

**THE USE AND INTERPRETATION OF
THE DYNAMIC CONE
PENETROMETER (DCP) TEST**

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LIST OF ABBREVIATIONS

A summary of the abbreviations used in the text and equations in these notes follows:

A - Deviation of DCP data from standard pavement strength-balance curve (SPBC)
AASHTO - American association of State Highway and Transportation Officials
B or BN - Balance Number (Standard Pavement Balance Curve)
BN₁₀₀ - Number of blows as a percentage of the DSN₈₀₀ required to penetrate 100 mm
CBR - California Bearing Ratio
C_m - Moisture factor
D - Pavement depth
DCP - Dynamic Cone Penetrometer
DN - DCP number (mm/blow)
DSN₈₀₀ - DCP structural number (number of blows to 800 mm depth)
E80 – Equivalent standard 80 kN axle
E_{eff} - Effective elastic modulus
LSD - Layer strength diagram
MISA - Million standard axles (80 kN) to achieve a rut of 20 mm
SPBC - Standard pavement balance curve
TMH – Technical Methods for Highways
TRH – Technical Recommendations for Highways
UCS - Unconfined Compressive Strength
HVS – Heavy Vehicle Simulator

1 INTRODUCTION

LEARNING OUTCOMES

Module 1 consists of the first two chapters of the notes, Introduction and DCP Equipment and Use.

At the end of this module the learner will:

- Understand the history and development of the DCP apparatus and its relevance to shear strength of pavement materials
- Understand the relationship between laboratory and in situ CBR derived from a DCP
- Be able to carry out a DCP test and manually plot and interpret the results

HISTORICAL BACKGROUND TO DCP AND DEVELOPMENT PROGRESS

During the early 1930's the California Bearing Ratio test (CBR) was developed for the testing of material strength in the laboratory for the design of pavements. The test involves the compaction of a potential road-building material into a standard mould under a standard compaction effort at a predetermined moisture content, soaking the mould for 4 days and then penetration with a standard plunger at a fixed rate. The loads required to penetrate to selected depths are then compared with those necessary to penetrate a standard material and a CBR value is obtained. The procedures for the determination of the Maximum Dry Density (MDD), Optimum Moisture Content (OMC) and CBR are given in TMH1¹.

In the test, all stones greater than 19 mm diameter are removed (sometimes replacement fines are added), the material is compacted under a dynamic impact load and the material is then soaked. In the field the coarse aggregate remains, the material is normally compacted under a vibrating force and the material seldom becomes soaked. The test results are thus really incomparable with the actual conditions, which are likely to prevail in the field. The CBR test has been adapted for the field using a portable CBR but it is difficult and time consuming and is

seldom done because of the equipment needed and the fact that the moisture content changes with time.

Most early pavement design procedures were, however, based on the CBR method where the CBR values of the subgrade and structural layer material were used to determine the required thickness of imported material necessary.

In Australia in 1956, Scala developed a Dynamic Cone Penetrometer (DCP), based on an older Swiss original, to evaluate the shear strength of the material in a pavement². This consisted of a 9 kg (20 pound) mass dropping 508 mm (20 inches) and knocking a cone with a 30° point into the material being tested³.

The potential of this was noted and development of the device continued in South Africa⁴. With time a number of variants were in use, all with different masses, fall-distances and even cone dimensions although the energy imparted (mass x fall) was generally similar. During the early 1970's the device was standardised in South Africa with the following dimensions (Figure 1.1):

Mass	8 kg
Fall distance	575 mm
Cone	60°

It should be noted that a device with a 10 kg mass falling 460 mm is also used in South Africa. Although the potential energy (mgh) is the same for both configurations, the kinetic energy applied ($\frac{1}{2}mv^2$) differs significantly. The momentum (mv), which may be a more relevant parameter, however, of the two configurations is the same. It is therefore recommended that only the configuration shown in Figure 1.1 be used, as the ensuing discussion and remainder of the course are based on developments using this apparatus.

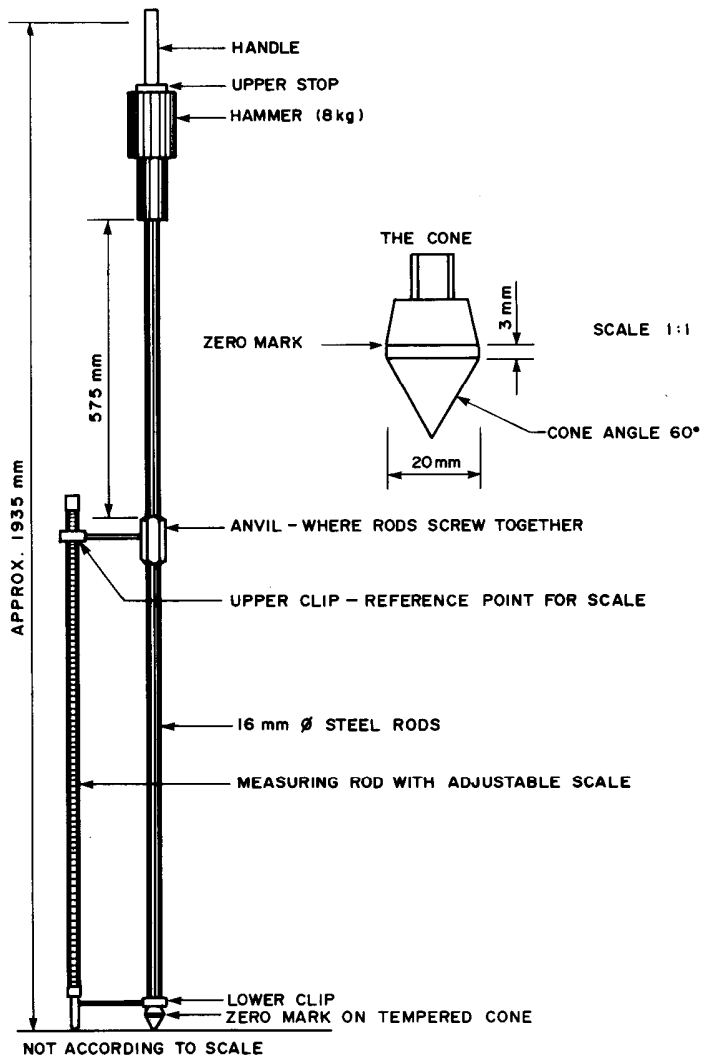


FIGURE ST6/1 THE DYNAMIC CONE PENETROMETER

Figure 1: The Dynamic Cone Penetrometer⁵

A large number of comparative tests between laboratory and field CBR values and the cone penetration rate (DN in mm/blow) were carried out during this period (at the respective moisture contents)⁶. These allowed the development of correlations and models to predict the CBR (at the in situ moisture and density) from the DCP penetration rate. This was carried out for natural and treated materials giving relationships in terms of both CBR and Unconfined Compressive

Strength (UCS). The following models can be used for estimating the CBR from the DCP and these are shown graphically in Figure 2⁷.

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

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

$$\text{UCS} = 15 \times \text{CBR}^{0.88}$$

$$\text{or } \text{UCS} = 2900 \times DN^{-1.09}$$

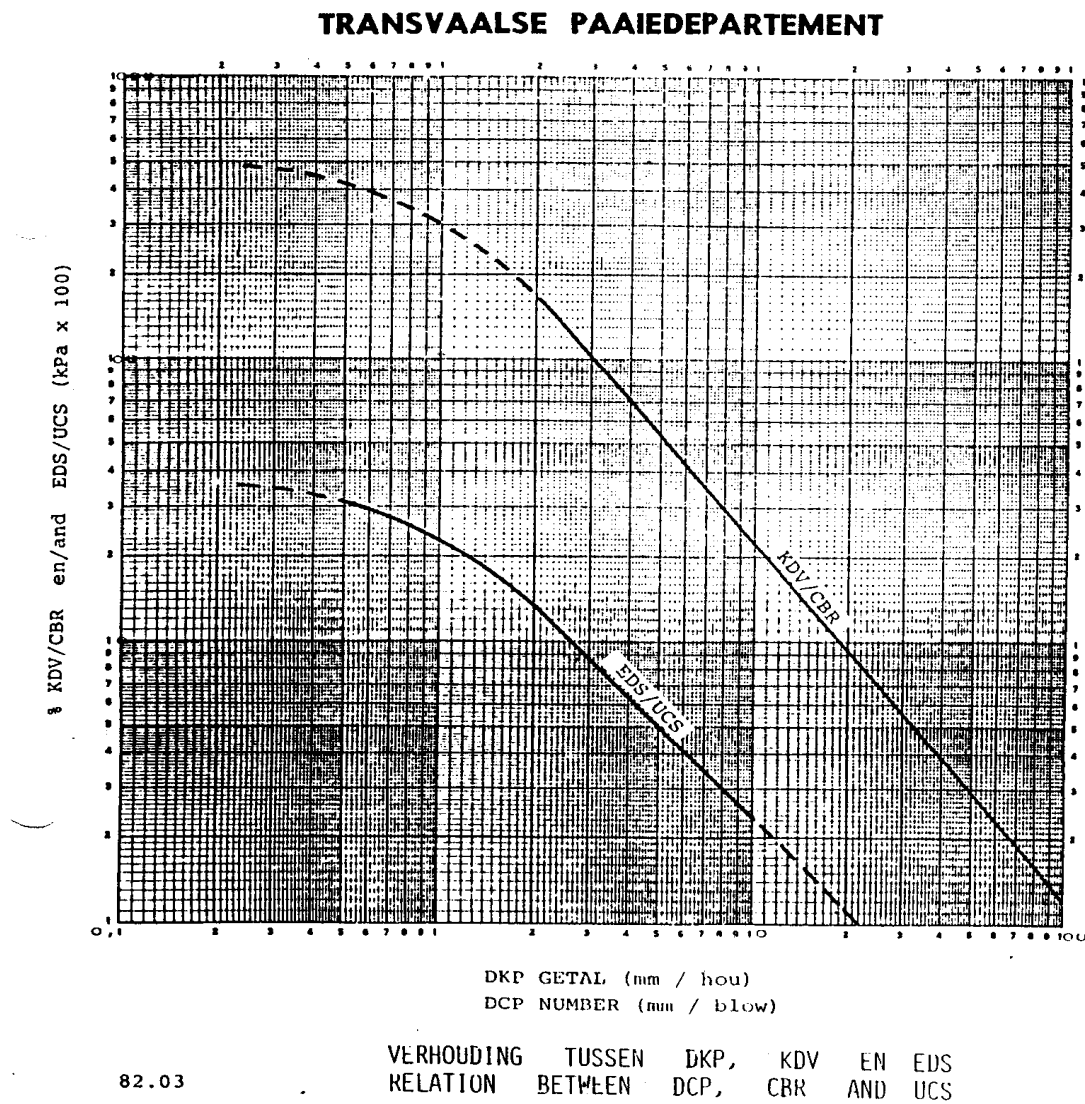


Figure 2: Relationship between DCP number (DN) and CBR and UCS⁷

Various other models for converting DCP penetration rate to in situ CBR are available these include the following (Table 1):

Table 1: Penetration rate – CBR relationships

Cone angle	Reference	Relationship
60°	TRL ⁸	$\log_{10}(\text{CBR}) = 2.48 - 1.057 \log_{10}(\text{DN})$
60°	Sampson ⁹ Plastic materials only PI > 6 materials PI < 6 materials PI = 0 materials	$\log_e(\text{CBR}) = 5.8 - 0.95 \log_e(\text{DN})$ $\log_e(\text{CBR}) = 5.93 - 1.1 \log_e(\text{DN})$ $\log_e(\text{CBR}) = 6.15 - 1.248 \log_e(\text{DN})$ $\log_e(\text{CBR}) = 5.70 - 0.82 \log_e(\text{DN})$ $\log_e(\text{CBR}) = 5.86 - 0.69 \log_e(\text{DN})$
60°	Harison ¹⁰ Clayey soils Sand S-W Gravel G-W Combined data Soaked samples Unsoaked samples	$\log_{10}(\text{CBR}) = 2.81 - 1.32 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 2.56 - 1.16 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 3.03 - 1.51 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 2.55 - 0.96 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 2.81 - 1.32 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 2.76 - 1.28 \log_{10}(\text{DN})$ $\log_{10}(\text{CBR}) = 2.83 - 1.33 \log_{10}(\text{DN})$
30° cone	Smith and Pratt ¹¹	$\text{Log}_{10}(\text{CBR}) = 2.555 - 1.145 \text{Log}_{10}(\text{penetration rate})$

It is clear that all of the relationships have similar equations, with different coefficients. The correlation coefficients, however, vary significantly from as low as 0.47 to 0.99 (the number of samples obviously affects the statistical significance of the correlation coefficients). It is also clear that the nature of the material affects the DCP penetration rate, but this can seldom be included in the analysis of full DCP profiles.

These relationships allow the use of the data in a basic manner where the strength of different layers could be read off manual plots and an indication of the thicknesses of various layers could be determined (See section 2). Some indication could be obtained of the material type as well as the DCP structural number, although no predetermined depth of DCP testing was specified.

Research into the use of the DCP continued in South Africa in conjunction with Heavy Vehicle Simulator (HVS) testing. This allowed parameters such as the penetration rate with time, traffic, moisture, performance, cracking, deformation and deflection at various depths to be correlated and the development of empirical relationships between expected pavement life and DCP penetration rates.

During the mid 1980's, this data was used to develop a formal computerised analysis method for the DCP bringing in new concepts and methodologies. This software has been upgraded a number of times incorporating recent advances and improvements. The latest version used in South Africa is WinDCP (version 5.0).

Research has been carried out in South Africa, the United States, Australia and the United Kingdom on improving the prediction models between penetration rate and CBR with the results being presented at International Conferences in the United States, South America, Europe, Australia and South Africa. New regression models are continually being produced but most are material dependent and incorporate aspects such as grading and plasticity parameters and are not practical for general use (see Table 1).

The DCP software and various aspects associated with it are widely used in southern Africa with great success. The 1993 version of Road Note 31⁸ also specified the DCP as a test method. A computerised analysis method has recently been developed in the UK (UK DCP 1.1.1).

The significant advantages of the DCP are that it is a low cost, robust apparatus that is quick and simple to use. Very little damage is done to the pavement being tested (effectively non-destructive) and very useful information is obtained. One of the major advantages of the test is that the pavement is tested in the condition at which it performs. The simplicity of the test allows repeated testing to minimise errors and also to account for temporal effects.

It should be noted that there are inherent inaccuracies in most CBR test results and these coupled with the material dependency of the DCP results make the DCP interpretation a very good indicator, but it should never be used as an absolute indicator of the in situ CBR strength of a material in a pavement. The results should be assessed in terms of the material properties,

particularly grading and maximum particle size, plasticity, aggregate hardness, whether stabilized, etc.

It must always be remembered that the DCP CBR is determined at the in situ moisture content (and density) of the pavement layers at the time of testing. Various attempts to relate this, through the CBR derived from the DCP, to the material G-classes used in South Africa have been made, with the following approximate correlations being proposed for materials in unsealed roads¹² (Table 2) and in sealed low volume roads¹³ (Table 3).

Table 2: Relationship between DCP CBR and G class for unsealed roads¹²

Material classification	Soaked CBR	Approximate field DCP- CBR : Unsealed road					
		Subgrade		Wearing course			
		Wet climate	Dry climate	Very dry state	Dry state	Moderate state	Damp state
G4	80			318	228	164	117
G5	45			244	175	126	90
G6	25	59	65	186	134	96	69
G7	15	45	50	147	106	76	54
G8	10	38	43				
G9	7	33	37				
G10	3	20	24				

Note: moisture contents are expressed as ratios of in situ to Mod AASHTO optimum moisture content as follows: very dry = 0.25; dry = 0.5; moderate = 0.75; damp = 1.0

Table 3: Relationship between DCP CBR and G class for sealed low volume roads¹³

Material classification	Soaked CBR	Approximate field DCP- CBR : Low volume roads					
		Subgrade		Base, subbase and selected layers			
		Wet climate	Dry climate	Very dry state	Dry state	Moderate state	Damp state
G4	80			260	205	151	96
G5	45			188	148	109	69
G6	25	56	66	146	115	85	54
G7	15	52	62	137	108	79	50
G8	10	39	46	101	80	59	37
G9	7	38	44				
G10	3	35	41				

Note: moisture contents are expressed as ratios of in situ to Mod AASHTO optimum moisture content as follows: very dry = 0.25; dry = 0.5; moderate = 0.75; damp = 1.0

The onus remains on the user of the DCP, however, to understand the situation, environment and implications of each test in relation to the in situ state of the material. This includes aspects

such as material composition, presence of large stones or hard layers, moisture content, density, etc. Significant engineering judgement and understanding as well as knowledge of the specific site are necessary to maximise the information that can be obtained from a DCP profile. Many cases have been seen where the engineer has erroneously drawn conclusions or extrapolated data provided from site teams, without actually comprehending the field conditions.

2 DCP EQUIPMENT AND USE

EQUIPMENT

The specifications of the DCP equipment are shown in Figure 1. As discussed in the previous lecture, the apparatus is robust, simple and easy to use but a few points need to be noted to ensure repeatable and consistent results.

During assembly of the apparatus it is imperative that the hammer is located the right way up. The lower end is conically indented to provide a good contact with the anvil on impact.

The handle at the top of the hammer rod should be screwed in to its limit to ensure that the fall is exactly 575 mm. The lower cone-bearing rod should be checked for linearity as they are prone to bending if used repeatedly on very hard or very stony materials.

The upper support for the measuring staff absorbs enormous shocks, which results in frequent fatigue failure. Spares of this need to be available at all times during testing.

The cones wear and deform when testing hard materials and need to be replaced periodically. Prior to any test, the condition should be checked to ensure that the point is sharp, the whole cone is screwed into the shaft and the lower surface of the cone is not excessively rough. High tensile or tempered cones are not recommended, as they tend to shear off when striking a hard stone. The use of disposable cones is increasing, where the cone remains in the test hole – the effort to remove the apparatus from the test hole is greatly reduced by leaving the cone behind (Figure 3).



Figure 3: Typical cones and problems

(From left to right: disposable cone, conventional cone, worn cone tip, worn cone, incorrect cone with shoulder too wide, 30° cone)

The DCP has been used to evaluate the strengths and depth of thick soft materials using a 2 metre (and even 3 m) long lower shaft. This is not recommended for harder materials (CBR > 15) where inertia effects, side friction on the rod and other energy losses may influence the results. Energy can be lost through compression of the DCP rod, elastic compression of the soil and various other unknown factors. It is not clear whether the standard DCP-CBR correlations can be directly applied to longer DCPs.

An automatic DCP (Figure 4) has been developed which is trailer mounted and automatically applies the hammer action and extraction of the apparatus after the test. The test data is automatically recorded and stored on a computer disk in a form suitable for analysis using WinDCP.

The traditional DCP apparatus is safe and apart from ensuring that no hands are caught between the hammer and the anvil, few precautions need to be taken to prevent personal injuries.

High stresses are generated during use of the apparatus and it is thus recommended that for large or remote projects various spare parts be retained with the apparatus. The parts prone to wear and tear (and fatigue) are the lower rod holding the cone, the upper support for the measuring scale and obviously, cones. Any local steel fabrication or repair shop can usually remedy problems occurring with the apparatus.



Figure 4: Automatic DCP

USE OF THE DCP

A standard method for the measurement of the in situ strength of soils by the DCP is provided in Draft TMH 6¹. This covers the test method as well as manual determination of the penetration rate or "DCP number" (DN) in mm/blow. Some important aspects and other useful tips are discussed or provided below.

During testing, five aspects need to be carefully controlled:

- The apparatus must be held vertically at all times. Any deviation from the vertical results in difficulties getting repeatable readings from the measuring staff. In addition the friction effects between the falling mass and the upper rod reduce the energy imparted to the cone.
- The hammer must just touch the base of the handle before being released, without jolting the equipment vertically. The hammer should be released to fall under its own mass and not "thrown" down.
- When testing "hard" materials, the hammer will often bounce a number of times on the anvil before coming to rest. It should not be lifted for the next drop before coming to total rest.
- The test should start with the upper portion of the shoulder of the cone flush with the surface of the layer being tested.
- During testing of hard materials, it is common to note that uplift or mounding of the layer around the DCP hole occurs. This may result in a gradual rise of the measuring staff relative to the test apparatus and hence a reduction in the reading obtained. Care should be taken that the base of the measuring staff is not affected by this "mounding".

Frequently the cone rests on a large stone. When this occurs:

- The stone may either break and the test continues normally;
- The cone may be deflected and the rod will be found to move off the vertical; or
- Refusal may be reached and the test cannot proceed.

In the first case the test results are not invalidated but in the other two the test should be recommenced 1 metre away from the initial test. If refusal is obtained three times at different locations, it can be assumed that there is a very hard, continuous layer at that depth or the material is extremely stony. In either of these cases, results obtained by continued testing would be unreliable.

The optimum number of operators is typically 3, two labourers and the supervisor. The supervisor controls the reading and recording of the results, whilst the two labourers alternate between holding the apparatus vertical and operating the hammer. It is recommended that the operator has a low stool and a clipboard to make the taking and recording of readings more comfortable and repeatable. A typical field data sheet is attached (Figure 5).

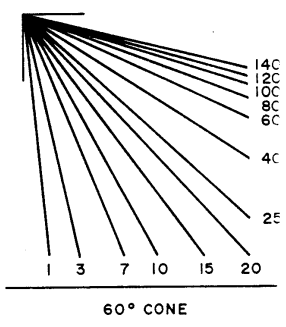
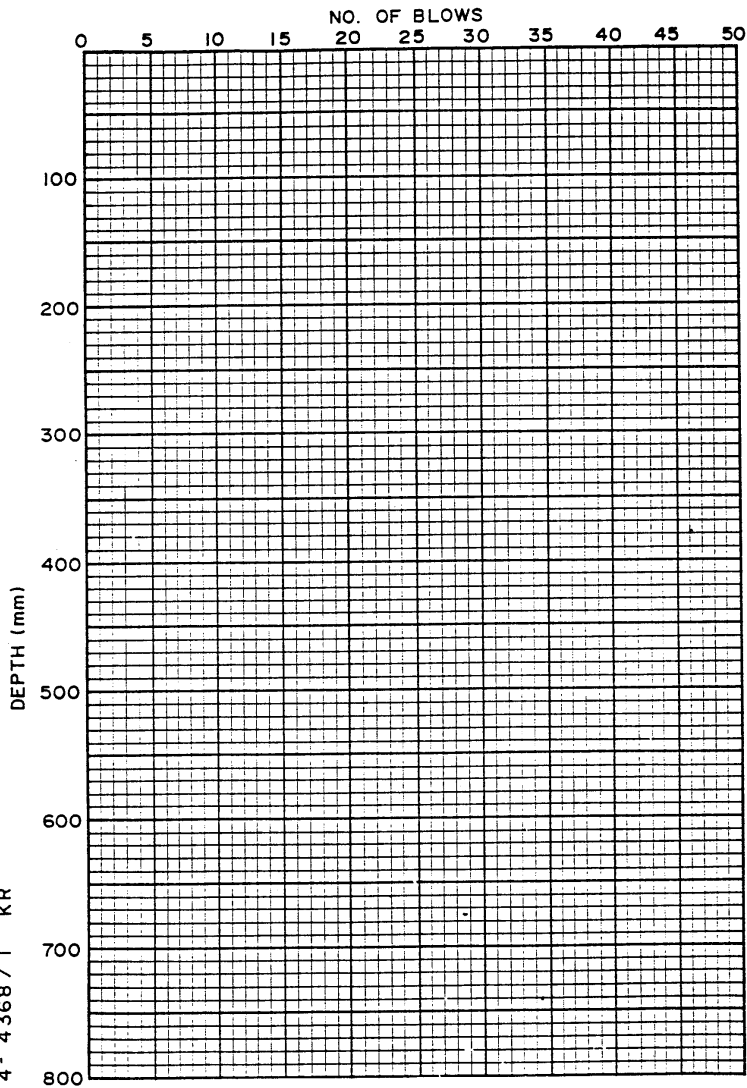
It is often necessary to determine what is below a very hard layer and in this case a 20 mm hole can be drilled through the hard layer or a small hole excavated and the test resumed at the top of the underlying layer (this does result in the test losing its non-destructive nature). In these cases accurate measurements of the thickness of the hard layer are necessary and an assumed penetration rate is plotted or used for computer processing. This cannot be done when a disposable cone is used.

It is important to assess the results being produced during DCP testing as they are obtained. During the days when data was processed manually, this was routine during data collection and forms were used that facilitated this with the actual penetration depth being written as a label at the specific depth plotted, directly on the form (Figure 6). The data points could then be joined by straight lines to differentiate layers in the pavement. By determining the slope of each line (subtracting the beginning value from the value at the end point) the penetration rate (DN) for that layer could be determined. This could then be converted directly to in situ CBR using the table provided on the form.

Subsequently, the data was analysed by computer and all data reduction was done automatically, with the operators losing the "feel" for what was happening in the pavement structure.

DCP RECORD FORM

ROAD NUMBER ----- DATE -----
 SECTION ----- RECORDED BY -----
 POSITION L Sh R SOUND DISTRESSED FAILED
 REMARKS RUTTING DIFF.SETTLE PUMPING CRACKS STABILIZATION CROCODILE LONG. OTHER



No. Blows	1	5	10	15	20
CBR	PENETRATION mm				
1	109,6	548	-	-	-
3	47,2	236	472	-	-
7	24,6	123	246	369	492
10	18,7	94	187	281	375
15	13,7	69	137	206	274
20	11,0	55	110	165	220
25	9,3	46	93	139	185
40	6,5	32	65	97	129
60	4,7	24	47	71	95
80	3,8	19	38	57	76
100	3,2	16	32	48	64
120	2,8	14	28	42	56
140	2,5	12	25	37	49

Figure 5: Example sheet for manual collection of DCP data

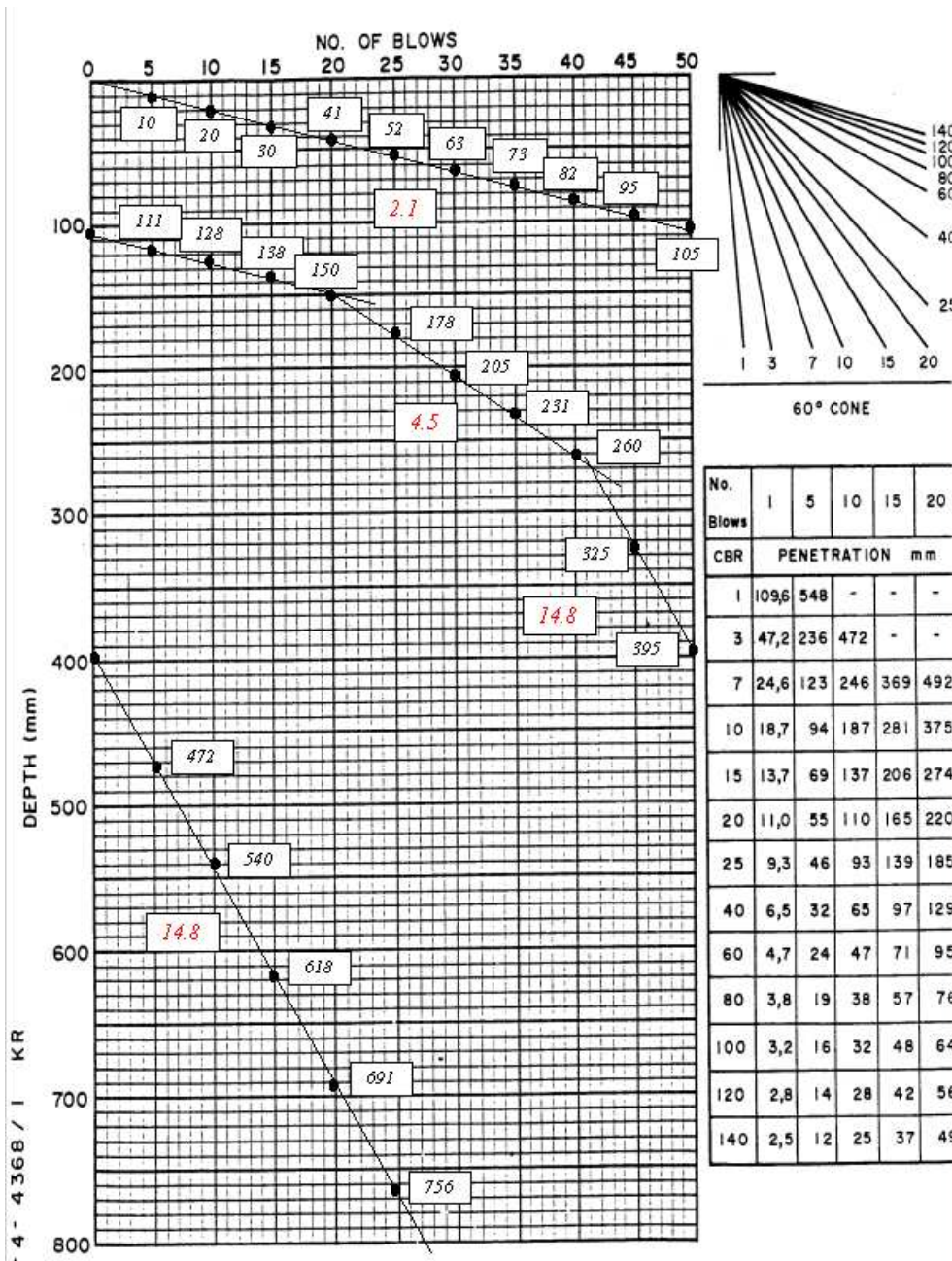


Figure 6: Example of manual collection of DCP data

It is, however, often more useful to view the data in terms of the DCP penetration number (DN) or CBR as a function of depth, i.e., as specific layers. This can be easily determined and plotted as shown in Figures 7 and 8 to give a direct indication of the pavement structure (layer strength diagram).

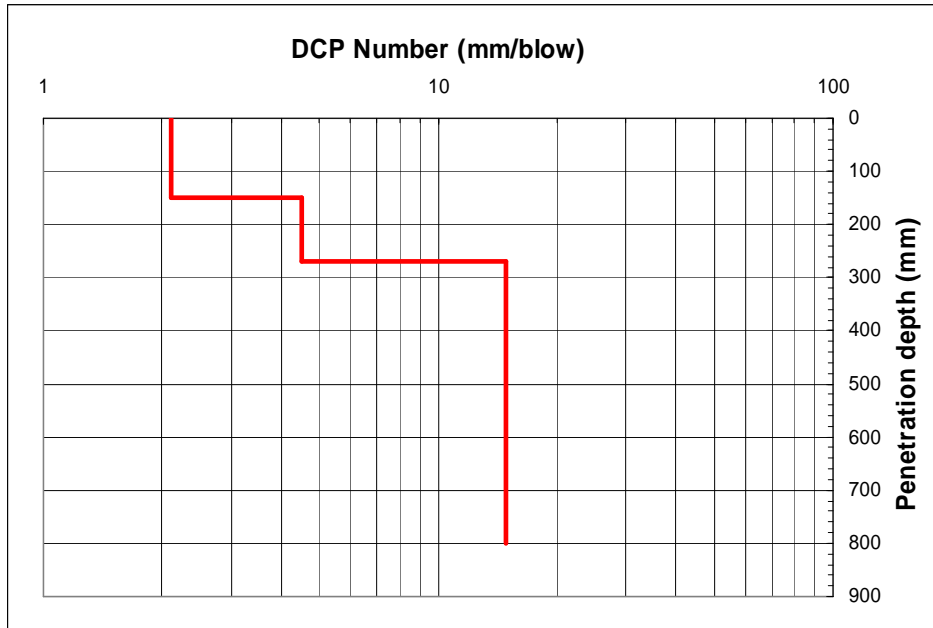


Figure 7: Data represented as DN versus depth (layer strength diagram)

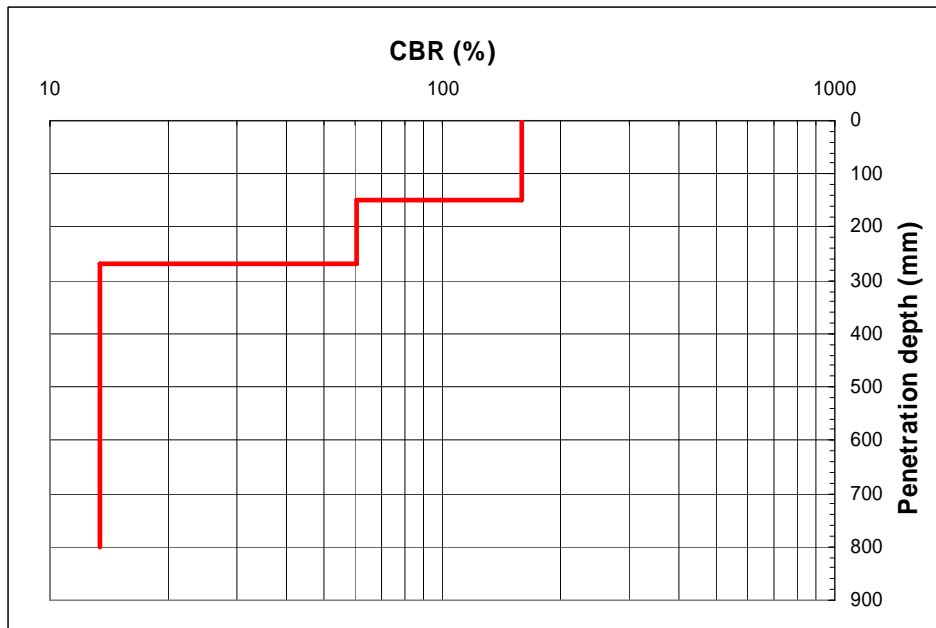


Figure 8: Data represented as CBR versus depth

It is important to ensure that a full DCP penetration profile is obtained to a depth of 800 mm, bearing in mind that the starting reading is seldom exactly zero. In order to determine the DCP structural number (DSN_{800}) the number of blows required to reach a depth of 800 mm is required. Typically, when a depth of 800 mm is not attained, the penetration profile can be extrapolated either based on the last few readings or using a specified or expected penetration rate.

When carrying out DCP testing along a road, it is also useful to assess the moisture regime in the road in relation to the expected moisture regime during service. This can be used to provide a statistically based appreciation of the existing material strength for design purposes. In this way a percentile of the in situ material strength can be identified for upgrading designs¹⁴. This is discussed further in Module 3.

FREQUENCY OF TESTING

Significant debate exists around the frequency (and location) of testing along roads. The required frequency will typically depend on the purpose of the investigation, the degree of variability expected, the level of confidence required, length of the road and probably more often, the available funds. The number of tests should, however, be sufficient to ensure confidence in any conclusions drawn.

Various recommendations have been made and these vary from one test every 500 metres¹⁵ to between one every 10 km and more than one every kilometre, depending on the required confidence¹⁶. It is, however, suggested that a minimum of 15 tests per uniform section is carried out.

3 THEORETICAL ASPECTS OF DCP RELATED TO PAVEMENT DESIGN

LEARNING OUTCOMES

Module 2 of the course consists of Chapter 3 of the notes.

At the end of this module the learner will:

- Have briefly reviewed the basic principles of pavement design
- Understand the principles of pavement balance based on DCP results
- Be able to determine the layer depths and structural capacity of a pavement from DCP results

PRINCIPLES OF PAVEMENT DESIGN

The function of pavement layers is to spread the stresses due to wheel loads so that no part of the underlying structure is overstressed and at the same time to provide a wearing course for traffic. Typically the strength of individual pavement layers decreases with depth but the total pavement thickness must still protect the subgrade from the traffic. Inputs necessary for successful pavement design include the following¹⁷:

Analysis and Design Periods

The analysis period is that period during which complete reconstruction of the road would be unacceptable (rehabilitation would be acceptable). The structural design period is that period during which no structural maintenance will be required and specific indicators of the road condition, eg, riding quality, rut depth) are generally within pre-determined terminal conditions over a specified area of the road (depending on the road category).

Traffic

The traffic which the road will be expected to carry needs to be quantified in terms of the total cumulative equivalent standard axles (usually 80 kN) including aspects such as annual growth,

captured and generated traffic and distribution by lane and direction. The equivalent standard axles take the estimated degree of vehicle overloading into account.

Material availability

The availability of materials (eg gravels, aggregates, cement, bitumen) all affect the possible final choice of the pavement structure and type.

Environmental aspects

The environment in which the pavement will be expected to perform is an important input parameter. Wet, arid, very hot or very cold climates all define certain requirements for the pavement design.

Subgrade materials

The thickness and composition of the pavement structure necessary to carry any traffic loading is a direct function of the subgrade material, ie, the in situ naturally occurring soil materials. A representative value for the subgrade strength needs to be determined. The actual value used will depend on the pavement design system employed, ie, mean, percentile, etc.

Material depth

The material depth denotes the depth below finished road level to which soil properties and characteristics have a significant effect on the pavement behaviour. This typically varies between 700 and 1200 mm depending on the category of road¹⁷ but is 800 mm for Category C roads.

PAVEMENT DESIGN METHODS

Numerous pavement design methods are currently used in practice. These include, for example, the CBR cover curve, AASHTO structural number, mechanistic-empirical, catalogue and DCP

methods. Only the DCP method will be covered in detail in this course. The other methods are briefly introduced.

CBR cover curve method

This is one of the original design methods and is not used as extensively these days. Various design charts have been prepared (example in Figure 9) from which the depth of construction required to protect a subgrade of any defined strength (in terms of CBR) is defined for various traffic categories and equivalent wheel loads.

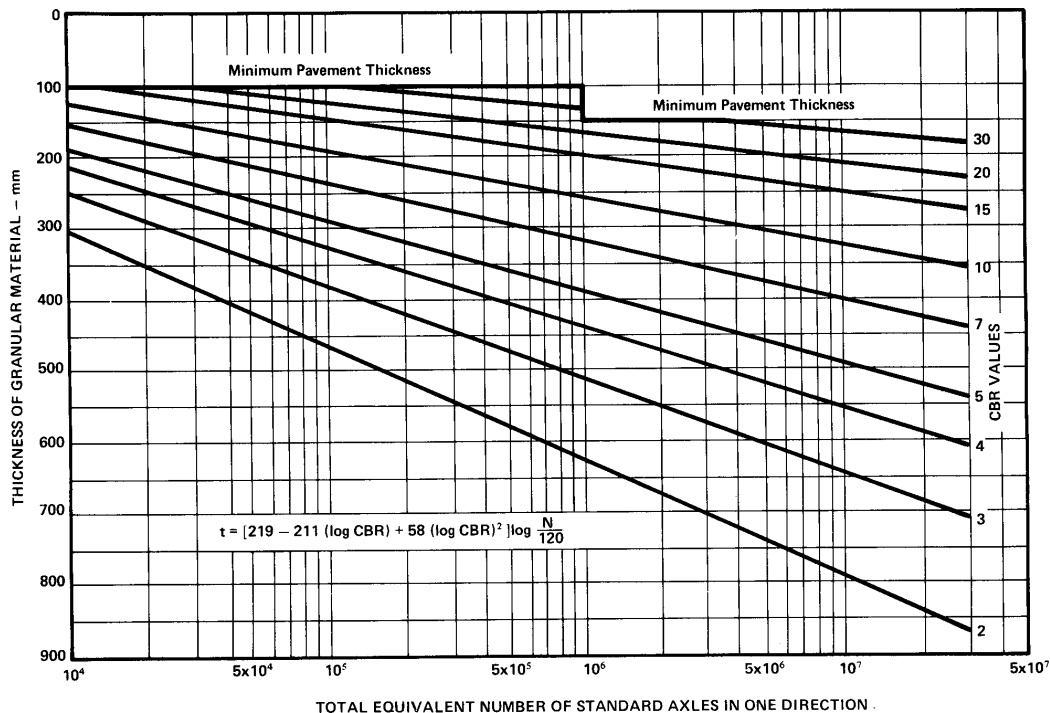


Figure9: Typical CBR cover curve design chart

AASHTO Structural Number method¹⁸

This method compares the Structural Number of a proposed road determined from various input parameters (traffic, reliability, variation in traffic and pavement performance prediction, subgrade modulus and designed decrease in serviceability of the road) with the value obtained for various

pavement designs (based on layer thickness and various coefficients related to material types and properties). This is summarised in Appendix A.

Mechanistic-empirical design method¹⁹

Mechanistic design methods are theoretically based methods, which consider the pavement as a mechanism. The various pavement layers interact in response to loading. Stresses and strains developed in the pavement are analysed mechanistically and these are related through empirical transfer functions to the distress that can be expected. These distress criteria are based on performance studies of roads and limits are given. Various components of the road have different limiting criteria, eg, the strain at the top of the subgrade is evaluated in terms of permanent deformation; the total stresses in granular layers are evaluated in terms of the Mohr-Coulomb strength parameters and bituminous materials are evaluated in terms of the tensile strains at the base of the layer). In this way the maximum traffic volume any structure can carry is determined.

Like all design methods, this method has a number of shortfalls, the primary one being that the pavement materials are considered to be homogeneous and isotropic and are assumed to perform in a linear and elastic manner. It is known that few natural materials are homogeneous and isotropic and most granular pavement materials are in fact non-linear, inelastic (ie, the stress-strain relationship is curved) and current research is developing techniques to account for this in analyses. This has a direct bearing on the selection of input values in the analyses.

An example of the use of mechanistic techniques is shown in Appendix B.

Catalogue method¹⁷

Design catalogues are the easiest design process to use as all the practical and theoretical work has been carried out and different structures are presented in catalogue form for various combinations of traffic, environmental effects, pavement materials and design options. These catalogues have typically been based on accelerated testing, theoretical analyses and in situ testing and evaluation of pavements in service. An example of a catalogue is shown in Figure 10.

GRANULAR BASES (WET REGIONS) DATE 1996											
PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 kN AXLES/LANE)											
ROAD CAT.	ES0.003 < 3000	ES0.01 0,3-1,0x10 ⁴	ES0.03 1,0-3,0x10 ⁴	ES0.1 3,0-10x10 ⁴	ES0.3 0,1-0,3x10 ⁶	ES1 0,3-1,0x10 ⁶	ES3 1,0-3,0x10 ⁶	ES10 3,0-10x10 ⁶	ES30 10-30x10 ⁶	ES100 30-100x10 ⁶	Foundation
A							30A 150 G1** 200 C3	40A 150 G1 300 C3 (250 C3)	50A 150 G1 400 C3 (300 C3)		
B						S 150 G2 150 C4 S 150 G2 200 G5	S/30A 150 G1** 200 C4	40A 150 G1 300 C4 (250 C4)		150 G7 150 G9 G10	
C				S 100 G5 125 C4 S 125 G4 125 G6	S 125 G5 125 C4 S 150 G4 150 G6	S 125 G2 150 C4 S 150 G2 150 G5	S 150 G2** 200 C4 S 150 G2 150 G4				
D	S1 100 G5 100 G7	S1 100 G5 125 G7	S1 100 G4 125 G7	S1 100 G4 125 G6 S1 100 G5 100 C4	S 125 G4 125 G6 S 100 G5 125 C4	S 150 G4 150 G6 S 125 G5 150 C4				150 G9 G10	

Symbol A denotes AG, AC, OR AS. AO, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray.
 S denotes Double Surface Treatment (seal or combinations of seal and slurry)
 S1 denotes Single Surface Treatment
 * If water is prevented from entering the base, the subbase thickness may be reduced to the value indicated in brackets.
 ** Base thickness may be reduced by 25 mm if cemented subbase thickness is increased by 50 mm.

Figure 10: Example of typical pavement design catalogue¹⁷

PRINCIPLES OF DCP INTERPRETATION

AVERAGE PENETRATION RATES

The average penetration rate over a full layer, eg, a 150 mm base course is often determined during analyses²⁰. The simple arithmetic average is not always representative if the penetration rate differs through the layer and a weighted average should be determined. When the top 50 mm of a 150 mm base layer for instance has a penetration rate of 1.1 mm/blow and the lower 100 mm has a value of 4.0 mm/blow, the simple arithmetic mean would be 2.55 mm/blow $(1.1 + 4.0)/2$ whereas the weighted mean would be 3.03 mm/blow $((1.1*50)+(4.0*100)/150)$.

PAVEMENT STRENGTH BALANCE CONCEPT

Experience with road design, construction and investigation over the years has shown that a well-designed pavement should be well balanced, ie, the strength should decrease progressively with depth from the surface. The strength balance of a pavement structure is defined as the change in the strength of the pavement layers with depth^{21,22,23}. If the strength decrease is smooth and without any discontinuities, the pavement can be regarded as being in a state of balance. The DCP design and analysis method is strongly based on this concept.

The pavement balance at any depth can be determined from a simple formula:

$$\text{DSN (\%)} = \{D*[400*B + (100 - B)^2]/[4*B*D + (100 - B)^2]\}$$

where

DSN = pavement structure number (%)

B = parameter defining the standard pavement balance curve (SPBC)

D = pavement depth (%)

This model obviously allows a series of curves to be developed for different pavement structure numbers and depths. These can be plotted as Standard Pavement Balance Curves (SPBC) as shown in Figure 11.

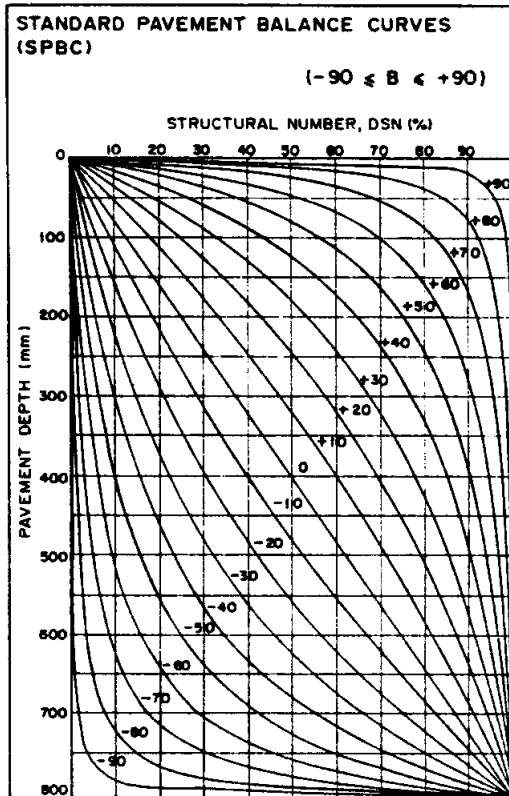
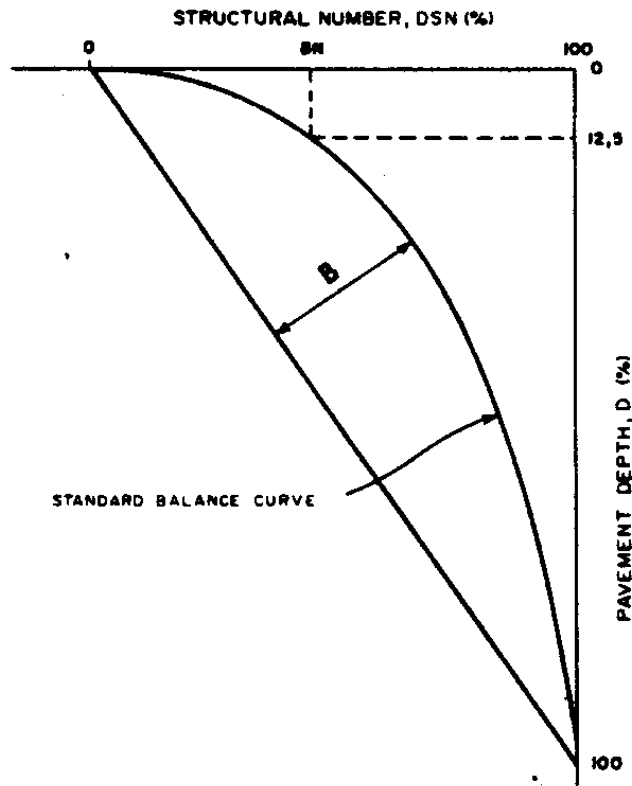


Figure 11: Standard Pavement Balance Curves²³

The number of blows of the DCP required to reach a certain depth for a balanced pavement expressed as a percentage of the DCP Structural Number (DSN_{800}) is defined as the Balance Number (BN) at that depth (Figure 12). For example, the BN_{100} is the number of blows as a percentage of the DSN_{800} required to penetrate to a depth of 100 mm (40 at 12.5 per cent of 800 mm in Figure 12).



$$DSN (\%) = \frac{D [400B + (100 - B)^2]}{40B + (100 - B)^2}$$

$$\text{WHERE } B = 100 - \frac{2}{(BN-D)} \left\{ [1094 BN (100-BN)]^{0,5} - 12,5 (100 - BN) \right\} \text{ IF } D = 12,5 \%$$

$$\text{AND } B = 0 \text{ IF } BN = 12,5$$

Figure 12: Graphic representation of BN on standard pavement balance curve²³

The Balance Number (BN) thus represents the percentage of the DCP strength of the pavement to a certain depth. Pavements with a high BN_{100} (approaching a BN of 80) are considered to be shallow whilst those with low BN values are considered to be deep. A relationship between the BN_{100} value and the “n” exponent used to calculate the load equivalency factor has also been found shallower pavements being more susceptible to high loads (ie, a higher n exponent) than deep pavements.

Pavements with smooth strength balance curves avoid any stress concentrations and are well balanced. However in practice, smooth curves are seldom found. The implications of this are discussed in the following section.

PAVEMENT CLASSIFICATION

The pavement strength balance curves have been used to develop a classification system. In this, any pavement is classified in terms of the Balance Curve (B) which is the balance curve most closely followed by the measured balance curve of the pavement and the deviation (A) between the Standard Pavement Balance Curve (SPBC) and the measured curve (Figure 13). This takes into account the deviation from a perfectly smooth balance curve.

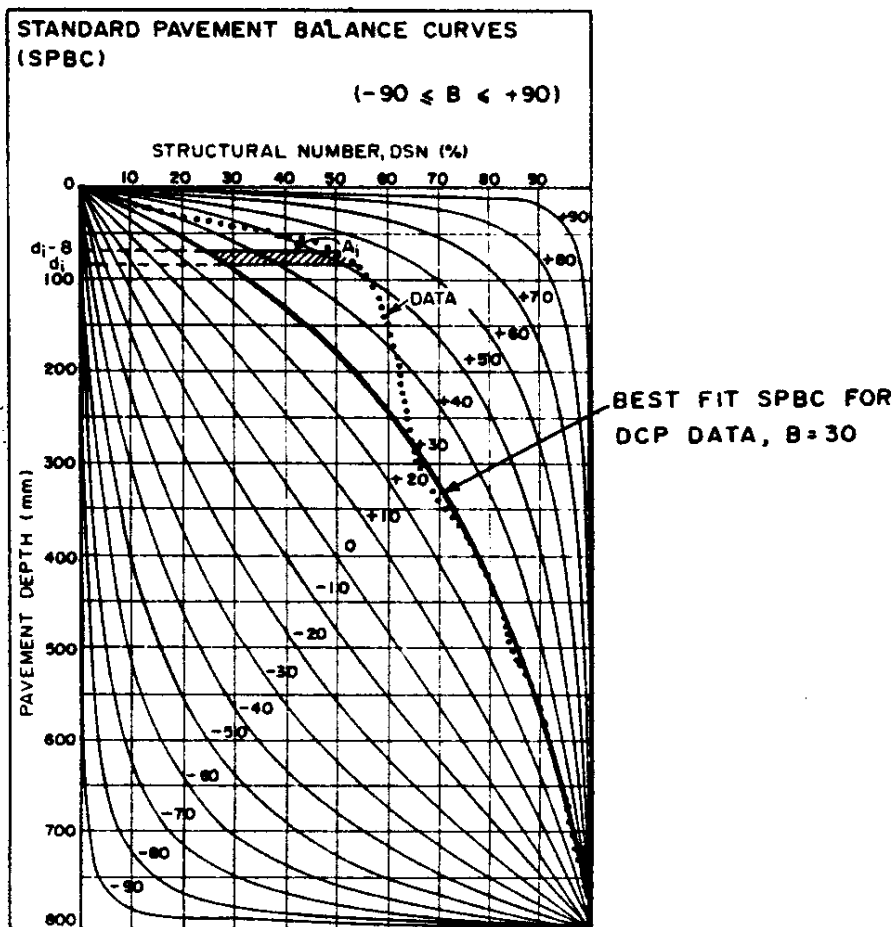


Figure 13: Graphic representation of BN on standard pavement balance curve²³

The classification system is illustrated in Figure 14 and the limits for defining the different categories are summarised below.

Shallow pavements	$B \geq 40$ (BN $\geq 42\%$)
Deep pavements	$0 \leq B < 40$ ($12.5\% \leq \text{BN} < 42\%$)
Inverted pavements	$B < 0$ (BN $< 12.5\%$)
Well balanced	$0 \leq A \leq 1200$
Averagely balanced	$1200 < A \leq 3000$
Poorly balanced	$A > 3000$

Each cell in the classification system is defined by an A and a B descriptor (ie, deep averagely balanced pavement), resulting in a possible 9 classification categories.

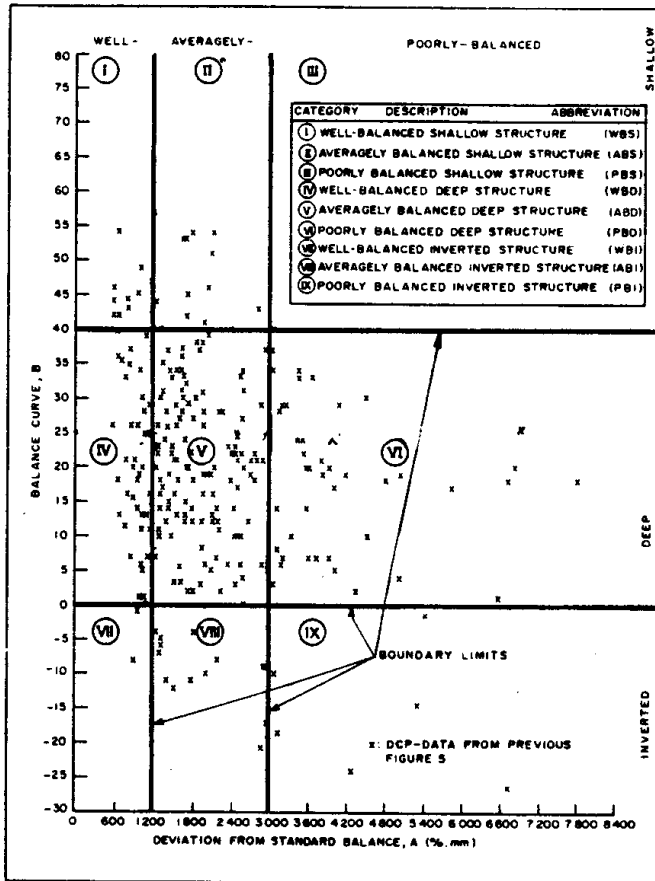


Figure 14: Graphic representation of BN on standard pavement balance curve²³

LAYER THICKNESS DETERMINATION

It is also possible to analyse the DCP data by normalising the deviation of the actual penetration profile from the best-fit SPBC (Figure 15). Maxima and minima on this normalised plot indicate boundaries between layers of different strengths and effectively provide layer thicknesses (Figure 16).

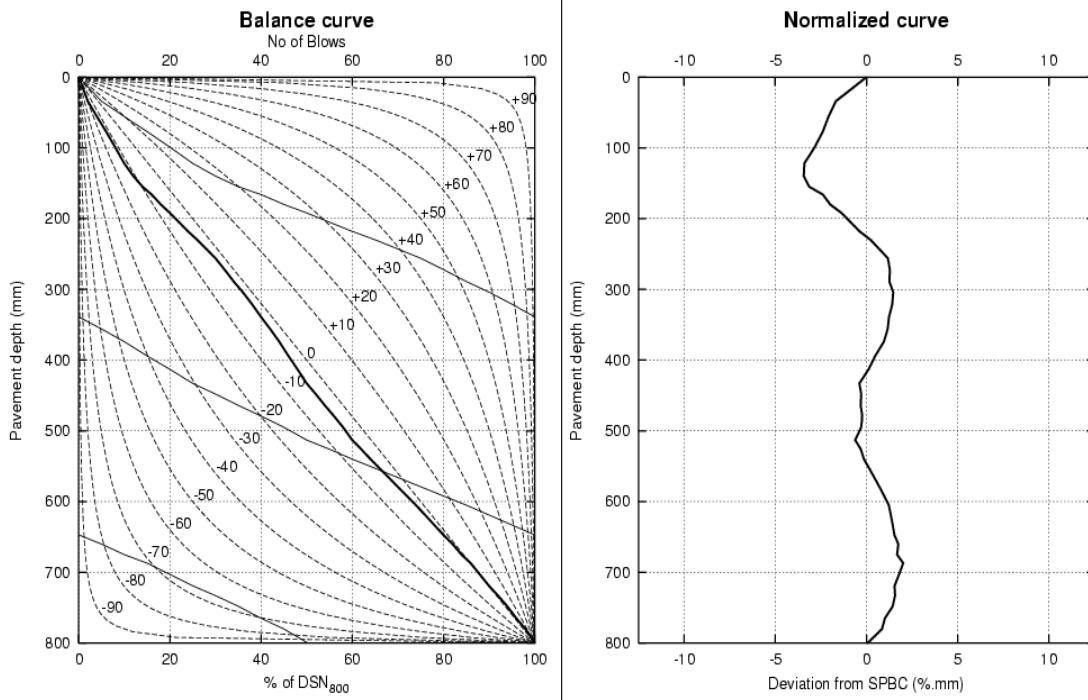


Figure 15: Normalized curve illustrating layer depths (B = - 4, A = 997)

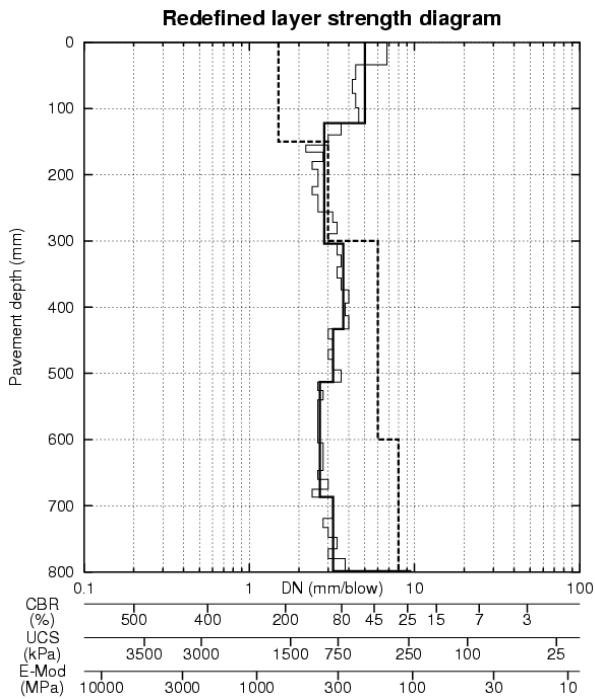


Figure 14

Various other techniques can also be used for identifying layer boundaries. These include simple methods such as the use of the cumulative sum to more complex statistical methods. The cumulative sum method is used in the UK DCP software and uses the cumulative sum of the deviations of each reading from the mean of all the results¹⁵. When these are plotted against the depth, any change in direction indicates a change in layer properties, which can be equated with the layer thickness. This technique has been applied to the data shown in Figure 7 and the results are shown in Figure 17 below.

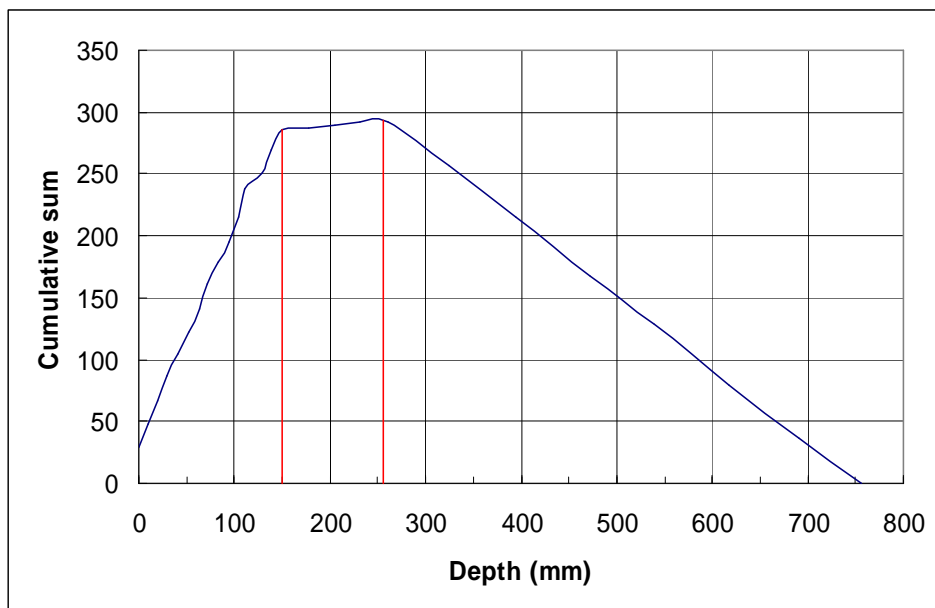


Figure 17: Results of cumulative sum plot to indicate layer thickness

STRUCTURAL CAPACITY

Research has shown that for well-balanced pavements, the structural capacity of a pavement can be determined from the DCP profile, specifically the DSN_{800} using the following model (Figure 18)^{20,24,25}:

$$MISA = C_m \times (DSN_{800})^{3.5} \times 10^{-9}$$

where MISA = million standard 80 kN axles to achieve a rut depth of 20 mm

C_m = moisture factor (64 dry, 30 optimum, 14 wet and 6.5 soaked)

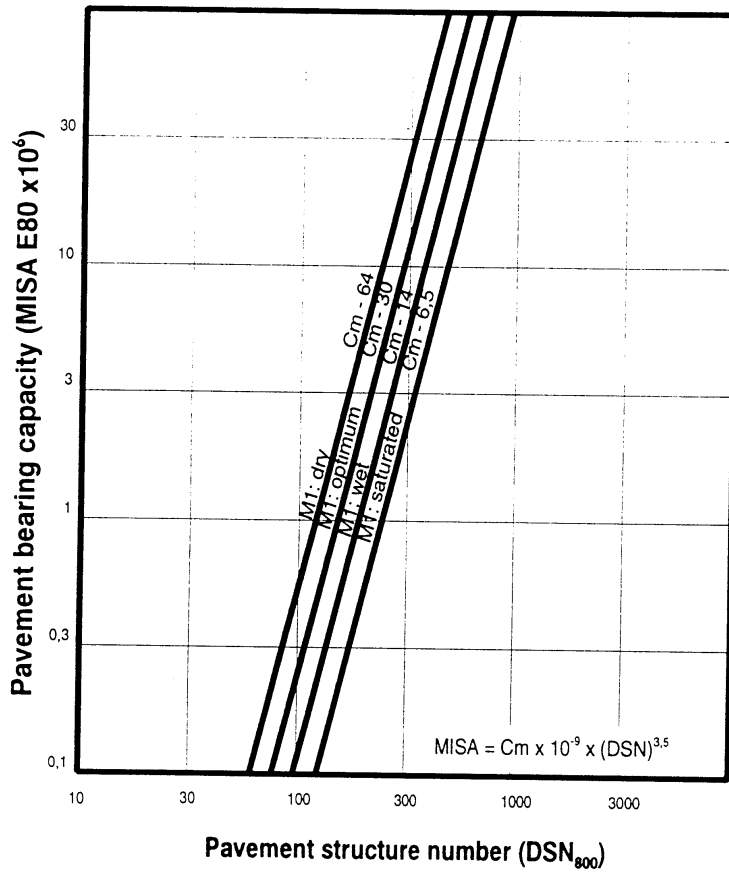


Figure 18: Relationship between pavement bearing capacity (MISA) and DSN_{800} ²⁵

The structural capacity of lightly cemented pavement layers (unconfined compressive strength less than 3000 kPa) can be estimated from the DCP using the DN_{50} and DSN_{200} . A linear rate of permanent deformation (R_L) can be determined as follows^{26,27}:

$$R_L = \left[\frac{DSN_{200}}{10^{((3.82806 - DN_{80}) / (1.38572))}} \right]$$

with R_L in mm/million E80s

DN_{50} in mm/blow (weighted average penetration rate in the upper 50 mm of the cemented layer)

DSN_{200} being the total number of blows required to penetrate the upper 200 mm of the pavement.

ELASTIC MODULUS

The elastic modulus is a complex parameter to determine accurately in the laboratory as it is dependent on the in situ density, moisture and stress conditions and assumes linear elasticity of the material (most construction materials are non-linear elastic).

However, analysis of results obtained from DCP testing associated with accelerated testing of pavements allowed the correlation of the effective elastic modulus (obtained from back analysis of deflection data at different depths) with the DCP penetration rate²⁸.

The relationship is as follows and is illustrated in Figure 19:

$$\text{Log}(E_{\text{eff}}) = 3.04758 - 1.06166(\text{log}(\text{DN}))$$

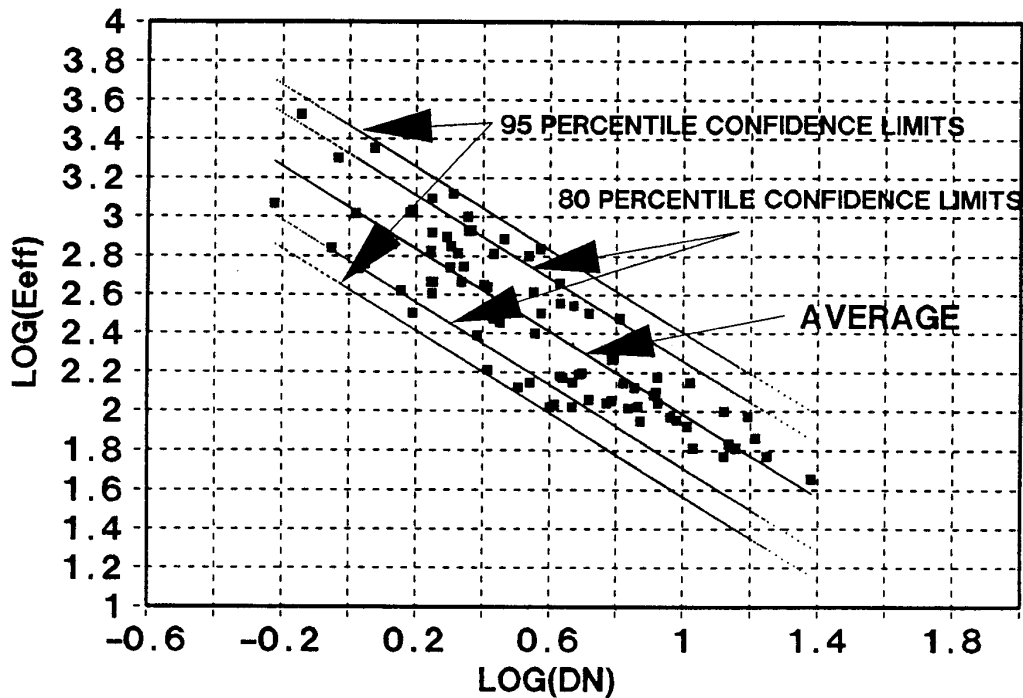


Figure 19: Relationship between effective elastic modulus and DCP penetration rate²⁸

This is a useful relationship allowing mechanistic analysis of any pavement, which provides stresses, strains and deflections and is used in pavement design, rehabilitation studies and theoretical analysis of pavements.

It is seen that the data obtained from the manual interpretation (DN, layer thicknesses, material types, DCP structural number) are the basic parameters used in the theoretical interpretations discussed above. It is clear that this can all be carried out in a much more time and cost-effective manner using modern computers. This process is included in WinDCP.

TRAFFIC

Standard pavement designs have been developed for different traffic categories (Figure 20). These are based on well-balanced pavement structures and in situ material strengths and are illustrated for heavy, medium and light traffic. The important aspect to note is that the in situ strengths plotted are significantly larger than the conventional requirements for the TRH 4 G-classes. This allows for the fact that the in situ materials are not soaked.

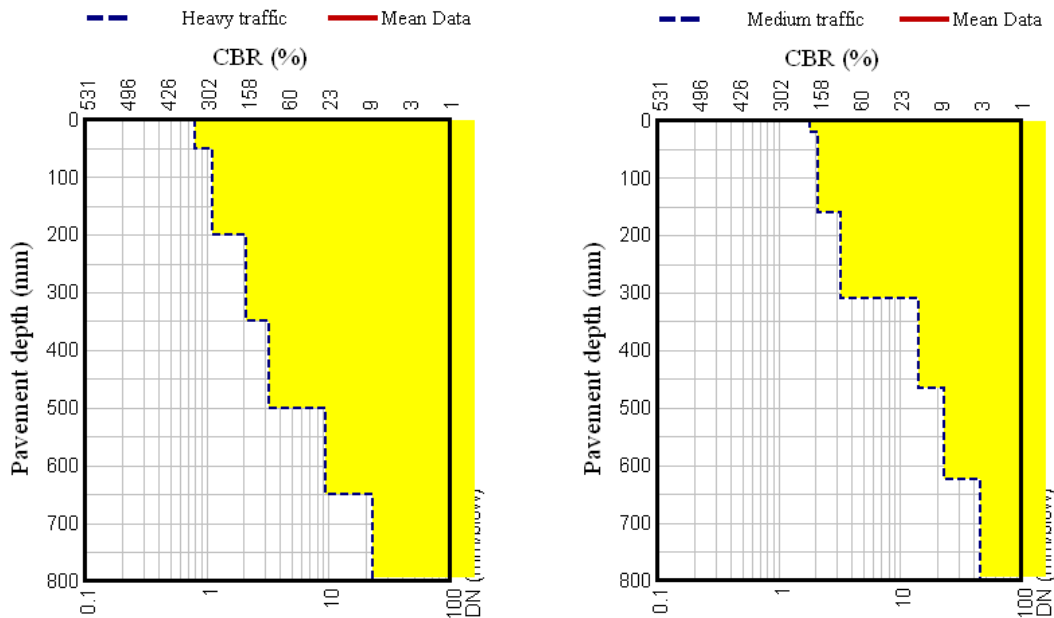


Figure 20: Design curves for heavy and medium traffic

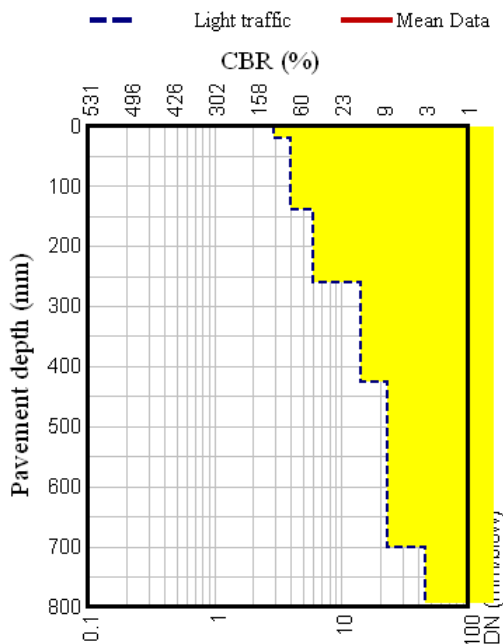


Figure 20 (cont): Design curves for light traffic

PAVEMENT LOAD SENSITIVITY

The damaging effect of a particular load on the pavement structure relative to a standard load is usually expressed by the “equivalency factor” F :

$$F = \left(\frac{P}{80} \right)^n$$

- where
- P = Applied load
 - 80 = Standard 80 kN axle load
 - n = An exponent (usually 4.2) that describes the sensitivity of the pavement to loads that are larger or less than 80 kN

Figure 21 shows the relationship between the pavement balance number (BN) and the n exponent more likely to be related to that pavement structure²¹.

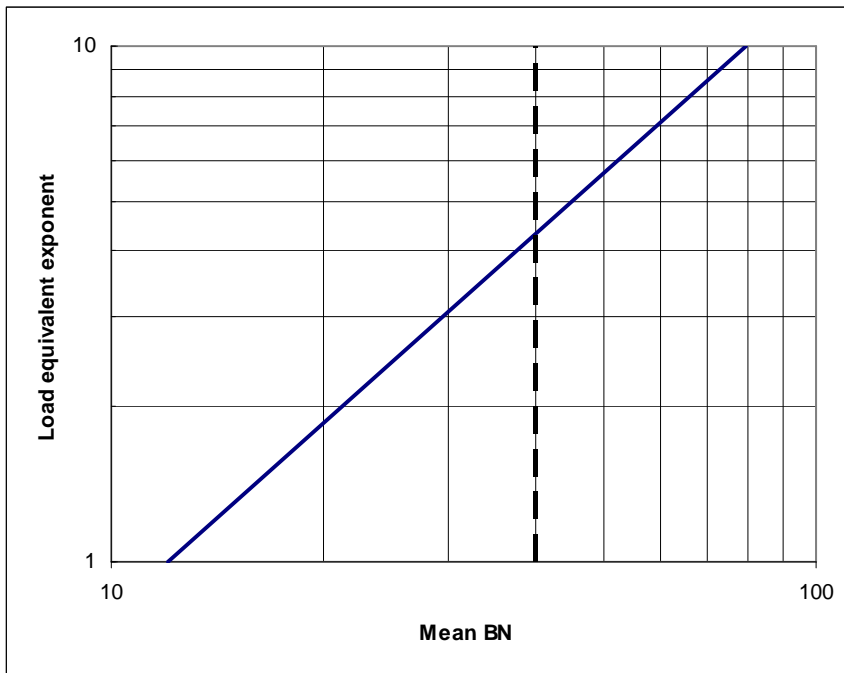


Figure 21: Relationship between “n” and pavement balance number (BN)

MOISTURE

The importance of moisture content at the time of carrying out the DCP test has been emphasised a number of times. The practice of assessing the ratio of the moisture regime affecting the road during the DCP survey (M_{SUR}) in relation to the anticipated moisture regime in service (M_{SER}) is a useful concept that has been applied¹⁴. This can best be done in terms of the season of testing (dry or wet) and local moisture conditions. If the testing is done at the end of the wet season, the moisture regime ratio ($MRR = M_{SUR}/M_{SER}$) will be greater than 1 and vice versa. The selection of the appropriate percentile for either the DN value or CBR, suggested in Table 4 will thus depend on the MRR and the moisture sensitivity of the materials (high for clays and silts and low for sands and gravels).

Table 4: Suggested percentile of minimum in situ strength profile to be used

MRR	Percentile of minimum strength profile (DN) for materials with:		Percentile of maximum strength profile (CBR) for materials with”	
	Low moisture sensitivity	High moisture sensitivity	Low moisture sensitivity	High moisture sensitivity
< 1	50 – 75	> 75	25 – 50	< 25
± 1	25 – 50	50 – 75	50 – 75	25 – 50
> 1	< 25	25 – 50	> 75	50 – 75

APPENDIX A

To design a road using the AASHTO structural number method, the following input is necessary:

- Design traffic
- Subgrade strength (Modulus of resilience)
- Design serviceability loss in terms of Present Serviceability Index (PSI)
- Overall standard deviation of material properties, traffic determinations and performance
- A Reliability function to quantify the road not attaining its design life

This data is applied to the attached Design chart (Figure A1) and the required structural number is obtained.

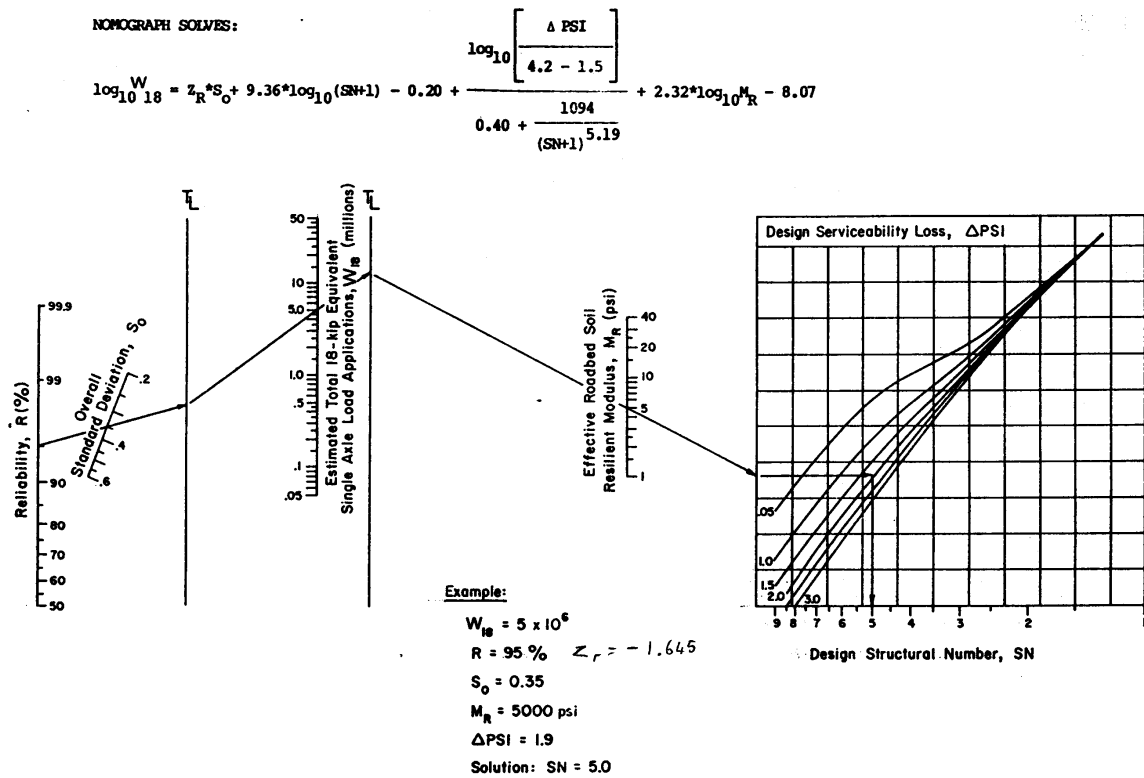


Figure A1: Nomograph for AASHTO design method

This is then used to design the pavement structure to provide the required structural number in terms of the following model:

$$S_n = \sum a_i D_i$$

where a_i = layer coefficients (See Table A1)

and D_i = thickness of layers in inches

Pavement layer	Strength coefficient a_i	
Surface course		
Asphalt mixtures (cold or hot premix of low stability)	0.20	
Asphalt concrete (hot premix of high stability) ¹		
MR ₃₀ = 1 500 MPa	0.30	
MR ₃₀ = 2 500 MPa	0.40	
MR ₃₀ = 4 000 MPa or greater	0.45	
Base course		
Granular materials²	For maximum axle loading	
	< 80 kN	> 80 kN
CBR = 30 % ³	0.07	0
CBR = 50 %	0.10	0
CBR = 70 %	0.12	0.10
CBR = 90 %	0.13	0.12
CBR = 110 %	0.14	0.14
Cemented materials⁴		
UCS = 0.7 MPa	0.10	
UCS = 2.0 MPa	0.15	
UCS = 3.5 MPa	0.20	
UCS = 5.0 MPa	0.24	
Bituminous materials⁵	0.32	
Subbase and selected subgrade layers (to total pavement depth of 700 mm)		
Granular materials		
CBR = 5 %	0.06	
CBR = 15 %	0.09	
CBR = 25 %	0.10	
CBR = 50 %	0.12	
CBR = 100 %	0.14	
Cemented materials		
UCS > 0.7 MPa	0.14	

- 1) Applicable only when thickness > 30 mm. MR₃₀ = resilient modulus by direct tensile test at 30 °C.
- 2) $a_i = (29.14 \text{ CBR} - 0.1977 \text{ CBR}^2 + 0.00045 \text{ CBR}^3)10^{-4}$; the coefficient a_i may be increased by 60 per cent if CBR > 70 and the subbase is cement- or lime-treated. Note $a_i = 0$ for CBR < 60 when axle loading exceeds 80 kN.
- 3) CBR = California Bearing Ratio (per cent) determined at equilibrium in situ moisture and density conditions.
- 4) $a_i = 0.075 + 0.039 \text{ UCS} - 0.00088 \text{ UCS}^2$; where UCS = Unconfined compressive strength in MPa at 14 days. "Cemented" implies development of tensile strength through Portland cement or lime treatment, or the use of certain flyash, slag, lateritic or ferricrete materials that are self-cementing over time.
- 5) Dense-graded bitumen-treated base of high stiffness, e.g., MR₂₀ = 4 000 MPa, resilient modulus by indirect tensile test at 20 °C.
- 6) $a_i = 0.01 + 0.065 \log_{10} \text{CBR}$.

Table A1: Pavement layer strength coefficients for structural number²⁹

When the calculated S_n from this model exceeds the value determined from the Design Chart, an adequate pavement design is obtained. This system does have deficiencies for roads with high traffic volumes as it is extrapolated from roads carrying less than 10 million standard axles.

APPENDIX B

Mechanistic analyses are carried out by analysing the stresses and strains developed in a multi-layered system using linear elastic analysis. The various layers of the pavement interact together in response to different wheel loads. From knowledge of the pavement structure, material properties, mechanisms of behaviour and the stresses, strains and displacements induced in the pavement, it is possible to deduce what type of distress is likely to occur and therefore to predict where and when.

The input data required is:

- Number of layers and their thicknesses;
- Elastic modulus and Poisson's ratio for each layer;
- Load per wheel and tyre pressure;
- Number of loads and coordinates;
- Coordinates of points to be investigated.

The calculations are time-consuming and tedious and it is best to use a computer to carry this out¹⁹. From this the relevant data can be determined to evaluate the pavement performance.

An example of this is the strain at the top of the subgrade - the value determined is substituted into the transfer function

$$N = 10^{(A-10\log \epsilon_v)}$$

where A is shown in Table B1 for a terminal rut condition of 20 mm and the model is graphically represented in Figure B1.

Table B1: Regression coefficients for the general subgrade deformation transfer function

Road Category/Service level	A
A	36.30
B	36.38
C	36.47
D	36.70

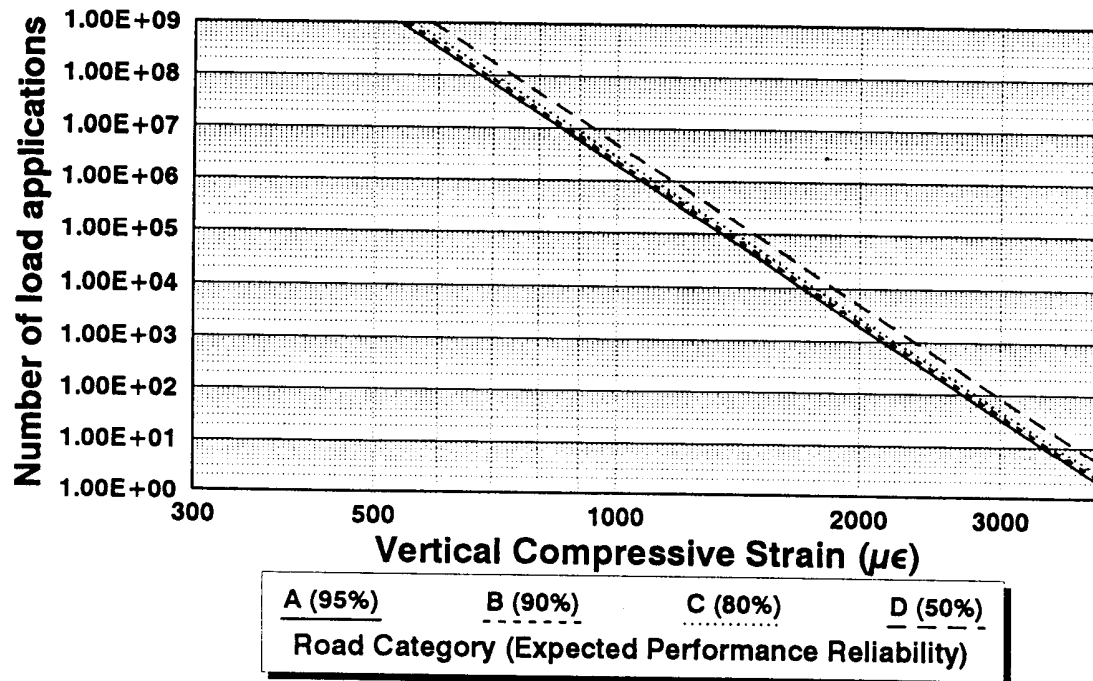


Figure B1: 20 mm subgrade deformation transfer functions

This gives the carrying capacity of the pavement before failure of the subgrade in million standard axles. Various models exist for different degrees and modes of failure applicable to different categories of road.

If the maximum tensile strain at the base of an asphalt wearing course was calculated for example as $348 \mu\epsilon$ for a thin gap graded asphalt with a stiffness of 2630 MPa, substitution of this value into the following transfer function for a Category B road (graphically shown in Figure B2):

$$N = 10^{15.85(1 - \log \epsilon_t / 3.72)}$$

indicates that the asphalt is unlikely to crack before about 70 000 standard axles have been applied.

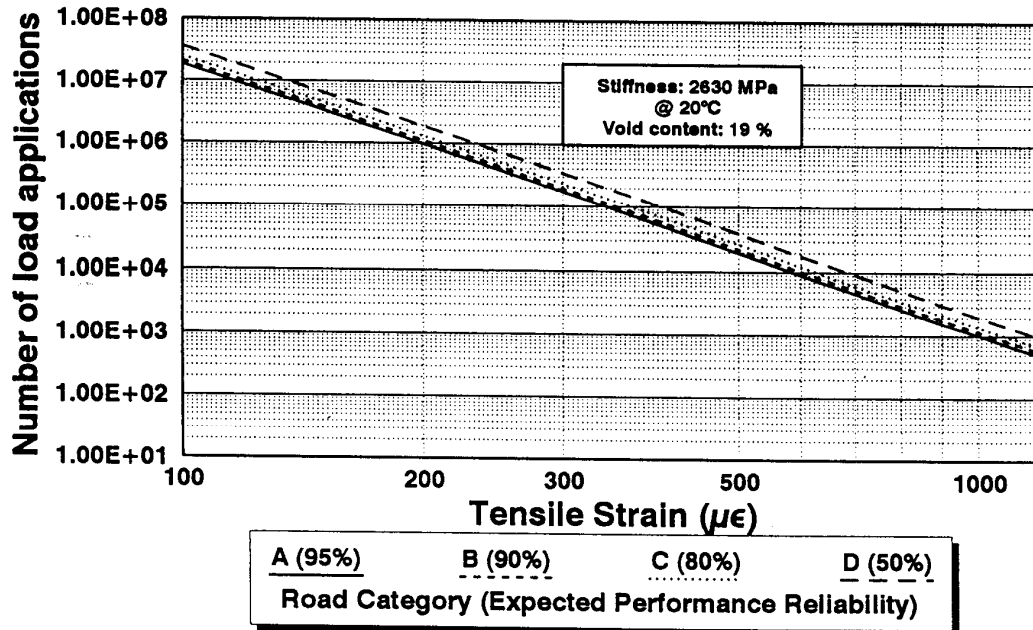


Figure B2: Fatigue crack initiation transfer functions for gap graded thin asphalt surfacing layers

This type of analysis is carried out for each layer (using different transfer functions) and the layer with the minimum structural capacity is taken as the design loading for that structure. The effect of overloading, different layer thicknesses, variation in modulus with season, etc, can be easily modelled by changing the input parameters in the program.

4 WinDCP 5 SOFTWARE PACKAGE

LEARNING OUTCOMES

Module 3 consists primarily of practical use of the WinDCP 5 software.

At the end of this module the learner will:

- Be able to input data into WinDCP 5
- Analyse both single and average DCP data
- Understand and interpret the outputs from WinDCP 5

WinDCP 5 is a powerful analysis package developed by the CSIR incorporating all the developments associated with the DCP apparatus.

The software is protected against copyright infringement with a key, which needs to be entered before the software will operate.

The software is loaded into a directory on a hard disk drive from which it is operated. All data and output files are saved by default to this directory (unless otherwise specified). The program has the facility to import Excel files directly for use.

This module involves installation of and familiarisation with the software.

The software can analyse each DCP profile individually, but for project level analyses it is better to group the DCPs by uniform section and assess them as an average for each section. This has the benefit of minimising the effects of anomalies, such as stones, poor mixing of stabilizer, etc.

5 APPLICATIONS OF DCP TESTING

LEARNING OUTCOMES

Module 4 summarises possible applications for the use of DCP testing and analysis.

At the end of this module the learner will:

- Know when and how the DCP can be applied for various applications
- Understand the limitations of the equipment and test method

The DCP test technique can be applied to various aspects of road design, construction and rehabilitation, each of these being a study in itself. The important aspect concerning these is to understand the process, theoretical background and hence the limitations and assumptions incorporated in the analysis in order to develop confidence in using the procedure. Some applications are briefly discussed in this part of the course but for certain applications are themselves subjects of individual courses.

Preliminary investigations

The DCP can be used to investigate subgrades along proposed new road alignments prior to construction. The data produced include in situ strengths and thicknesses of subgrade layers, relative compactions, and a broad indication of material types. This is a quick way of determining typical subgrade strengths for pavement design and identifying uniform sections and the design strengths for these sections.

It should be noted that the data obtained are at in situ moisture and density and this needs to be taken into account. It is possible to determine soaked values by building a low earth embankment around the site to be tested and soaking the area with water for a short period (2 to 4 hours depending on the material permeability).

The data obtained from these investigations can be used to determine bills-of-quantity for preliminary budgeting and even tendering purposes as well as providing valuable input into the design process.

DCP testing has also been used for borrow pit location and determination of overburden thickness. This has been particularly useful for locating calcretes under sand where refusal is obtained and a trace of the calcrete may adhere to the tip of the cone for confirmation on removal of the DCP.

Regravelling and upgrading of unsealed (gravel) roads

A DCP survey of any unsealed road prior to regravelling indicates the existing structure and is useful in determining the required quantity of material which needs to be imported as well as any work necessary prior to the importation, eg, replacement of poor material, recompaction, scarification and recompaction, etc.

The same process is also a useful indication of the requirements for upgrading an unpaved road to paved standard. A simple analysis using an overlay system identifies the thickness and quality of material necessary to provide the structure required for the design traffic.

Pavement design

A comprehensive method of designing lightly trafficked roads using the DCP has been developed. This provides a light but well-balanced pavement structure for specific design traffic categories and is summarised in a catalogue. The design strength profile is integrated with the in situ soil strength profile to optimally utilise the in situ material strength.

This process is covered in the paper "Application of the Dynamic Cone Penetrometer (DCP) to light pavement design"¹⁴,

The use of the DCP for the design of road structures for traffic categories up to 10 million standard 80 kN axles is covered in the paper "Use of the Dynamic Cone Penetrometer (DCP) in the design of road structures"²⁸.

Quality control

The DCP is a quick, (relatively) non-destructive test, which can be used for quality control during construction³⁰. It can either be used for absolute comparison with a required datum or relative comparison within an area. Although it is a measure of the shear strength of a material, it can be used for checking the compaction quality or ensuring that refusal compaction has been obtained *for any specific material*. This is best based on proof rolling prior to compaction.

This involves the preparation of the material to the required moisture content and DCP testing of the layer after each roller pass. A point will be identified at which no further densification (or even de-densification in some instances) occurs and this can be used as a method specification for that material, layer thickness, plant and moisture content.

Using standard statistical techniques the natural variability of the materials being tested and the repeatability of the test can be incorporated to minimise the risk to both the contractor and the client.

Pavement Rehabilitation

Significant work has been carried out using the DCP for rehabilitation design of asphalt surfaced roads. Comparisons with various rehabilitation methods including the Asphalt Institute method, Mechanistic methods and standard catalogues have been carried out. A low cost DCP survey can provide sufficient information to design appropriate overlays (or identify areas where overlays are insufficient and additional structural material is required). Rehabilitation should typically follow a multi-analysis approach.

Rehabilitation methods are described in the next part of the course.

Failure investigations and Audits

The DCP is an invaluable tool for failure investigations and technical audits. It can be used prior to any in destructive testing to determine layer thicknesses and condition with respect to the original design specification. This assists with the selection of areas for detailed investigation and allows optimisation of the in situ testing to minimise investigation costs.

Foundations

The DCP penetration rate has also been correlated with the bearing capacity of soils for founding structures. This provides a general indication and should not replace conventional testing, but can be a useful addition to extend the results of other tests using a cheap in situ test method. One such model is:

$$\text{Bearing capacity (kPa)} = 3426.8 \text{ DN}^{-1.0101}$$

Research

The DCP is an invaluable research tool and can be used for numerous applications. A number of examples are listed below:

Evaluation of pavement performance

The performance of various pavement structures can be evaluated and compared in terms of their balance, material properties, layer thicknesses, etc and indications of why some pavements perform well whilst similar ones do not can be obtained. Remember that moisture content changes have a significant effect on the DCP results and must be taken into consideration.

Investigation of moisture effects in roads

The seasonal influence of moisture on the performance of roads and zones of moisture influence within the pavement structure can easily be determined through a regular testing programme. This type of information can be used to determine ideal paved shoulder widths, fill heights, drainage locations, equilibrium moisture contents and strengths, etc.

These are only some of the research applications that can be carried out and the DCP can in fact be applied to almost any materials related research programme. The use is mostly self-explanatory and as a research tool each application will need to be suited to the specific situation. General philosophies regarding this will be discussed during the course.

LIMITATIONS OF THE DCP

As discussed through this course, the DCP is a very simple and basic piece of equipment. As such, the results will seldom compare with more sophisticated and expensive testing such as Falling Weight Deflectometers (FWD), Benkelman Beams, Test pitting, etc.

However, provided an understanding of the DCP test, the expected site conditions and the limitations of the test are taken into account, there is no reason why good interpretations of the data cannot be made. The main limitations that are likely to affect the results and interpretations and need to be considered include:

- Very stony materials
- Very hard cemented layers
- Heavily patched and repaired roads, particularly when overlaid
- Highly variable pavement structures and materials
- Old, dry asphalt
- The possibility of not recording very weak layers when taking depth measurements after every 5 blows
- Poorly executed tests (hammer not falling the full distance, non-vertical DCP, excessive movement of the depth measuring rod, etc)

Many of these are controllable if noted early enough on site.

6 REHABILITATION DESIGN METHODS USING DCP ANALYSIS TECHNIQUES

LEARNING OUTCOMES

Module 6 covers the application of DCP investigations in the rehabilitation of roads.

At the end of this module the learner will:

- Be able to apply the results from DCP investigations to design pavement structures for the rehabilitation of roads

This module discusses the use of DCP tests for the rehabilitation design of pavements and is basically a modified extract from the original reference³¹.

The DCP method is an empirically derived “pavement component (layer) analysis method” which therefore incorporates many assumptions that can seriously limit its general applicability. Nevertheless, when found applicable, methods based on pavement component testing give an easy to use and reliable procedure to determine the rehabilitation needs of flexible pavements. However, because of the empirical nature and the limitations incorporated into the method it is recommended that the method be applied in a multi-analysis approach, together with other methods such as deflection analysis, visual surveys and test pit information. The reliability of the use of empirically derived component analysis rehabilitation design methods depends strongly on whether the method is applicable for use on a specific pavement: the pavement needs to have a reasonably well-balanced structure. Consequently, the applicability of the method should thoroughly be investigated before application. However, the evaluation procedures based on these tests are of importance also as an input into mechanistic design methods.

The California Bearing Ratio (CBR) test, measuring the shear stress of pavement materials has been widely used as a pavement materials test throughout the world, since its conception in the 1930's. Several countries have developed or adopted pavement design methods based on the measurement of the CBR of materials.

In South Africa, the measurement of the in-situ shear strength of the pavement layers using a Dynamic Cone Penetrometer (DCP), has also led to the development of pavement evaluation and rehabilitation design methods. The DCP method is much further developed and more advanced than the CBR methods, allowing for the detailed evaluation and analysis of pavement structure. Nevertheless, both the CBR and DCP component (layer by layer) analysis methods are empirically derived based on material shear strength and can only be accurate if used for the evaluation and analysis of pavements similar to those from which they were derived.

It follows that the CBR and DCP test provide meaningful, but incomplete information about the expected behaviour of a pavement. The key to the successful application of empirically derived methods based on CBR and/or DCP measurements lies in the applicability of the method to a specific pavement and can give extremely good results and information about the future behaviour of a pavement. It is, however, advised that the method be used in a multi-analysis approach together with other methods.

PRE-DEFINED DCP DESIGN CURVES

The first in the series of rehabilitation design methods using DCP data is an empirically derived comparison between the collected DCP data and data from historical pavements, which have shown to have adequate strength for a certain traffic demand. It is based on observations and experience with use of the DCP mainly in the old Transvaal Province of South Africa³². The method was originally developed for use on pavements with thin surfacings and natural gravel sub-layers. However, research has shown that the method can also be used on pavements with lightly cemented layers (UCS < 3 000 kPa³³).

The DCP instrument measures the penetration rate per blow through all of the individual pavement layers. As this penetration rate is a function of the in-situ shear strength of the material, the profile in depth gives an indication of the effective in-situ properties of the materials in each layer up to the depth of penetration (800 mm is the recommended depth of testing).

The first objective in the development of the rehabilitation design method was to improve the utilization of DCP tests as a measurement of pavement bearing capacity. Many of the concepts

used originated from practical experience. Results from HVS tests (58 HVS tests performed from 1976 to 1983⁷) were used to verify these concepts and to establish expected life versus DCP penetration curves for granular base pavements. The development of these curves was based on a rut depth of 20 mm measured under a 2 m straightedge, which was defined as representing a terminal pavement condition. The design curves were derived using mean values measured and are therefore only an indication of mean expected life.

The first step is to study the DCP structural number (DSN_{800}). This is done during the initial assessment of the rehabilitation design and the DCP measurements are used only as an indicator of the overall pavement condition. Measurements for each significant pavement length (uniform section) are classified according to the processed data as being Sound, Warning or Severe in terms of the criteria given in Table 5²⁵.

Table 5: Performance criteria recommended for the assessment of pavement condition²⁵

Structural Number DSN 800	Moisture Regime	Category of Road					
		A		B		C	
		X	Y	X	Y	X	Y
total # of blows	M1	350	155	230	110	155	70
to penetrate	M2	430	190	290	130	190	90
to a depth of	M3	540	240	360	160	240	110
800mm	M4	670	300	440	200	300	140

where: M1 = a dry moisture regime or good drainage condition
M2 = an optimum moisture regime or average drainage condition
M3 = a wet moisture regime or poor drainage condition
M4 = a soaked moisture regime, or saturated conditions

and: $DSN_{800} > X$ = Sound condition
 DSN_{800} between X and Y = Warning condition
 $DSN_{800} < Y$ = Severe condition

Detailed assessment

It is during this phase of an investigation that the DCP tests can give valuable information about the existing pavement structure and its future structural behaviour. The DCP data can be processed to give an indication of the adequacy in strength of various pavement layers (using the layer strength diagram).

The DCP data in terms of the layer strength diagram, of which examples are shown in Figures 7 and 8, gives an indication of the in-situ strength (DN or CBR) of the pavement materials in depth. This DCP profile of the rate of penetration is then compared with minimum specified standards, called DCP master design curves, shown in Figure 22, to determine the adequacy of the various pavement layers in depth for the expected future traffic loading. Points lying to the right of the DCP design curve for a specific traffic category indicate material of inadequate quality at that depth. With the use of Figure 22 it is also possible to get a good indication of the existing cause and mechanism of distress in terms of the past cumulative traffic loading.

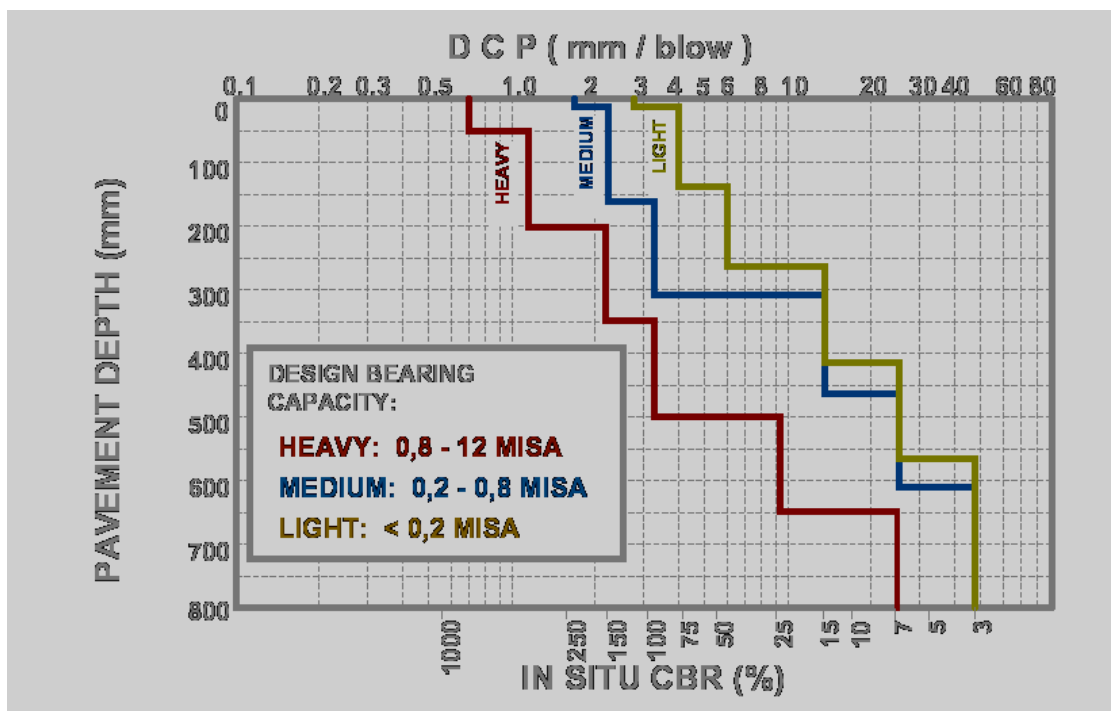


Figure 22: DCP design curves for various design traffic classes

Three master design curves have been developed through observations and experience with the DCP, mainly in the old Transvaal Province of South Africa, and calibrated during Heavy Vehicle Simulator (HVS) tests as explained earlier. The three design classes are for pavements where the expected numbers of E80s (expressed in MISA, or Million Standard Axles) are:

- Light traffic: less than 200 000 E80s
- Medium traffic: between 200 000 and 800 000 E80s, and
- Heavy traffic: between 800 000 and 1.2 million E80s

In order to investigate if a pavement has the required structural strength, the DCP field data expressed in terms of the DCP-layer-strength-diagram is projected on to the appropriate DCP master curve as shown in Figure 23. If the field data plots to the left of the selected design curve it signifies that the pavement has adequate structural strength to carry the traffic for that traffic class. Any area plotted to the right hand side of the selected design curve indicates a region of the pavement structure with insufficient shear strength.

The WinDCP 5.0 software package has these master design curves built into the package. Whenever the DCP field curve plots to the left of a particular selected design curve, the area between the DCP field curve and the selected design curve is coloured in green, indicating that adequate shear strength is provided for the selected traffic class at a certain depth. When the DCP field curve plots to the right of a selected design curve, the area is coloured in yellow, which indicates that there is not enough structural strength in the pavement layer to carry the selected traffic.

Examples of the output from the DCP software package illustrating this are provided in Figures 23 and 24.

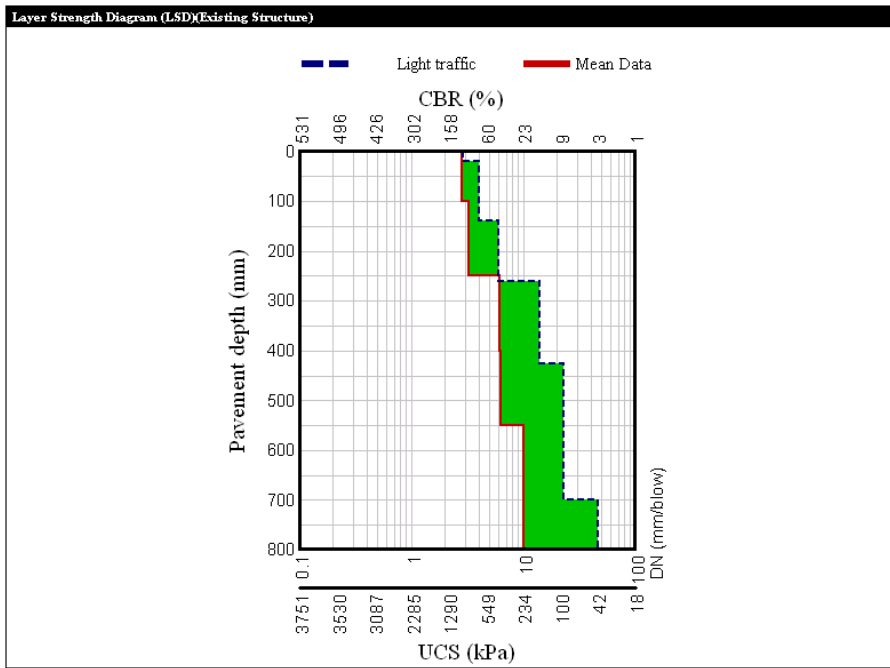


Figure 23: Example of pavement structure with adequate strength for a lightly trafficked pavement (< 0.2 million standard 80kN load applications)

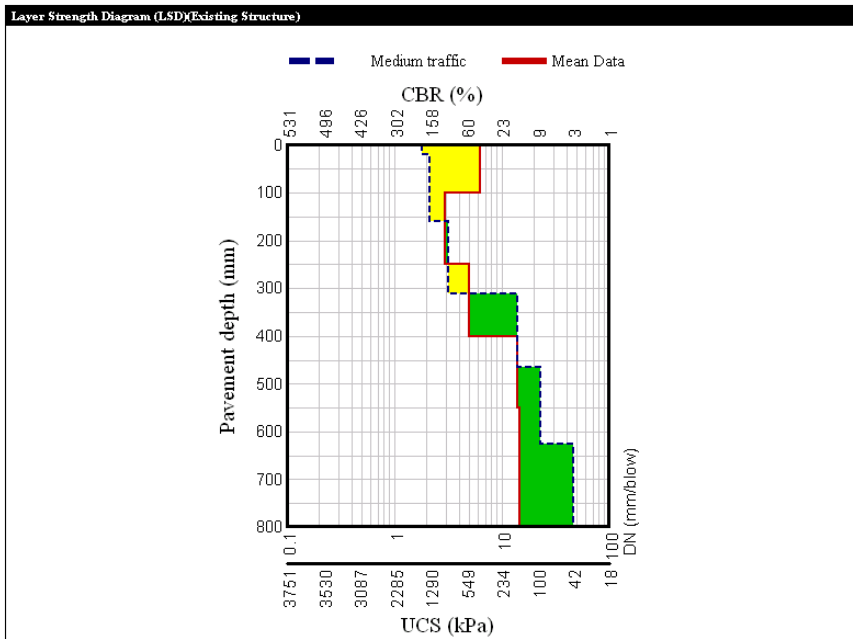


Figure 24: Example of pavement with insufficient structural strength in upper 300 mm for medium traffic

The DCP field data (plotted in red) is compared with a pavement, which is designed to carry less than 200 000 standard E80 load applications (Light Traffic class indicated as blue dotted lines in

Figure 23). This is done through selecting the LIGHT traffic class in the software prior to running the calculations. The results can be seen in Figure 23 where the DCP field data for all the layers plot to the left of the selected design curve as indicated by the green areas, which signify that the pavement has adequate strength to carry at least 200 000 load applications.

In this case the mean values are plotted. It is also possible to plot, for example the 90th percentile values in cases where a number of DCPs have been recorded and the data is analysed together to get a result that accommodates the variability in the pavement sections.

Figure 24 shows the DCP profile of a pavement designed to carry between 200 000 and 800 000 E80s. This is an example of a pavement with inadequate strength and it is clear that the upper 300 mm of the pavement (plotted in yellow) does not have sufficient strength to carry the design traffic of between 200 000 and 800 000 E80s.

Example of rehabilitation design using the Design Master Curves

An example of a complete rehabilitation design using the master design curves is given below:

Step 1:

Carry out a DCP survey on the segment of road to be rehabilitated. It is recommended that the rehabilitation design should be based on a representative number of at least 10 DCP tests taken in the outer wheel track. The different DCP penetration rates are collectively plotted on the layer strength diagram to give an indication of the variability of the strength of the pavement structure. Various percentile values can be used as the representative penetration rate for the pavement segment, depending on the required reliability of the road design¹⁷. For instance the mean value (50th percentile) value can be used for a road of very little importance (Category D) and 95th percentile for roads of high importance (Category A). Figure 25 shows the effect of penetration rates with respect to various confidence limits.

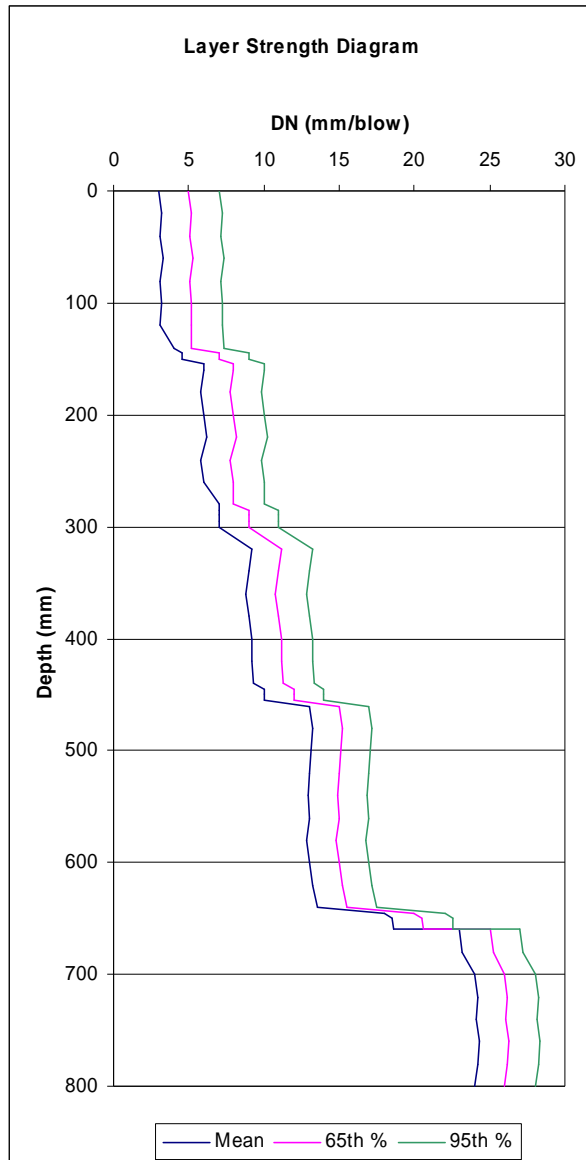


Figure 25: Example of a layer strength diagram with different confidence limits

Step 2:

Determine the design traffic and select the correct design master curve: Light, Medium or Heavy traffic. Note that this traffic prediction is the additional traffic that the pavement will be expected to carry after rehabilitation.

Step 3:

Superimpose the layer strength plot on top of the selected design master curve. An example of this is shown in Figure 26.

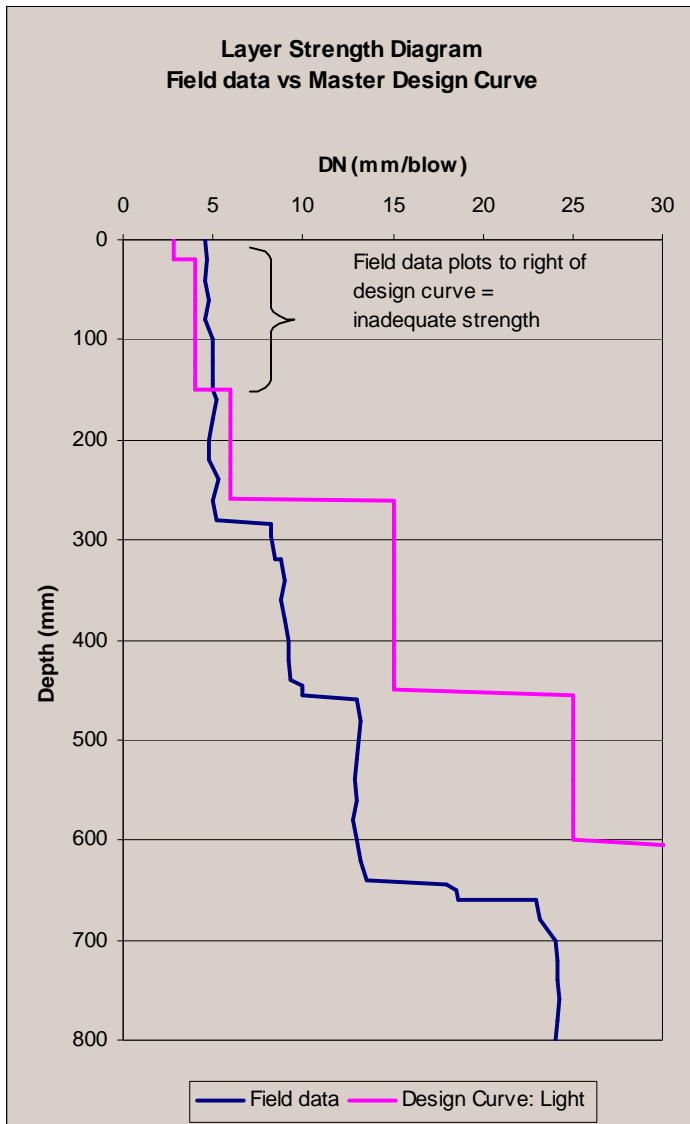


Figure 26: Pavement with inadequate strength in the upper layer

Step 4:

Analyse the Penetration rate versus master curve graph and decide on a rehabilitation strategy.

From the graph it can be seen that the pavement does not have adequate strength in the top

150 mm. According to the design master curve the top 150 mm should have a penetration rate of not greater than 4mm/blow. To correct this through rehabilitation of the pavement any one of three strategies can be followed:

- a) Mill out the top 150mm of the pavement. Rework (improve) and replace the material to a layer depth of 150 mm ensuring a material strength higher than that required by the selected master design curve. In this case, the reworked layer will require a maximum penetration rate in the new upper 150 mm of 4mm/blow. This is illustrated in Figure 27.

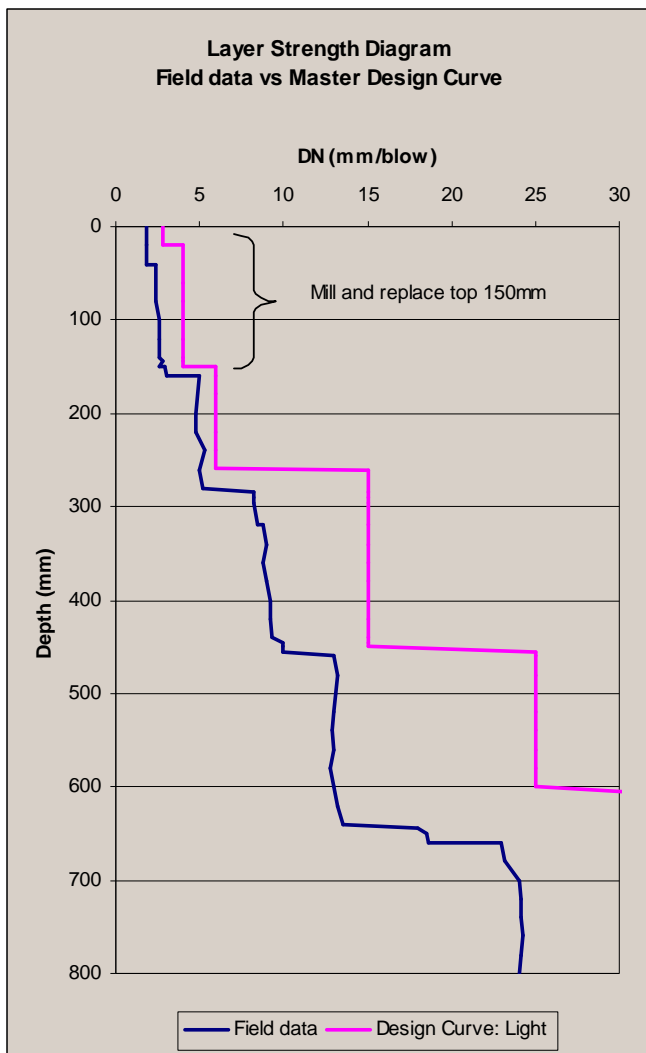


Figure 27: Illustration of a rehabilitation strategy where the top 150mm is reworked to an acceptable standard

- b) If the top 150mm of material is not of sufficient quality the material may be removed and replaced by imported better quality material.
- c) Strengthening of the top 150mm can also be achieved through adding an overlay of appropriate better quality material. For instance if the same example as in Figure 26 is used it would be equally effective to rework and compact the top 75 mm of the pavement and add a 75mm overlay of sufficient strength. This is illustrated in Figure 28.

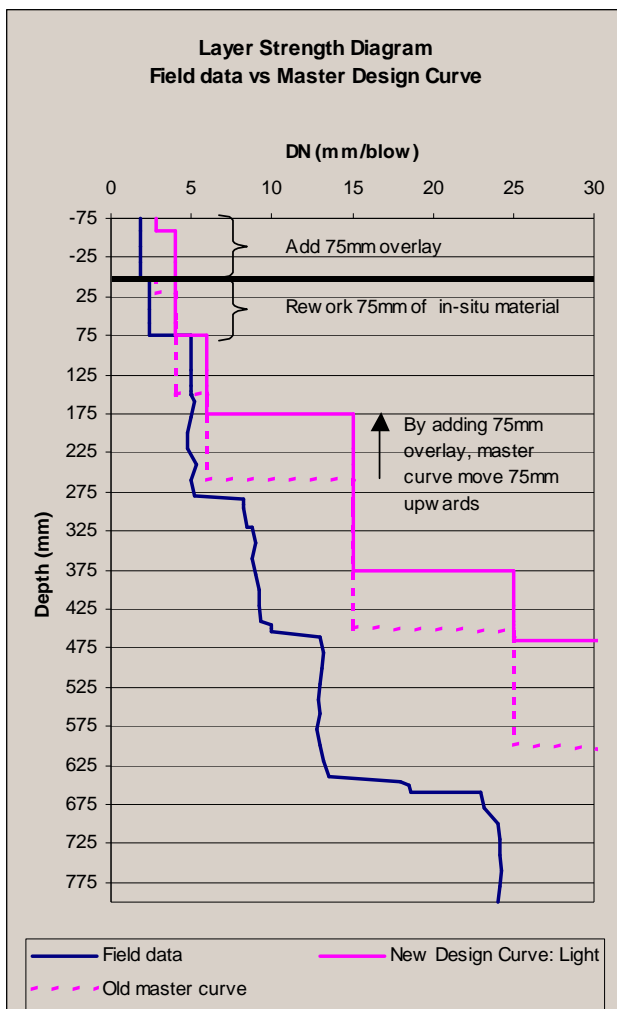


Figure 28: Rehabilitation by reworking 75 mm and adding 75 mm overlay

The chosen strategy will depend on economic considerations, height clearances and levels, and availability of appropriate imported materials.

Example 2

Say for instance that the pavement does not have adequate strength at a depth between 200mm and 275mm. This is illustrated in Figure 29.

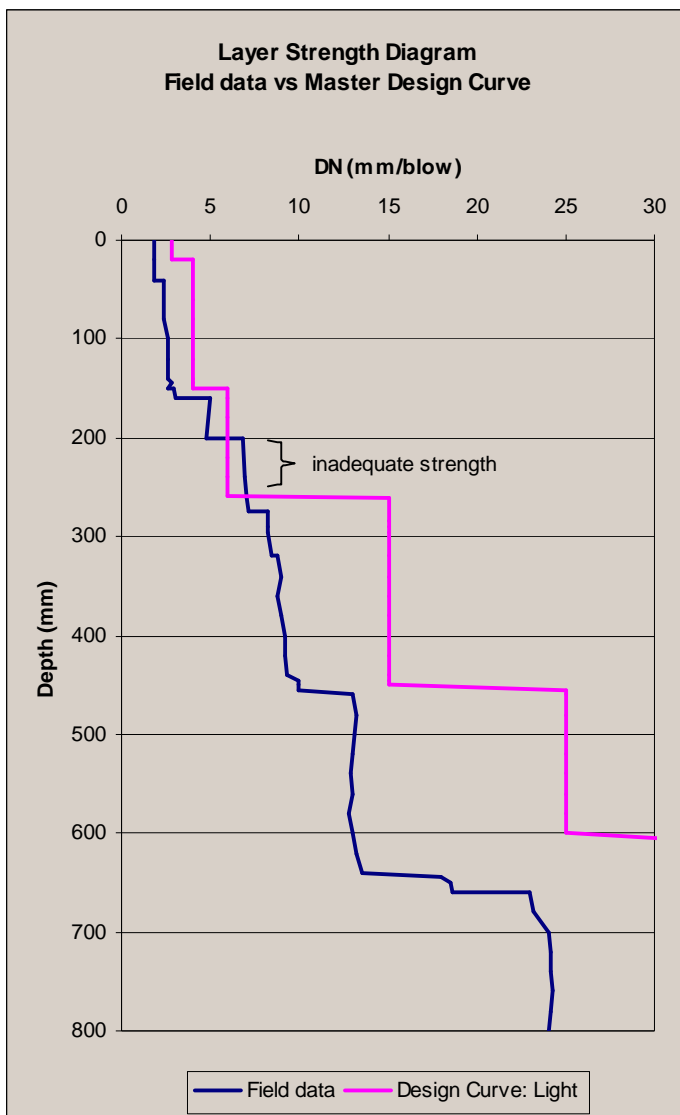


Figure 29: Example of a pavement with inadequate strength at a depth of 200mm

Similarly to the first example, it is possible to rehabilitate this pavement by milling out 275 mm, rework and compact it so that the new DCP penetration rates will be lower than those required. This option may be a very costly exercise, as the complete upper part of the pavement will have to be milled out, reworked and compacted.

Alternatively, the problem can be overcome by simply adding 75 mm of overlay similar to the previous example. In this case the structural inadequacies at the depth of 200 mm are rectified by displacing the new design master curve 75 mm upwards due to the addition of 75 mm of overlay. This is illustrated in Figure 30.

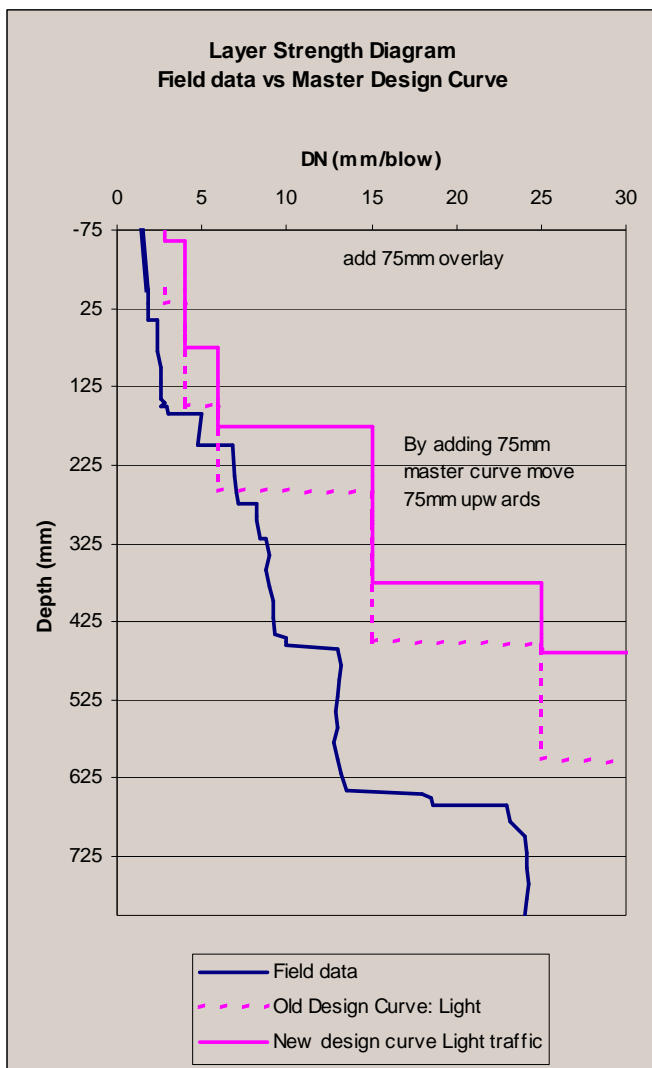


Figure 30: 75mm of overlay fix problem at a depth of 200mm

From Figure 30 it is clear that the field data plots to the left of the design master curve, which signifies that the new pavement has adequate strength to carry the design traffic (in this case less than 200 000 E80s).

Using the Balanced Pavement Concept

The design philosophy behind using the balanced pavement concept is that the maximum in-situ bearing capacity of the existing pavement should be utilized, while a well-balanced pavement is created without any localised stress concentrations. Sudden changes in the structural strength of individual pavement layers cause stress concentrations, which negatively affect the overall bearing capacity of the pavement in the long term.

The first step of this method is a repeat of the initial assessment of the structural behaviour of the pavement using Table 4 as explained earlier.

An example of a complete rehabilitation design using the concept of a balanced pavement is illustrated below.

Step 1:

With the future expected cumulative traffic loading over the rehabilitation design period and the expected moisture regime known, determine the required pavement Structure Number (DSN_{800}) of the rehabilitated pavement using the following equation as shown in Figure 30.

For granular layers:

$$\text{Pavement Bearing Capacity (million E80s)} = C_m \times 10^{-9} \times (DSN_{800})^{3.5} \quad \text{Equation 6.1}$$

where:

- $C_m = 64$ in Dry Conditions
- $C_m = 30$ in Optimum conditions
- $C_m = 14$ in Wet conditions
- $C_m = 6.5$ in Saturated conditions

The DSN_{800} and the moisture regime of the pavement is used in Figure 31 to obtain the traffic loading that the pavement structure is able to carry before developing a rut depth of

20 mm. The existing rut depth of the pavement section should be taken into account in calculating the remaining "life" of the pavement.

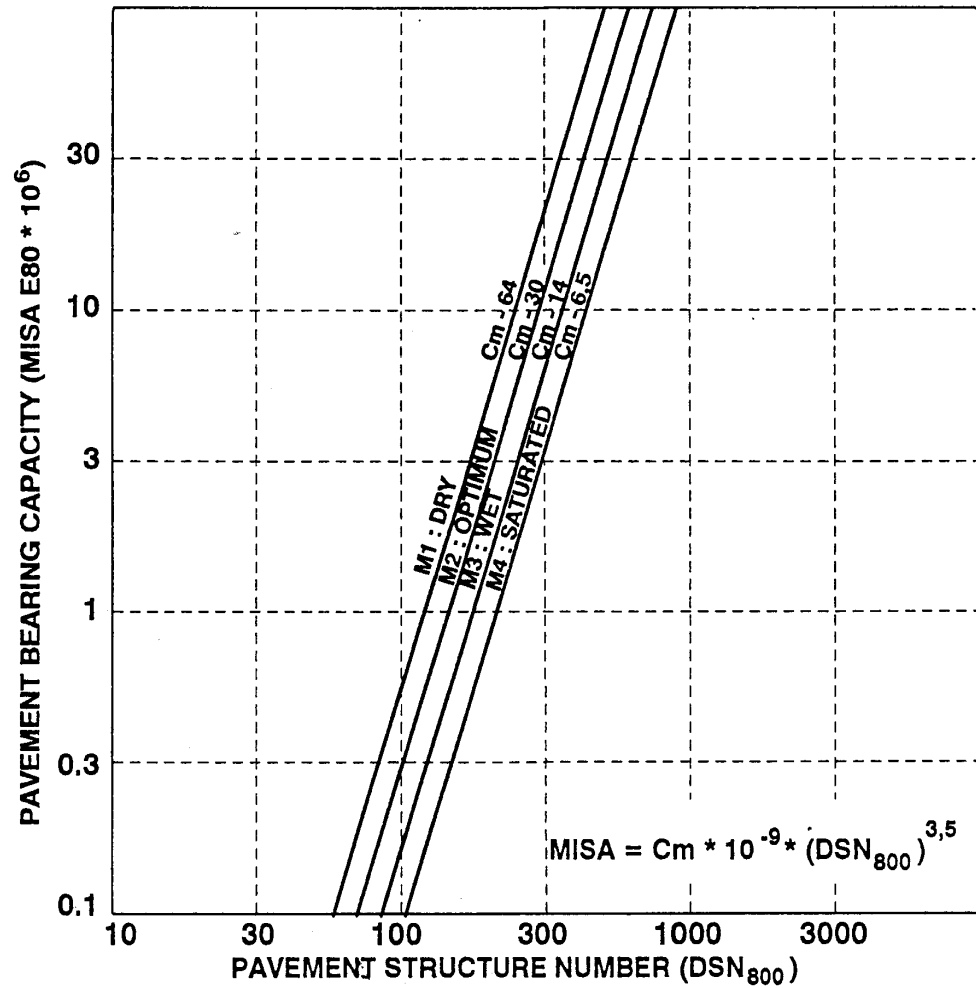


Figure 31: Relationship between bearing capacity and pavement structural number

Pavements containing lightly cement-treated layers

The structural capacity of pavements containing lightly cement-treated bases is dependent on the characteristics of the cement-treated layers. For these pavements the

structural capacity is a function of the DCP rate of penetration through the top 50 mm of the pavement structure (DN_{50}) and the number of DCP blows required to penetrate the pavement to a depth of 200 mm (DSN_{200}).

The rate of deformation (RL) for pavements with lightly cement-treated layers is given by the following formula:

$$RL = DSN_{200} / [10^{((3,82806 \times DN_{50}^{(1,38572)})}] \quad \text{Equation 6.2}$$

where:

- RL = rate of increase in rut depth in mm per million E80s
- DN_{50} = rate in DCP penetration for the upper 50 mm of the pavement in mm/blow
- DSN_{200} = number of DCP blows to penetrate the pavement structure to a depth of 200 mm

With a known existing rut depth of the pavement and the rate of rut per million E80s determined, the remaining "life" of the pavement before a certain rut depth is reached can be determined.

As an example, assume that the rehabilitated pavement, consisting of granular layers only, should be able to carry 0.5 million E80s over its design life.

Step 1:

Using Equation 6.1, the required DSN_{800} number for such a pavement is 119 blows if the pavement is expected to operate in the Optimum moisture condition.

Step 2:

Plot the actual in-situ field collected data on the standard Balanced Pavement curves and select the Standard Balance Pavement Curve most closely associated with the behaviour of the existing pavement (Figure 32).

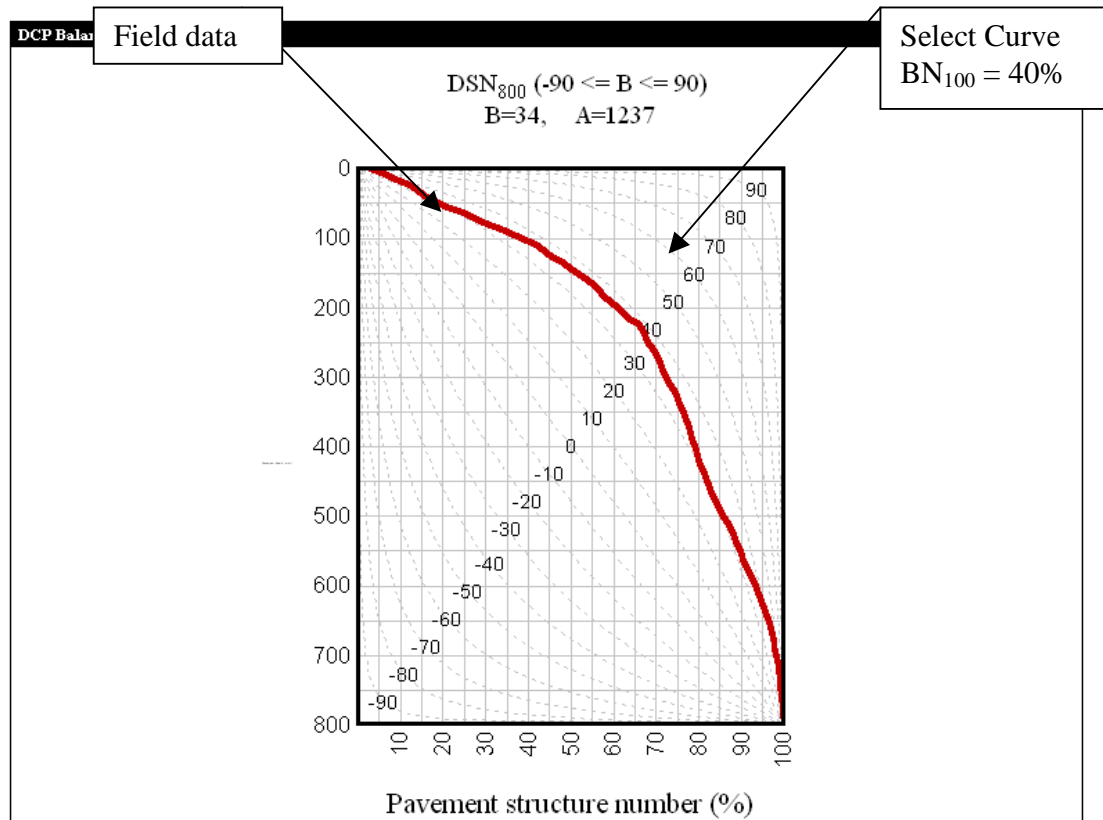


Figure 32: Selecting a standard pavement balance curve

This is done to maximize the existing structural capacity of the pavement and to make sure that a well-balanced structure will be built without any stress concentrations at layer interfaces. It is important to note that significant experience is required during this process. If for instance, the pavement is expected to operate in a wetter climate it might be more appropriate to select a shallower structure (for instance $BN_{100} = 50$) to make sure that the ingress of water does not destroy the main layers, which contribute the most to the structural capacity.

Vise versa, if the pavement is expected to operate where overloading and heavy vehicles are expected, a load sensitive pavement (with a $BN_{100} = 50$) might not be the most appropriate choice and a deeper structure ($BN_{100} = 30$) may be a more appropriate choice.

Step 3:

Using the $BN_{100} = 40$ curve, construct a sacrificial design pavement structure consisting of layers (each with the same structural strength) of 150mm thick. This design pavement is plotted to the right of the selected standard balance pavement curve. Read the corresponding BN_{100} values / layer off the graph for the various layers. This is shown in Figure 33.

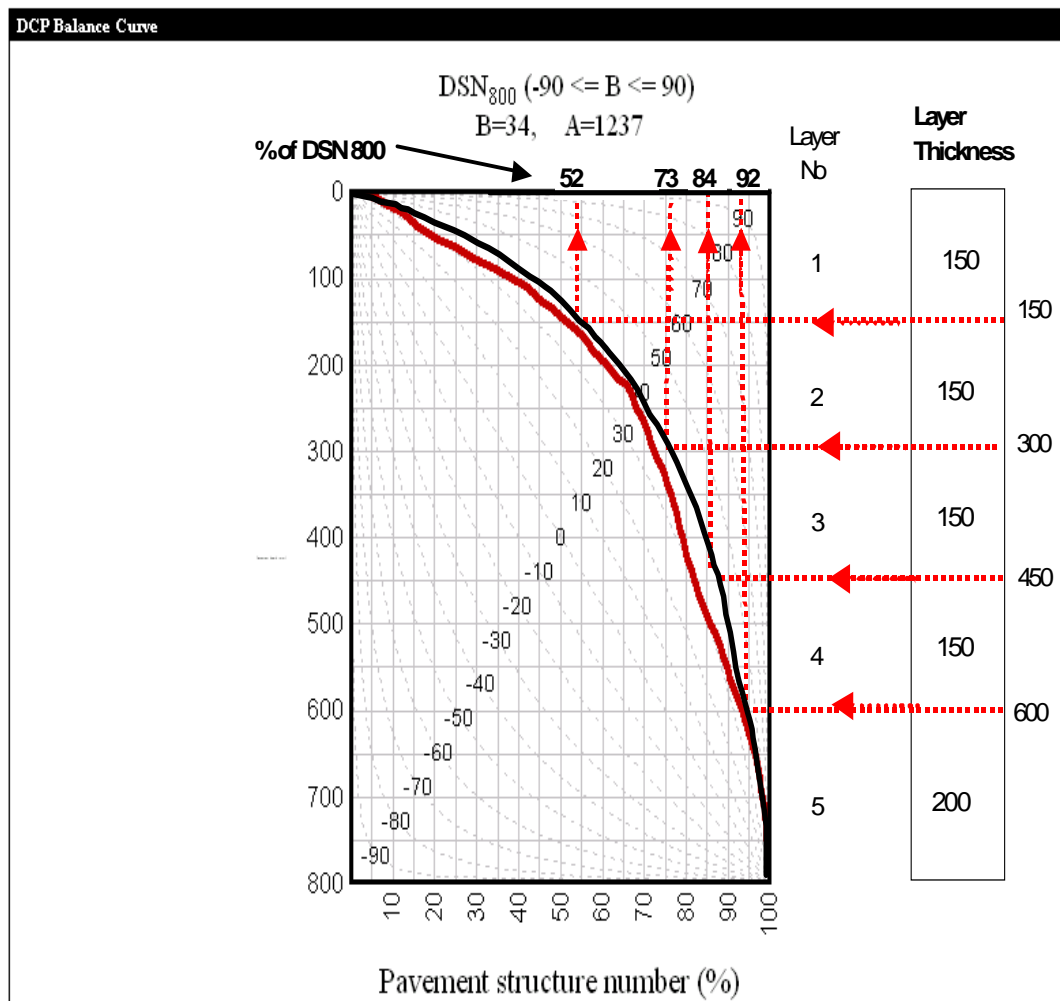


Figure 33: Pavement design using Balance Curve Concept

Step 4:

Read off the selected standard balanced pavement curve the percentage of DSN_{800} values for each 150 mm constructed pavement layer.

The percentage of the structural number (% of DSN_{800} number) to be taken up by each layer should then be determined:

Layer 1: 52%

Layer 2: $73\% - 52\% = 21\%$

Layer 3: $84\% - 73\% = 11\%$

Layer 4: $92\% - 84\% = 8\%$

Layer 5: $100\% - 92\% = 8\%$

Step 5:

Tabulate all values and calculate the required DN (penetration rate) values for each pavement layer. This is illustrated below in Table 6:

Step 6:

Plot the required Layer Strength graph for the sacrificial pavement which is designed to carry 0.5 million E80s (Figure 34).

It is also possible to determine the required penetration rate per layer using the relationships between CBR or UCS and DCP penetration rate. This procedure is only recommended if the designer of the pavement has a good knowledge and feel for CBR and UCS values of pavement materials used for all traffic classes and layer depths.

Step 7:

Superimpose the layer strength diagram of the in-situ field data on to that of the design pavement (Figure 35).

Using a similar approach to that discussed in the first method of this section, a rehabilitation strategy can be determined. Using the above example it is clear that the top 150 mm has insufficient structural strength (the penetration rate of the in-situ material is higher than the required) as its in-situ penetration rate plots to the left of that required.

Table 6: The determination of the required DN values per layer

Layer number	Layer Thickness	DSN800 = 119 Blows	% of DSN800 per layer	Required DN (mm/blow)
1	150		52 (52 - 0)	$\frac{150}{52/100 \times 119} = 2.4$
2	150		21 (73 - 52)	$\frac{150}{21/100 \times 119} = 6.0$
3	150		11 (84 - 73)	$\frac{150}{11/100 \times 119} = 11.5$
4	150		8 (92 - 84)	$\frac{150}{8/100 \times 119} = 15.8$
5	200		8 (100 - 92)	$\frac{200}{8/100 \times 119} = 21.0$

As in the earlier example, various rehabilitation strategies can be followed:

- a) The top layer of material may be removed and replaced by imported better quality material.
- b) Strengthening of the top 150mm can also be achieved by adding an overlay of good quality material. For instance, it is possible to only rework and compact the top 75 mm of the pavement and add a 75 mm overlay of sufficient strength.

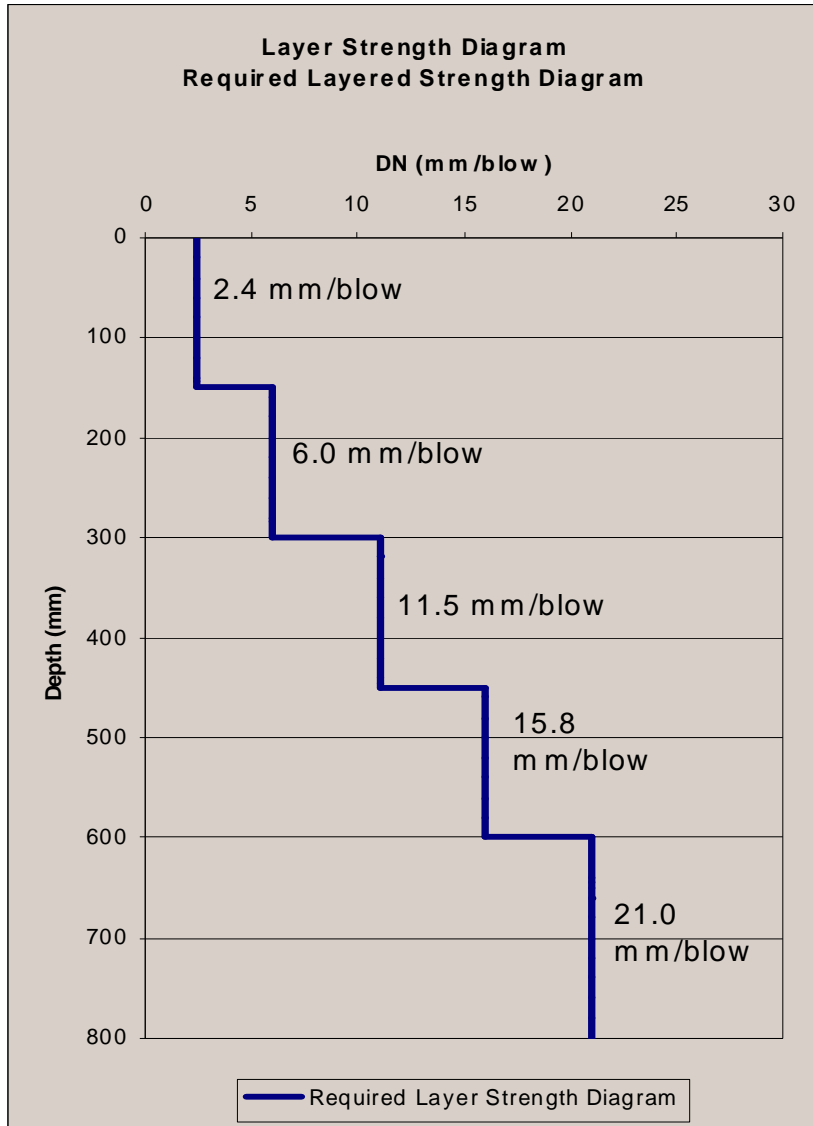


Figure 34: Layer Strength Diagram for the design pavement

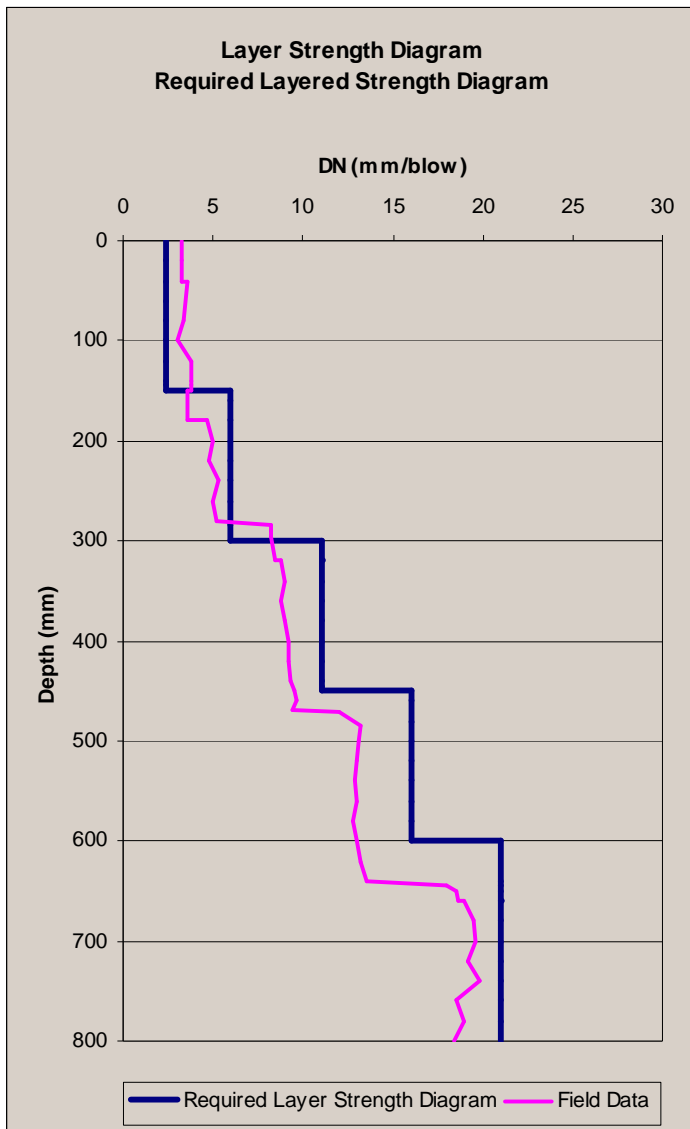


Figure 35: Layer strength diagram of field data

Calculating the cover requirement using nomograms

This method is similar to a procedure based on CBR measurements. The DCP penetration rates determined are used to classify the adequacy of the materials in depth in terms of the cover requirements of the material. Using the nomogram in Figure 36, the cover requirement can be determined for a known design traffic loading and a known DCP layer-strength diagram.

The nomogram can also be used to determine the required DCP penetration rate at certain depths within the pavement. The required rate of penetration can then be superimposed on the measured layer-strength diagram, as shown in Figure 37. Figure 37 illustrates the requirements for an expected future traffic load of 1.2×10^6 E80s. The sections of the measured DCP profile lying to the right of the required DCP profile are of inadequate quality. Similar to the design method described in the previous sections, strengthening can either be obtained through the improvement of the quality of the material in the existing pavement or by adding an overlay of good quality material to the pavement or by a combination of the options. When a stabilised layer is added, the required quality of the layer should be verified using the procedure described earlier.

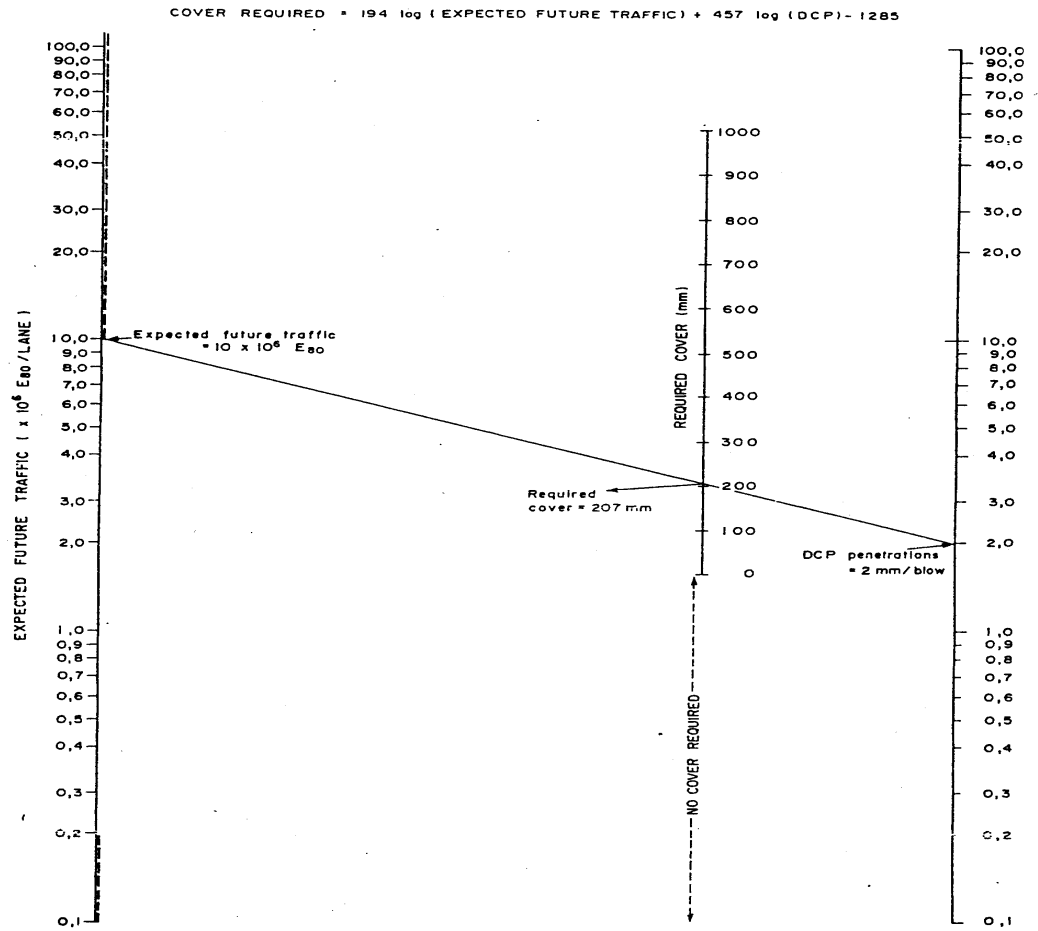


Figure 36: Nomogram to determine required cover

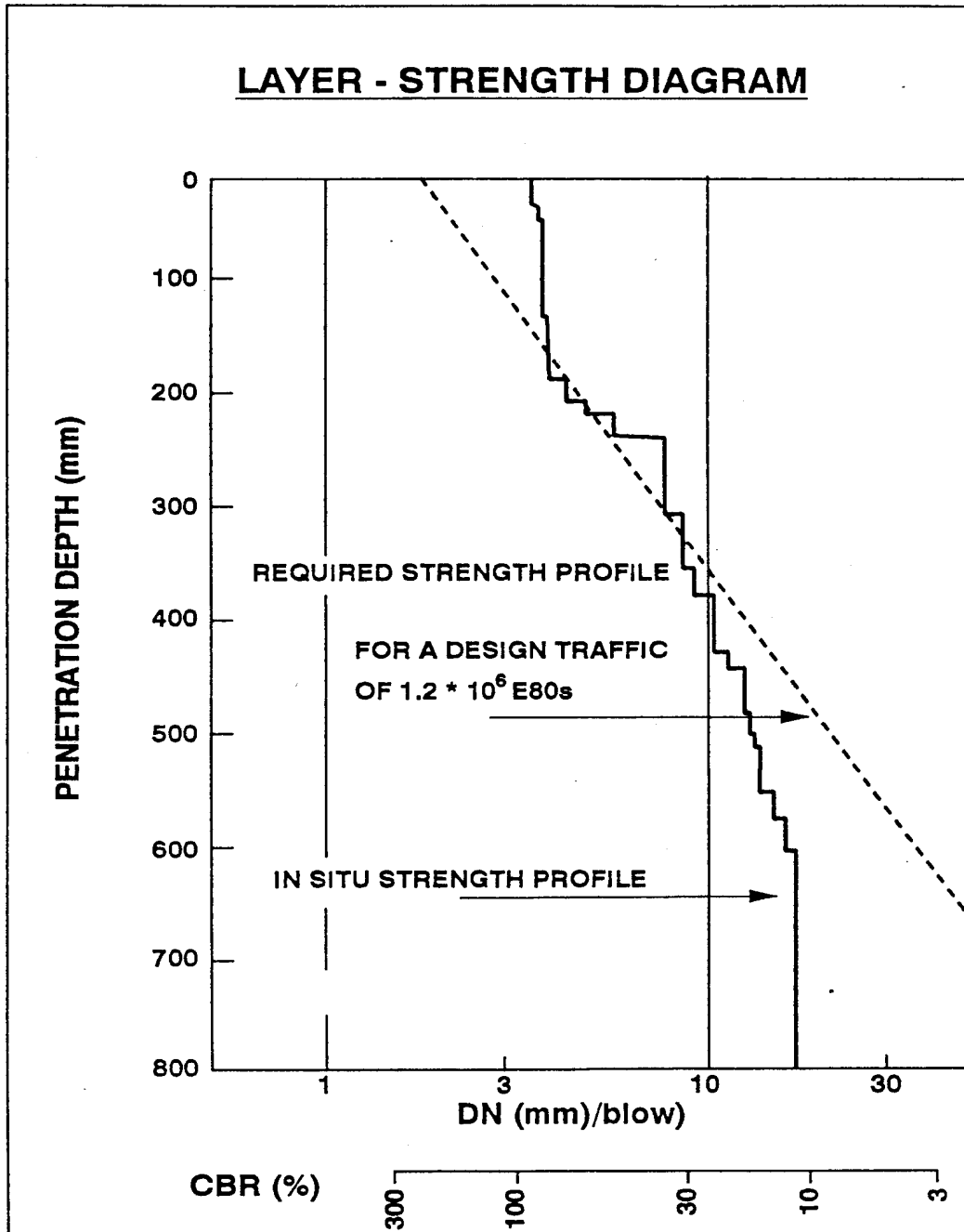


Figure 37: Pavement requirements (as DN) for 1.2×10^6 E80s

Rehabilitation design using material strength parameters

Using all of the empirically derived relationships between DCP penetration rates and CBR, UCS and layer stiffness (E-modulus), it is possible to do a successful rehabilitation design based on any of these design parameters.

For instance using the stiffness modulus it is possible to do a full rehabilitation design using the South African Mechanistic Design Method¹⁹. A full study of the South African Mechanistic Design Method is outside the scope of this course. However, material properties such as layer thicknesses, stiffnesses and position within the pavement for use in mechanistic analyses can all be estimated using DCP data.

Rehabilitation design using CBR/UCS and E modulus parameters do not, however, form part of this workshop. The reader is encouraged to study TRH 12²⁵ and other documents¹⁵ for more information regarding this.

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