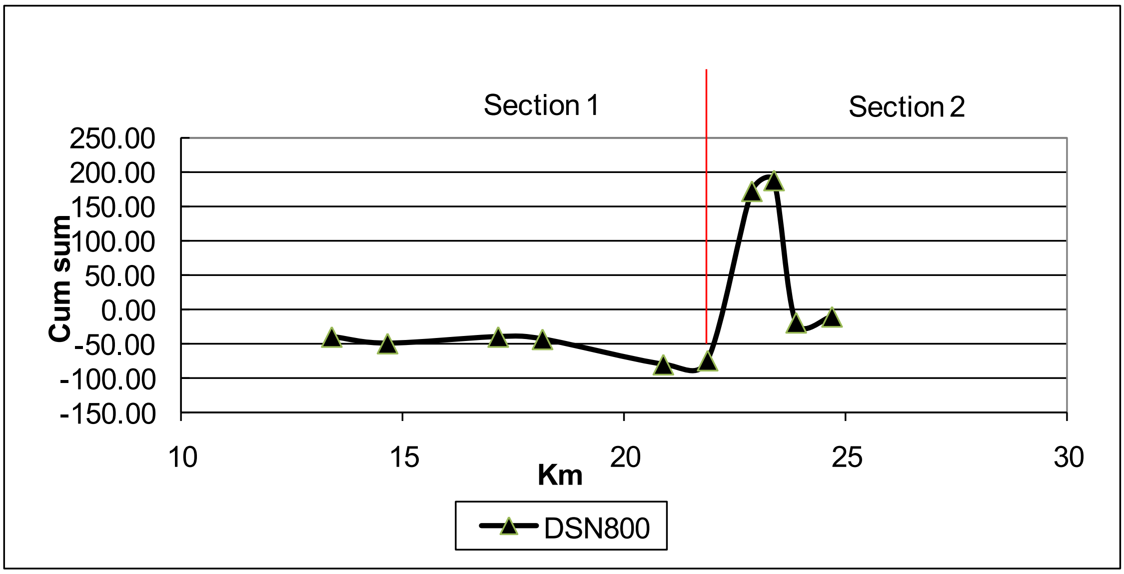

Figure 5: Cu-sum plot of DSN_{800} values

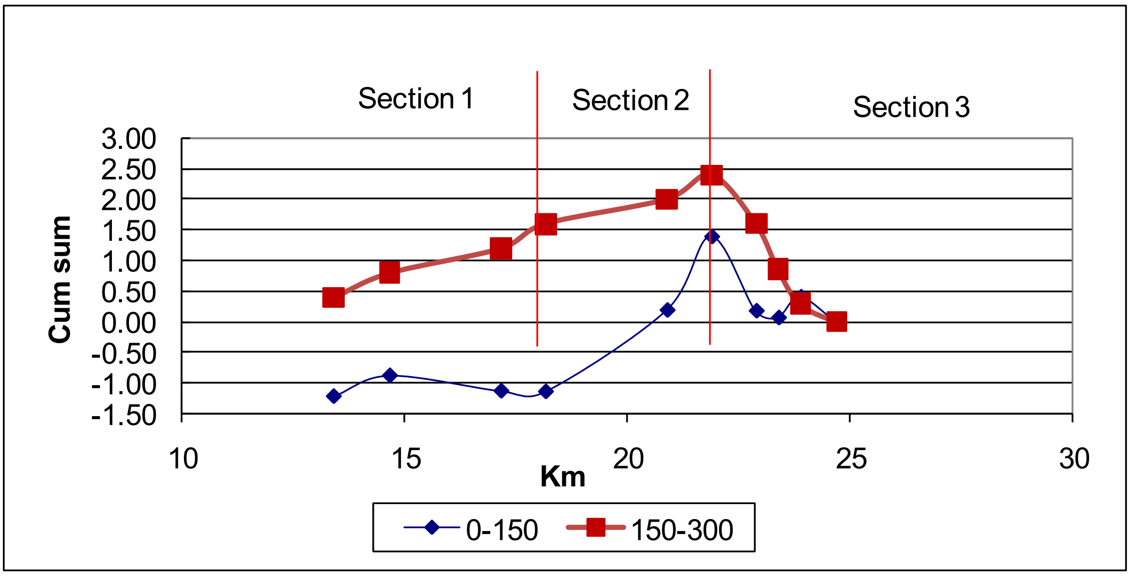

Figure 6: Plots of cumulative sum determinations on upper 150 mm and 150 – 300 mm layers

The actual strength profile of the materials in each DCP test for all of the results within a uniform section must then be inspected. This will normally entail plotting the individual weighted average (i.e. sum of products of DN and thickness of that DN value) penetration rates of each of the test results for the first and second (and more if required) 150 mm layers as shown in Figure 7.

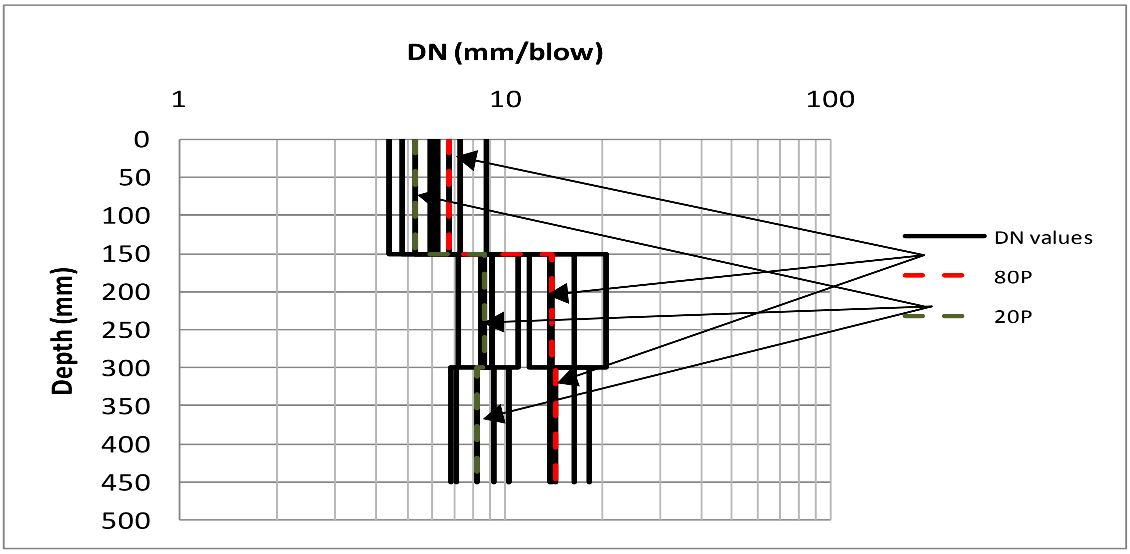

Figure 7: Plots of penetration rates and 20th (20P) and 80th (80P) percentiles by 150 mm layer

It is clear that there is typically a wide range of results. Based on the moisture regime at the time of testing, a percentile value for the DN value of each layer can, however, be determined. The recommended percentiles used are those shown in Table 1, although these can be modified depending on the experience and judgement of the designer.

Table 1: Percentile values of DN

Site moisture condition during DCP survey	Percentile of strength profile (maximum penetration rate – DN)	
	Materials with strengths not moisture sensitive*	Materials with strengths that are moisture sensitive*
Wetter than expected in service	20	20 – 50
Expected in service moisture	50	50 – 80
Drier than expected in service	80	80 - 90

* Moisture sensitivity can be estimated by assessing the 'flatness' of the CBR moisture content curve. Materials with a flat curve are considered to be of low moisture sensitivity while steep curves indicate highly moisture sensitive materials.

The rationale behind these percentile values is shown in Figure 8, where the dry and wet seasonal distributions of the DN values and their 20th and 80th percentiles are plotted and compared with the average in service condition. It can be seen that DCP data collected during the dry season will be stronger (lower DN) than that collected during the wet season. The use of the respective 80th and 20th percentiles effectively results in an estimate of the expected in service conditions. It should also be noted that by using the weighted average DN values, thicker parts of the layer with weak materials will result in a higher overall penetration rate. This ensures that the effects of weak sections within the layer are adequately taken into account.

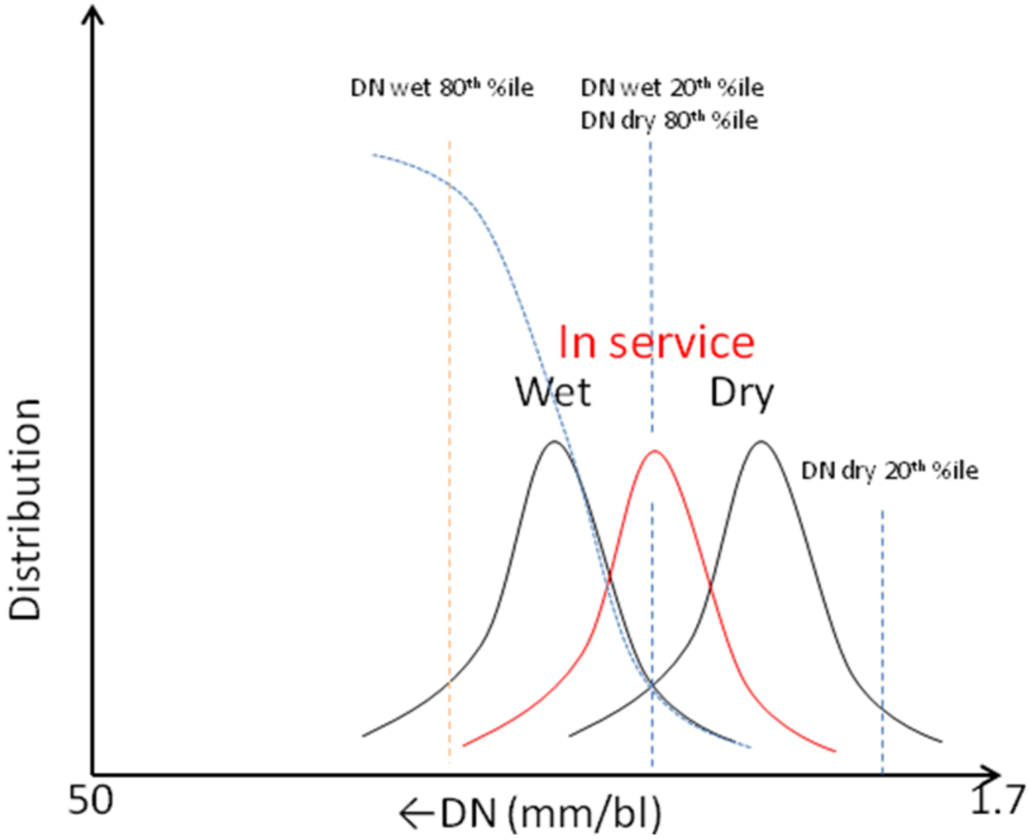

Figure 8: Plots of distributions and percentiles of DN

The pavement design then involves overlaying the LSD for the traffic over the in situ actual layer strength conditions and comparing the two plots (Figure 9). Where the layer strength lies to the right of the traffic requirement, the strength is insufficient and the layer will fail under the associated traffic. Strengthening of the layer thus becomes necessary. In the example (Figure 9) it is clear that the layers from 0 – 150 mm and 150 – 300 mm are too weak, while the lower layer is adequate.

In the example shown in Figure 9, if a single base course layer of the required quality is imported and placed on top of the existing gravel road, each of the underlying layers would move to the right relative to the traffic requirement and a suitable (and deep) pavement structure will be obtained, i.e. each of the layers identified by the DCP survey will effectively become one layer lower in the pavement structure. For the example provided (Figure 10), importation of a material with an in situ DN value of less than 4 will result in an appropriate pavement for a cumulative traffic count of 100 000 standard axles, irrespective of whether the DCP survey is carried out in the wet or dry season. It is also clear that for a traffic count of 300 000 standard axles (a maximum DN of 6.0 for the subbase is required (Figure 3), the existing upper layer would provide a successful subbase if the DCP survey had been carried out in the wet season (20^{th} percentile DN = 5.28) but not if it had been carried out in the dry season (80^{th} percentile DN = 6.76).

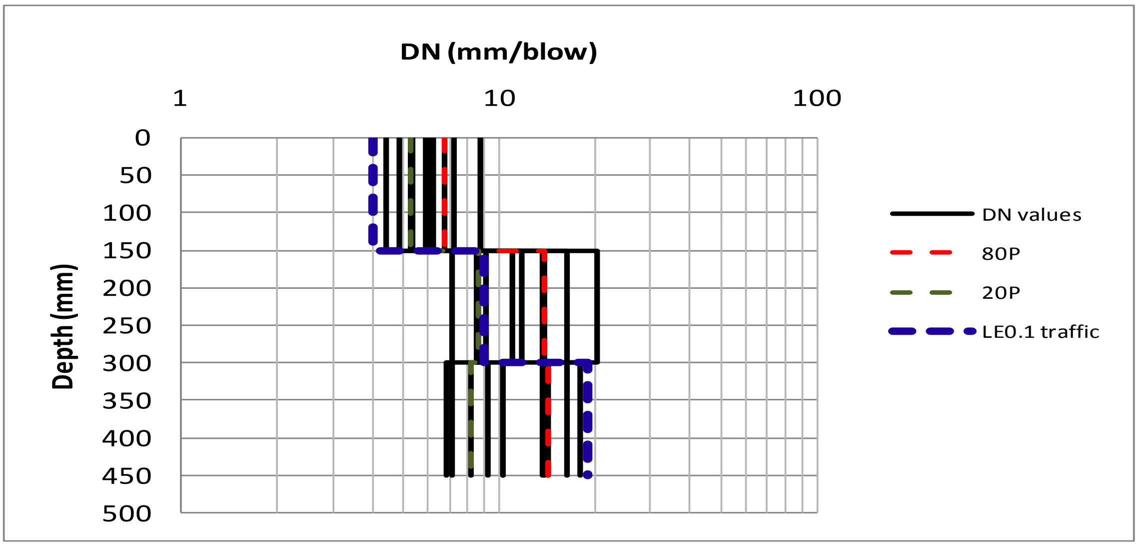

Figure 9: Comparing traffic requirements with pavement strengths

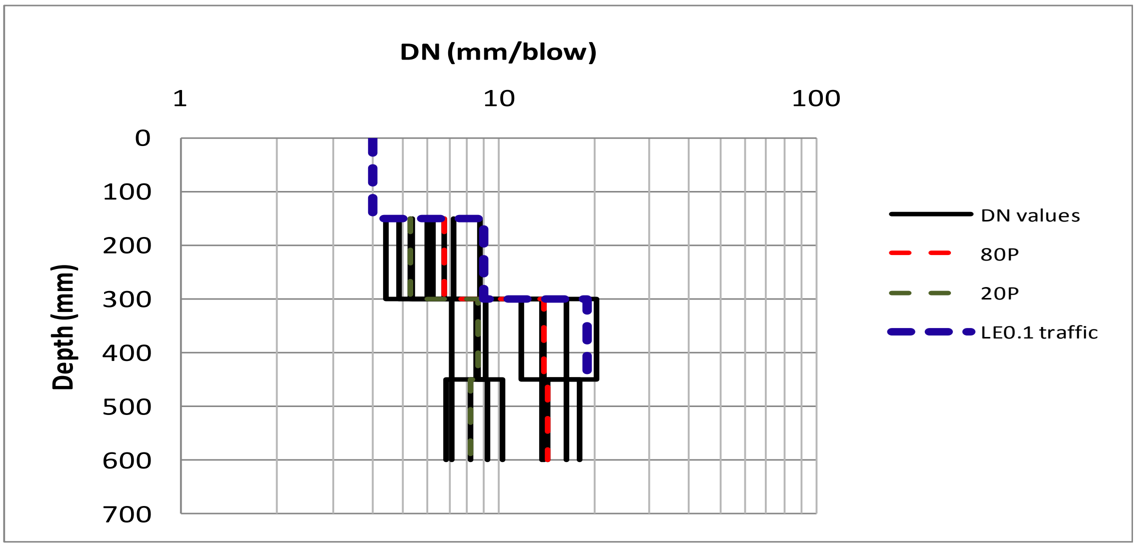

Figure 10: Effect of importing a single layer of material with DN < 4

It is necessary to test potential base course materials to ensure their suitability. This is best done by checking the DCP penetration rate in the moulds of materials tested conventionally for CBR at the specified compaction density and expected in service moisture condition. This penetration rate can also then be used in the control of compaction quality during construction (Paige-Green 2003).

The importance of good drainage cannot be overemphasised and the relationship between the drainage and the materials utilised (their strength and moisture susceptibility) must be clearly understood to ensure full confidence in the final design. Drainage should be designed such that the drain invert is at least 0.75 m below the crown of the road. A good impermeable surfacing is also a necessary requirement. Any drainage systems installed must be regularly and properly maintained to ensure effective performance of the pavement layers.

The use of an appropriate bituminous surfacing (Sabita 2012) on the new road can also go some distance in ensuring that the road will provide a satisfactory and cost-effective service over its design life.

CONCLUSIONS

The design of light pavement structures (up to about 300 000 equivalent standard axles) using DCP surveys has been successfully carried out on a number of roads in South Africa and Malawi. The procedure allows a simple and cost-effective design to be employed, often resulting only in the need to rip and recompact the exiting upper layer of materials or else to import a single layer of appropriate material that can be placed directly on the reshaped in situ material.

Using this technique, it will be possible to economically upgrade a significantly greater length of road (often using the in situ materials or at most requiring the importation of a single layer of material) than would be possible using conventional pavement design techniques, without increasing the risk of premature failures. The fundamental principle used in this pavement design process has been used for many years in southern Africa for pavement rehabilitation and thus the risk of premature failure is not increased over any other design method, provided that the initial layer strength diagrams for the traffic categories are based on local experience and are appropriate.

The method allows the designer to make use of local knowledge and experience in developing the appropriate layer strength diagrams for different traffic classes and environmental condition in order to optimise the pavement layer thicknesses and material strengths.

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