Lessons learned during regular monitoring of in situ pavement bearing capacity conditions

P Paige-Green
CSIR Built Environment, Pretoria, South Africa

ABSTRACT: An investigation into the temporal variations of various pavement properties has been carried out in South Africa with regular monitoring over a period of one year. This involved the measurement of moisture content, in situ strength and pavement deflection at designated points on each road. The investigation involved nine low volume roads consisting of a thin natural gravel base course on the in situ subgrade, sealed with thin surface dressing bituminous seals. The roads were selected to represent various climatic and drainage conditions with the main objective being to assess the variation in road performance in relation to the seasonal moisture fluctuations. During analysis of the results it became apparent that a number of problems occurred with the data collection. This paper discusses the lessons learned from these problems and means of overcoming them in similar investigations.

1 INTRODUCTION

Between 1990 and 1994, the performance of a large number of roads with light pavement structures in South Africa was assessed in significant detail (Paige-Green, 1996; 1999). These roads were all low volume roads (generally less than 100 000 standard axles), mostly consisting of thin layerworks (generally a natural gravel base course of 100 to 150 mm with or without a 150 mm subbase on the in situ subgrade), sealed with thin bituminous surface dressings. All of the sections had unsealed shoulders and many had marginal quality base course materials, by conventional standards. The investigation included comprehensive investigations into the pavement material properties and designs, construction quality, traffic loadings and the consequent functional and structural performance of each pavement, with all of the results being incorporated into a large database. The functional, structural and traffic properties were subsequently re-assessed in 1995 and 1998.

In 2001 and 2002, a follow-up investigation was carried out on a selection of these roads to assess the effect of seasonal moisture changes on the bearing capacity of the pavements. Sections of nine of the roads, covering a range of climatic (Thornthwaite Moisture Index of -20 to 20, Emery, 1992), drainage and surface conditions were selected for this monitoring over a one year period. These results were analyzed and made available to a third party for use in a larger project, but have never been published.

Recently, a similar but much larger and more widespread investigation has been initiated. As part of the preparation for this project, the original database and analysis has been revisited in order to eliminate some of the shortcomings and problems encountered previously. This paper summarizes some of the problems identified and makes recommendations for avoiding a repetition of them in the current investigation.

2 FIELD TESTING

The 2001/2002 investigation was essentially designed to assess the effect of the seasonal moisture changes on the structural performance of the thin pavement structures. In addition to the large database previously acquired and which was used to characterize each pavement, a program of fieldwork including a series of testing and sampling to provide the necessary information over a full annual rainfall cycle was designed. Each section was monitored seven times during the 12 month cycle. Full deflection bowls were measured using a Deflectograph, a single Dynamic Cone Penetrometer (DCP) test was done and samples of each pavement layer (base, subbase, where one was present, and subgrade) were collected for moisture content determinations during each monitoring trip. If no subbase was present, the upper 150 mm of the subgrade was considered as a subbase in the following discussion.

All testing was carried out in the outer wheel tracks of the road, i.e., that part of the road expected to be most affected by environmental variations, and attempts were made to test and sample as close to the designated point on each road section as possible, ensuring that disturbance of the pavement was minimal and did not affect subsequent measurements. All sample holes and DCP penetration points were repaired with cold-mix asphalt to ensure the exclusion of moisture from the pavement.

During the original fieldwork in the period 1989 to 1991, in situ testing and sampling was carried out in both wheel tracks as well as between the wheel tracks (in an attempt to assess the untrafficked/original material properties and the construction quality) of the heaviest trafficked lane of the road. All testing for this project was carried out as close to the original sample holes as was practically possible without being influenced by the patching of the sampling holes made earlier. The following investigation procedures were used. Some of the important parameters relative to this paper are summarized in Table 1. In situ densities were generally in the range 96 to 101 per cent of AASHTO T 180 compaction.

Table 1. Summary of selected road and material properties.

Road No	Base thickness (mm)	Subbase thickness (mm)	Thornthwaite's Moisture Index	Optimum Moisture Content (%)	Traffic (ESALs)
D540	100-135	No subbase	-2	15.1	13 000
D467	120-130	No subbase	-10	7.2	38 000
D2485	115-125	No subbase	-20	10.4	8 800
D404	85-100	70-80	-20	8.4	5 800
D132	220-265	No subbase	-20	8.7	8 700
D514	80-100	90-100	20	11.5	55 000
D518	150-200	No subbase	20	7.4	13 200
D646	160-250	No subbase	20	7.2	10 500
D466	160-180	No subbase	20	9.0	14 700

The measured densities of all of the base courses were between 96 and 101% AASHTO maximum dry density.

2.1 *Moisture content*

Samples for the gravimetric determination of moisture content were taken using a 50 mm diameter hand auger at depths representing the base course (50 to 125 mm), the subbase where it existed (150 to 225 mm) and the subgrade (below 300 mm) in the outer wheel track. The sample sizes varied between 0.2 and 1.0 kg, depending on the material type and consistency. All samples were then oven-dried to constant mass at 105°C and the loss in mass as a percentage of the sampled mass was determined as the moisture content. Although the primary objective of the exercise was to assess variations in the subgrade moisture content related to precipitation, the moisture contents of the base (and subbase where present) were determined as samples of these materials were necessarily removed to obtain the underlying subgrade samples.

Immediately after each of the samples was collected on site, they were sealed in moisture content tins with masking tape and dried in laboratory ovens on return to the laboratory (usually within 72 hours). Care was taken to ensure that the sample tins were handled to minimize damage or moisture loss.

2.2 *Pavement deflections*

Pavement deflection measurements were taken over a length of between 100 and 300 meters at each section during each visit, with the position of the original sampling site about midway. Deflections were recorded using the CSIR Deflectograph in both the inner and outer wheel paths. The Deflectograph tests the deflection with tire inflation pressures of 690 kPa and an axle load of 80 kN on a dual wheel axle at a speed of about 8 km/h. This equipment generally records between about 17 and 23 deflections per 100 meters travelled (depending on the friction between the road and the beam during placement) and the results are comparable with deflections measured using a Benkelman Beam. A full deflection bowl is measured with sensors recording the peak deflection and the deflections at distances of 127, 305, 610 and 915 mm from the peak measurement between the dual wheels and one measurement 100 mm behind the peak reading.

For analysis purposes, the peak deflection reading in the outer wheel track at the last point before the sample hole was reached was used. In addition, the mean and 90th percentile values for the 10 readings before and after the sample point were also determined (a distance of about 50 meters). The Middle Layer Index (MLI), normally indicative of the contribution of the subbase to the total deflection, but in these cases more indicative of the subgrade, is defined by the difference in deflections at offsets of 305 and 610 mm (Horak, 1988).

As any pertinent detail on or adjacent to the road was manually recorded on the Deflectograph printout (including the exact position of the sample point) it was possible to determine that the actual location of the deflection measurement could in reality vary from the required point by up to about 3 meters.

2.3 *Dynamic Cone Penetrometer (DCP) testing*

A Dynamic Cone Penetrometer (DCP) test was carried out during each site visit with the primary intention of assessing the impact of changes in the pavement moisture content on the strength of the layer and subgrade materials and the entire structural capacity of the road. The results were all plotted using a modified version of the CSIR Transportek WinDCP 5.01 analysis program (CSIR Built Environment, 2008).

DCP testing was carried out by measuring the penetration depth after every 5 blows, down to a depth of at least 800 mm. The number of blows to reach this depth is defined as the DCP structural number (DSN_{800}) and was determined for each test. In addition, the weighted mean penetration rates for the base and subbase of each section were determined as an indication of the material strength in the base and subgrade. Although the penetration rate was used in all analyses, this can be converted to a California Bearing Ratio (CBR) value using any of the standard models (Paige-Green and Du Plessis, 2008).

2.4 *Other details*

Monthly rainfall statistics for some months preceding the monitoring and during the monitoring period were obtained from the South African Weather Bureau for their stations nearest to the selected road sections. The rainfall recorded at the stations over the monitoring period (12 months) varied between 330 and 1110 mm.

3 SUMMARY OF RESULTS

The summary statistics of the results are provided in Tables 2, 3, 4 and 5.

3.1 *Rainfall*

The mean rainfall for each road over the project period compared with the long-term mean data from the nearest weather stations is summarized in Table 2.

Table 2. Summary of rainfall data.

Road No	Mean (mm)	Project period (mm)	Deviation from mean (%)
D540	621	611	-1.6
D467	621	330	-46.9
D2485	640	617	-3.6
D404	600	791	31.8
D132	600	644	7.3
D514	700	1110	58.6
D518	895	970	8.4
D646	895	970	8.4
D466	900	970	7.7
Average	719	779	7.8

The average rainfall during the monitoring period was slightly above the long term averages although the individual variations were high (-46.9 to +58.6%). Figures 1a and b show the rainfall at each site versus average rainfall for all of the sites. Although there are significant individual variations during the dry season, the trends are similar with two particularly wet periods. The variations in monthly rainfall outside these periods are generally less than about 60 mm.

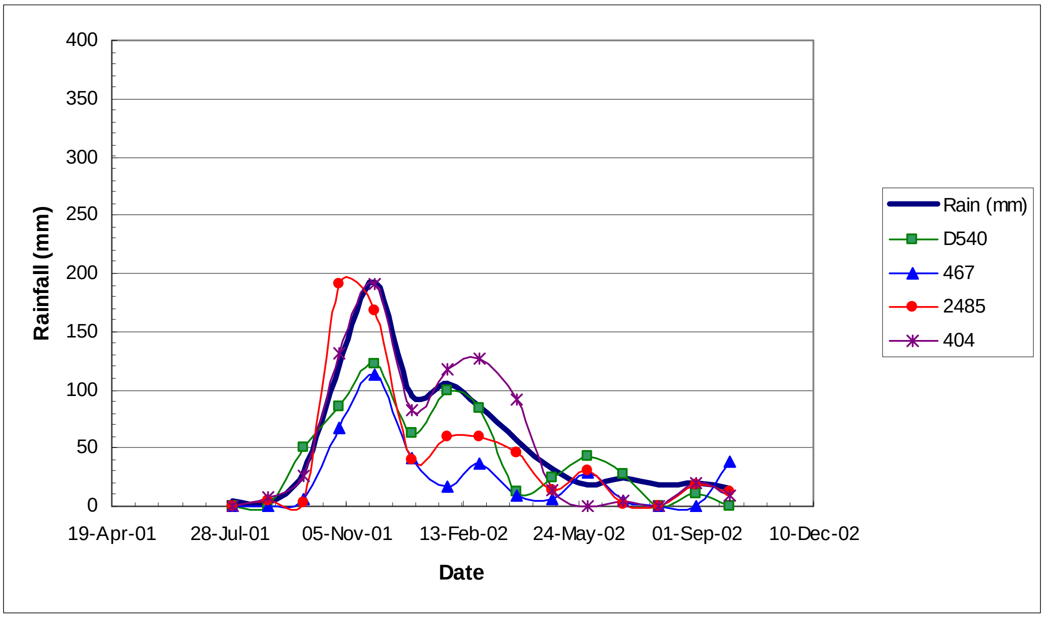


Figure 1a. Plots of rainfall at each site versus average rainfall (Rain) for sites D540, D467, D2485 and D 404

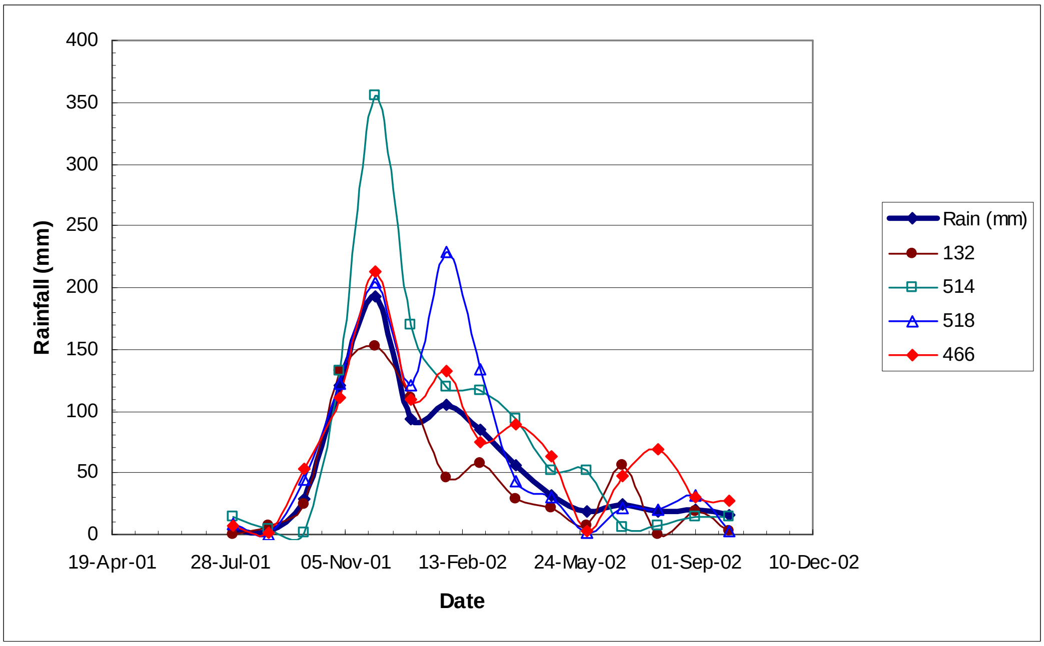


Figure 1b. Plots of rainfall at each site versus average rainfall (Rain) for sites D132, D514, D518 and D466 (D646 has same rainfall as D466)

3.2 *Moisture content*

The maximum, minimum and mean moisture contents for the bases and subgrades of each section over the duration of the monitoring (7 individual results per section) are summarized in Table 3. The table also includes the ratio of these values to the standard optimum moisture content (AASHTO T180) for each of the layers in each road (in parentheses) and the total variation in moisture content (around the mean) over the monitoring period.

Table 3.Summary of moisture content data.

Layer	Road No	Moisture content (%) with % of OMC in parenthesis			
		Mean	Min	Max	Variation*
Base	D540	15.8 (100)	14.6 (92)	17.4 (110)	18
	D467	7.5 (103)	6.5 (89)	8.3 (114)	24
	D2485	11.3 (112)	9.7 (96)	13.1 (130)	30
	D404	7.4 (85)	5.7 (66)	8.7 (100)	41
	D132	11.2 (123)	8.3 (91)	12.4 (136)	37
	D514	7.8 (68)	6.9 (61)	8.8 (77)	24
	D518	8.5 (123)	7.2 (104)	11.1 (161)	46
	D646	8.7 (150)	7.8 (134)	9.1 (157)	15
	D466	16.0 (90)	13.0 (73)	18.0 (101)	31
Sub-grade	D540	11.0 (126)	9.0 (103)	12.0 (138)	27
	D467	11.5 (121)	9.1 (96)	14.6 (154)	48
	D2485	16.3 (89)	10.7 (58)	25.4 (139)	90
	D404	7.0 (91)	6.0 (78)	7.8 (101)	26
	D132	11.1 (132)	9.7 (115)	12.8 (152)	28
	D514	12.0 (93)	6.6 (51)	14.7 (114)	68
	D518	10.3 (86)	8.6 (72)	11.3 (95)	26
	D646	9.7 (71)	8.0 (58)	13.5 (99)	57
	D466	10.6 (85)	8.3 (67)	11.8 (95)	33

3.3 *Deflection*

The ranges of deflection data for each road collected over the monitoring period are summarized in Table 4. These include the peak deflection, the mean and 90th percentile peak deflections of the 10 readings each before and after the monitoring points and the Middle Layer Index (MLI). The total variations in these properties over the monitoring period are also summarized.

Table 4.Summary of Deflection data.

Deflection property	Road No	Deflection (mm)			
		Mean	Min	Max	Variation*
Peak deflection	D540	0.92	0.64	1.2	61
	D467	1.05	0.85	1.19	38
	D2485	1.63	1.40	1.84	27
	D404	0.57	0.33	1.09	133
	D132	1.72	1.42	2.08	38
	D514	2.34	1.73	2.91	50
	D518	0.67	0.49	0.86	55
	D646	1.05	0.93	1.26	31
	D466	0.57	0.52	0.64	21
Mean peak deflection	D540	0.85	0.68	1.12	52
	D467	1.06	0.87	1.16	27
	D2485	1.88	1.71	2.01	16
	D404	0.45	0.35	0.61	58
	D132	1.64	1.44	1.83	24
	D514	2.16	1.88	2.58	32
	D518	0.77	0.67	0.87	26
	D646	1.03	0.88	1.12	23
	D466	0.53	0.47	0.58	21
90th Percentile peak deflection	D540	0.97	0.76	1.28	54
	D467	1.18	1.00	1.30	25
	D2485	2.23	2.06	2.49	19
	D404	0.56	0.41	0.88	84
	D132	1.87	1.72	2.04	17
	D514	2.67	2.36	3.07	26
	D518	0.87	0.79	1.00	24
	D646	1.13	0.97	1.26	26
	D466	0.62	0.53	0.71	29
Middle layer index (MLI)	D540	0.35	0.17	0.59	120
	D467	0.27	0.19	0.39	74
	D2485	0.56	0.41	0.90	88
	D404	0.15	0.09	0.20	73
	D132	0.48	0.36	0.57	44
	D514	0.85	0.58	1.18	71
	D518	0.28	0.15	0.43	100
	D646	0.29	0.08	0.42	117
	D466	0.21	0.15	0.24	43

* - variation about the mean during monitoring cycle (max-min / mean %)

3.4 *Dynamic Cone Penetrometer data*

The DCP data are summarized in Table 5. These include the mean DSN_{800} and the DCP penetration rates (DN) of the base and subgrade of all of the monitoring data for each pavement.

Table 5.Summary of DCP data.

Property	Road No	DCP parameters			
		Mean	Min	Max	Variation*
DSN_{800}	D540	147	118	189	48
	D467	115	85	173	77
	D2485	109	66	185	109
	D404	109	90	128	35
	D132	77	33	109	99
	D514	87	62	142	92
	D518	96	84	113	30
	D646	104	80	142	60
	D466	89	64	107	48
Mean		103			66
Base strength (DN) (mm/bl)	D540	5.85	2.54	7.70	88
	D467	4.31	3.49	5.49	46
	D2485	7.88	6.87	8.56	21
	D404	3.99	3.13	7.00	97
	D132	6.84	4.25	14.74	153
	D514	3.89	2.43	5.74	85
	D518	5.14	4.06	6.17	41
	D646	5.13	4.00	6.99	58
	D466	7.09	5.16	9.78	65
Mean		5.6			72
Subgrade (DN) (mm/bl)	D540	7.1	5.5	8.0	35
	D467	10.5	5.0	16.8	112
	D2485	8.9	4.9	14.9	112
	D404	17.0	14.5	19.7	31
	D132	20.2	11.0	47.0	178
	D514	16.5	14.4	19.7	32
	D518	12.1	10.4	13.9	29
	D646	13.9	10.4	18.9	61
	D466	18.9	16.1	21.6	29
Mean		13.9			71

* - variation about the mean during monitoring cycle (max-min / mean %)

4 ANALYSIS AND DISCUSSION

The data collected were analyzed in a variety of ways in an attempt to understand the influence of the moisture on the bearing capacity and structural performance of the pavements. Each pavement was analyzed individually and the investigations included, among other comparisons, the following, which are discussed in this paper:

- Relationships between rainfall and base and subgrade moisture contents with time;
- Influence of base and subgrade moisture content on peak deflection and MLI;
- Relationship between base and subbase moisture contents and DSN_{800}.

4.1 *Relationships between rainfall and base and subgrade moisture contents with time*

Figures 2a and b show typical examples of the relationships obtained. In general the trends were poor and often opposite to those that would be expected. Typically a lag between the (high) precipitation and an increase in moisture content was observed, the lag time being anything from 2 weeks to about 3 months. In general, a similar lag time was observed for the base and the subgrade, but in a number of cases, the subgrade lag was slightly longer.

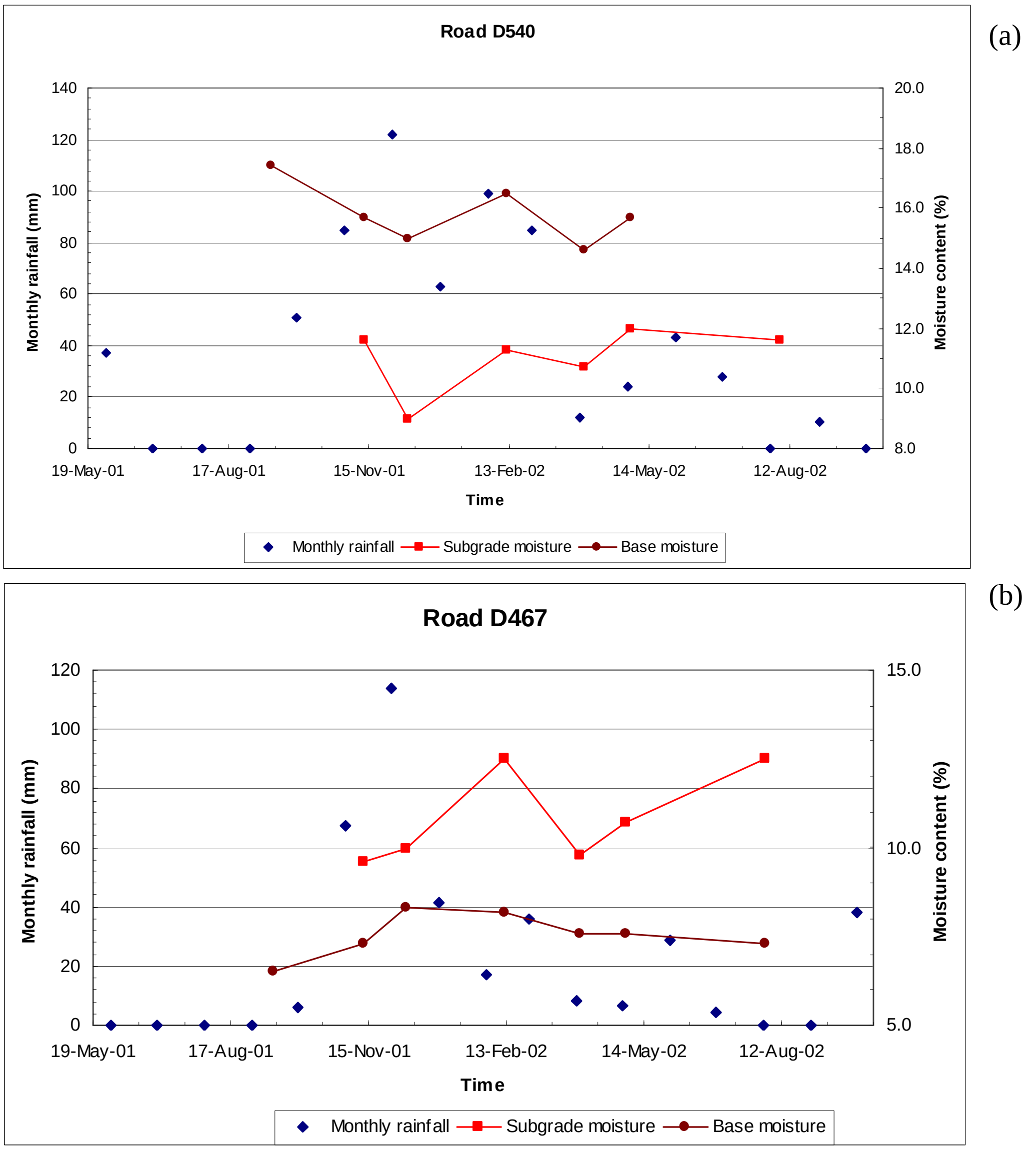


Figure 2a & b. Examples of relationships between rainfall and base and subbase moisture contents

Not all of the results, however, showed such trends. A number of the roads showed no definite increases in pavement layer moisture content while some even showed decreases in the moisture content after the maximum rainfall periods. No relationships could be established between moisture changes and time lags and the conditions of the seal (i.e. cracked or uncracked) or shoulders.

4.2 *Influence of base and subgrade moisture content on peak deflection and MLI*

The relationship between the moisture contents and peak deflection value and the MLI for two roads are shown in Figures 3a & b. It is clear that no typical values or strong trends in line with expectations were obtained.

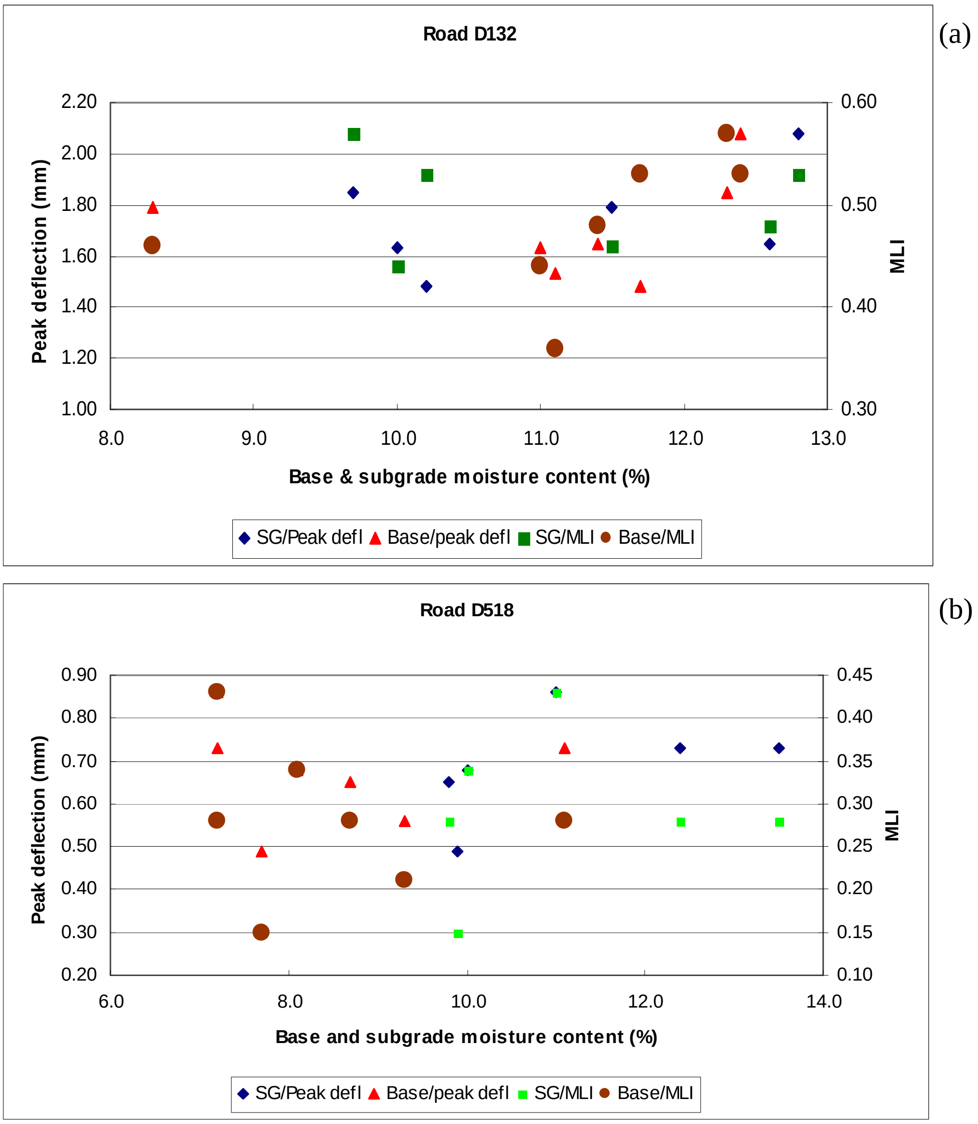


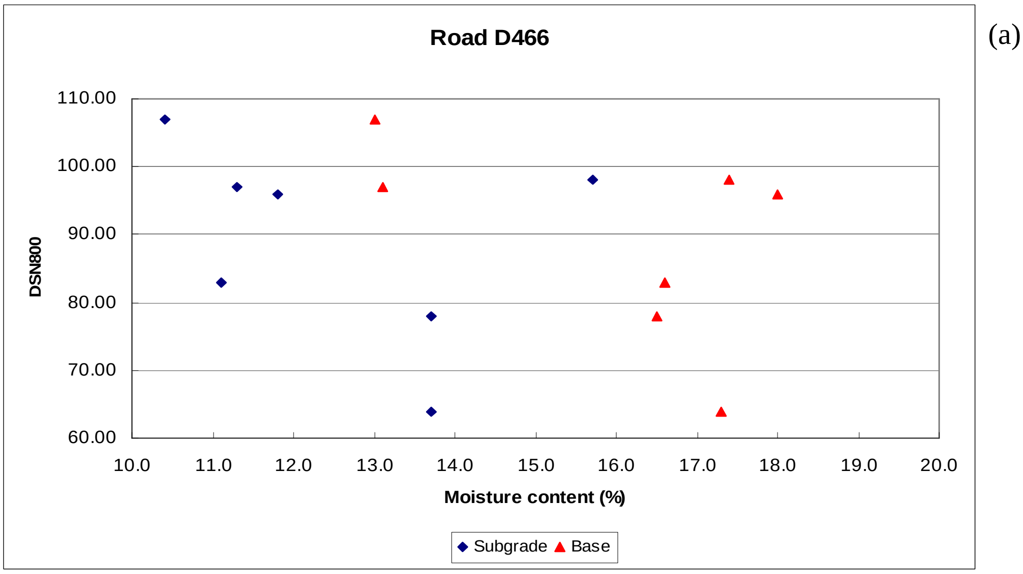
Figure 3a & b. Examples of relationships between the moisture content in the base and subbase and the peak deflection and MLI

Different trends are evident: The peak deflections on Road D132 show a general trend to increase with increasing base and subgrade moisture content as would be expected. The MLI tends to increase as the base moisture content increases but unexpectedly shows little trend as the subgrade moisture content increases. Road D518, a generally stronger road shows a weak trend for the peak deflection to increase with increasing base and subgrade moisture content, but the MLI shows little relationship with either the base or the subgrade moisture content. It should, however, be remembered that the pavement structure below 600 mm also contributes to the peak deflection: experience during this project has shown that a large proportion of the deflection originates in the subgrade but this has not been investigated in this paper.

4.3 *Examples of relationships between base and subbase moisture contents and DSN_{800}*

The influence of the base and subbase moisture contents on the DCP structural number (DSN_{800}) was investigated and typical results are shown in Figures 4a &b.

Again, contradictory conclusions were manifested in some of the sections. A decrease in structural number and layer strength with increasing moisture content would typically be anticipated. This was a general trend for road D499 (Figure 4a) although the highest moisture content value for both the base and subbase did not follow this trend on Road D466. No real trend was noted for Road D132 (Figure 4b).



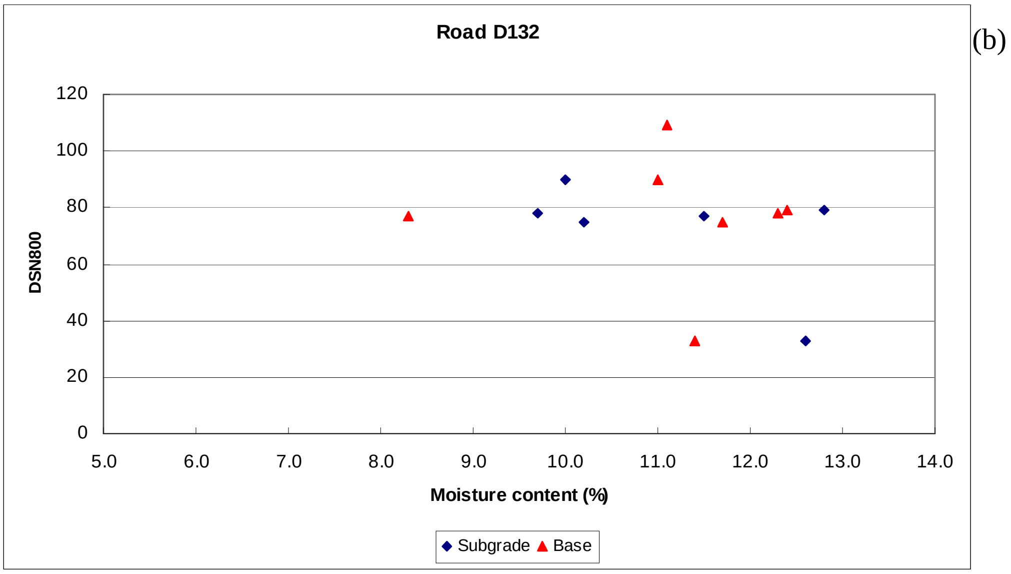


Figure 4a & b. Examples of relationships between the moisture content in the base and subbase and the DCP structural number (DSN_{800})

5 PROBLEMS OBSERVED AND LESSONS LEARNED

Although general trends were observed in the data, it was obvious that the repeatability of the measurements was not always that desired. The problems are aggravated by the need to minimize the area of road disturbed, the possible effects of sample sites on the structural performance of the road and the need to remove samples and test sites as close as possible to each other in order to cancel the effect of natural material and construction variability. Analysis of the data indicated the following problems, which should be considered in any similar project.

5.1 *Moisture content*

The samples taken for moisture content determination were generally between 0.2 and 1.0 kg. For fine materials the sample sizes seemed to be adequate, but many of the materials sampled contained large particles (often between 25 and 50 mm), which biased the moisture content determination significantly, these essentially dry materials comprising a large proportion of the sample mass. It is thus imperative that larger samples are collected when the material is coarse. This can, however, be a problem when the samples are removed using a hand auger and the pavement layers are thin. The inherent variability of natural gravels is well-known and thus requires that samples be obtained as close as possible to each other. It is thus important to take more than one sample where possible.

It is, however, recommended that means of determining the in situ moisture content without disturbing the layer are used for a proper result. This would entail the installation of durable and repeatable sensors, a number of which are appearing on the market. Experience with nuclear density probes (not undisturbed), small ceramic psychrometers and various tensiometers has proved unsatisfactory. Techniques using capacitance measurement, time domain reflectometry or fiber-optic systems should be investigated for use, but their long-term durability, repeatability and calibration still needs to be critically assessed.

5.2 *Pavement deflection*

It is suggested that devices such as the Falling Weight Deflectometer (FWD) or possibly the lightweight FWD systems be used to assess the pavement deflection. The depth of influence of the lightweight FWD needs to be carefully assessed and compared with conventional deflection measurements. It is also not clear what effect repeated testing at the same point using an FWD has on the properties of the pavement at that point – are compaction effects accumulated or not? The use of a traditional Benkelman Beam of course allows the deflection at an exact location to be determined.

5.3 *Dynamic Cone Penetrometer testing*

Although the DCP test is almost non-destructive, there is no doubt that the penetration and removal of the device does affect the material immediately surrounding the test point. Tests should thus be carried out at least 100 mm from each other and the test hole sealed after extraction of the tool. A single large stone can have a significant effect on the result and it is suggested that not less than two tests be carried out to get a reasonable average result. Even this may not be sufficient to account for material variability in natural gravels and only long-term averages can provide a realistic result.

It would be expected that a strong relationship exists between the deflection and DSN_{800}. Figure 5 shows the relationship obtained from all of the roads. It is clear that although the expected trend is generally observed, certain roads do not follow the trend. It is not clear at this stage whether this is the result of testing variability or the effect of deflections resulting from the subgrade beneath the 800 mm zone tested with the DCP.

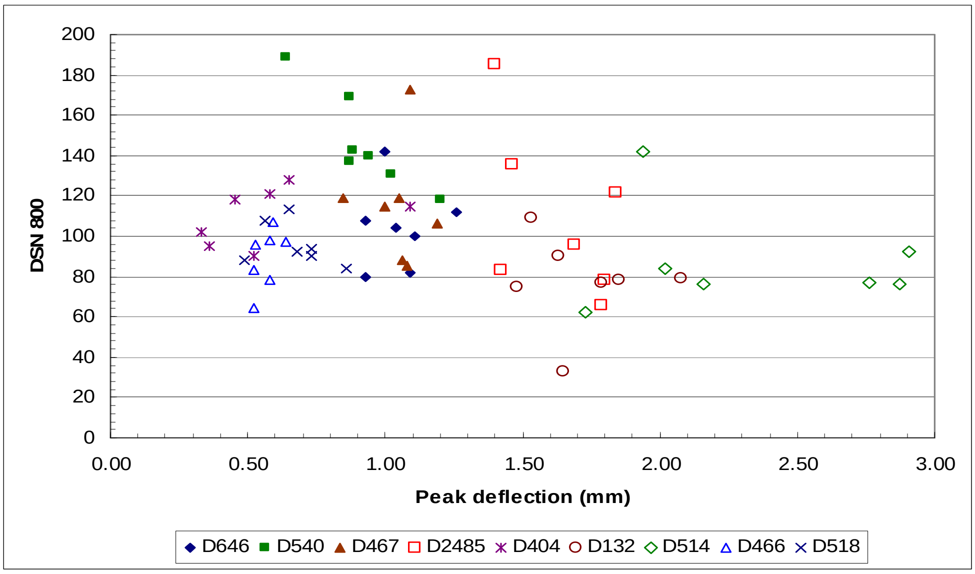


Figure 5. Plot of DSN_{800} against Peak deflection for all roads investigated

5.4 *Rainfall*

In tropical and sub-tropical areas rainfall can be highly localized with significantly different rainfalls occurring at sites only tens of meters distant from each other. It is thus important that rainfall recording stations are established as close as possible to individual sites. Acts of vandalism usually make this impracticable, and it is recommended that residents or farmers as close as possible to the site be requested to maintain rainfall records during the investigation period for the evaluation process.

6 CONCLUSIONS

During the planning of an extensive and widespread investigation into the effects of climatic factors on road pavements, a re-assessment of an existing database developed on a smaller scale was carried out. This indicated a number of problems regarding repeatability of measurements and properties which need to be overcome in order to obtain a comprehensive and accurate data base for the current project. The lessons learned are related to the problems of monitoring rainfall, pavement moisture content, deflections and structural data which are critical to such investigations. Methods for overcoming them need to be identified, proved in practice and implemented in order to ensure repeatable and comparable data are obtained for analysis.

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