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Prediction of Subgrade CBR using FWD for Thin Bituminous Pavements

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Abstract: Deflection based models developed by Jameson, Roberts et al and Queensland Department of Transportation and Main Roads are commonly used for predicting the subgrade CBR of asphalt pavements. The models utilise Falling Weight Deflectometer (FWD) deflection D_{900} recorded at 900 mm from the centre of the loading plate. The principal aim of the study is to enhance the prediction of the in-situ subgrade CBR using FWD for granular pavements with thin bituminous layers. The scope of the study included the comparison of subgrade CBR predictions from the three deflection based models and the predictions were verified using the in-situ CBR values derived from Dynamic Cone Penetrometer (DCP) from eleven pavement test sites. The study shows that the three models over predict the subgrade CBR because the deflections recorded at sensor D_{900} are consistently small. It is observed the impact load has little influence on the deflection at D_{900} for pavements with asphalt layer less than 50 mm. The inherent non-linearity behaviour of the thin pavement structure is also the reason for the discrepancies in the predictions. Consequently, a new predictive model is developed utilising the FWD deflection D_{450} observed at 450 mm from the impact load.

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***Key words**: Deflection based model, Falling Weight Deflectometer; Non-linearity of pavements; Subgrade CBR,*

Introduction

Falling Weight Deflectometer (FWD) is widely used by highway agencies worldwide for network level deflection survey for assessing the rate of pavement deterioration and to determine the timing for rehabilitation. FWD is a non-destructive deflection measuring device which became a popular pavement testing tool since the 1980s. Pavement surface deflection measurements provide valuable information on the structural condition of pavement systems [1]. FWD and Heavy Weight Deflectometers (HWD) are trailer mounted devices that record half deflection bowls at discrete test points on the pavement surface by measuring surface deflection at distances ranging from 0 mm to a user defined maximum (normally 1,500 mm, but up to 2,400 mm) from the centre of an impulse test load. This is achieved by applying a standard loading plate normally 300 mm in diameter by a falling weight on road pavement surface while the FWD or HWD device is at rest. The FWD produces an essentially half-sine single impact load 25-30 ms in duration, which corresponds to a moving wheel load [2]. It has been shown that deflections measured by the Dynatest FWD correspond closely to those measured for a moving wheel load at a same load level [3].

Considerable research has been devoted largely to the study of the application of FWD test results for pavement structural evaluation and for back-calculation of layer moduli of in-service pavements. The role of the non-destructive testing device in pavement evaluation of composite pavements has been reported by [4]. FWD deflection measurements on asphalt surface after completion of pavement construction were performed by Rahim & George [5]. The objective of the FWD tests was to obtain back-calculated subgrade moduli (E_{back}), with the pavement structure in place, and compare those values with the subgrade Resilient Modulus (E_{lab}) determined in the laboratory. In the study, it was found that for the back-calculated subgrade moduli are larger than the corresponding laboratory values. For fine-grain soils the ratio of E_{back}/E_{lab} was calculated to be 1.40 on an average. The E_{back}/E_{lab} ratio for the coarse-grain soil was found to be higher with an average value of 2.0.

Nazzal and Mohammad [6] carried out a study to develop regression models to predict the resilient modulus of subgrade soils from results of FWD backcalculated modulus for application in the design of pavement and overlays. The study examined the ratio between the FWD backcalculated moduli (E_{FWD}) and the laboratory measured resilient moduli (M_r) and evaluate the effect of the method of backcalculation on this ratio. Three backcalculation software packages were used to interpret the FWD data, namely, ELMOD 5.1.69, MODULUS 6 and EVERCALC 5.0. The study concluded that the E_{FWD}/M_r ratio varied from 0.51 and 8.10 for the tested subgrade soils. Furthermore, the ratio was higher at lower M_r values and hence weaker subgrade soils. The maximum adjustment factor value of 0.33, recommended by AASHTO to compute the M_r design from E_{FWD}, was found to be suitable for Louisiana subgrade soils and other subgrade soils with similar properties. The study also concluded that the E_{FWD}/M_r ratio was significantly affected by the backcalculation method. In general, ELMOD 5.1 software yielded significantly lower ratio values than the other methods.

Several State Road Authorities in Australia have developed methods for estimating subgrade CBR values from FWD deflection data [7]. These methods are generally empirically based and can

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provide indicative values for certain pavement types such as unbound granular pavements with thin bituminous surfacing. The deflections recorded at sensor D_{900} located 900 mm from the centre of the loading plate are used in the models. Deflection based models developed by Jameson (1993) [8], Roberts et al (2006) [9] and Queensland Department of Transportation and Main Roads (1992) [10] are commonly used for predicting the subgrade CBR in Southeast Queensland (SEQ). The models utilise FWD deflection data recorded at sensor D_{900} from the impact load. The principal aim of this study is to enhance predictions of subgrade CBR for thin bituminous pavements. The typical thickness of the granular layer of the pavements varies from 160 to 250 mm and the asphalt layer varies from 30 to 50 mm. A total of eleven test sites in Brisbane City with such pavement construction have been identified for the study. The scope of the study included the followings:

- Comparing the subgrade CBR predictions obtained from the three deflection based models;
- Developing a new deflection model using FWD deflection data at D_{450} sensor location; and
- Validating the predictions of the newly derived deflection model using the in-situ CBR values derived from Dynamic Cone Penetrometer (DCP).

Deflection Based Models

Three deflection based models commonly used in Australia are models which were developed by Jameson (1993), Roberts et al (2006) and Queensland Department of Main Roads (QDMR, 1992). Jameson developed the following relationship for predicting subgrade CBR from analysis of a wide range of road pavements in Hong Kong.

$$CBR_{subgrade} = 1836.54(D_{900})^{-1.018} \quad (1)$$

Where D_0 = peak deflection at 700 kPa (microns), $CBR_{subgrade}$ = California Bearing Ratio of subgrade (%) and D_{900} = deflection at 900 mm from centre of loading plate (micron).

Roberts (2006) demonstrated that the material strength of subgrade layer can be estimated using FWD deflection. It was shown that material strength of the subgrade layer of a pavement is related to the behaviour of outer fringes of the deflection bowl, largely independent of the shape of the inner parts of the bowl. The structural deflection data were sourced from FWD testing at 700 kPa impact load. Using the FWD data collected on a project in Australia, a relationship was derived, directly linking the subgrade CBR (as estimated from test pits by DCP) with the FWD D_{900} deflection value. The relationship is shown in Eq. (2).

$$CBR_{subgrade} = 850(D_{900})^{-1} \quad (2)$$

where the deflections are in microns and the FWD impact pressure is 700 kPa, $CBR_{subgrade}$ = California Bearing Ratio of subgrade (%) and D_{900} = the FWD deflection observed at 900 mm from the load centre (micron).

The third deflection based model was developed by the Queensland Department of Main Roads (QDMR). This model is currently used by Brisbane City Council (BCC) for evaluating the subgrade response using D_{900} deflection data. The subgrade response is reflected at D_{900} and is relatively independent of the pavement structure of overlying pavement. For pavements without bound, thick asphalt or rigid layers, the D_{900} deflection has been found to reflect a subgrade response that remains essentially unaffected by the structure of the overlying pavement and has been used to estimate the subgrade CBR at the time of testing (QDMR, 1992) [10]. This relationship is shown in Eq. (3).

Table 1. Target FWD Test Loads and Corresponding Surface Stresses [11].

Target Test Load (kN)	Corresponding Surface stress (kPa)	Rounded Surface Stress (kPa)
35	495	500
40	499	550
50	707	700

$$CBR_{subgrade} = 0.5996(D_{900})^{-1.4543} \quad (3)$$

where $CBR_{subgrade}$ = California Bearing Ratio of subgrade (%) and D_{900} = the FWD deflection observed at 900 mm from the load centre (mm).

Methodology

DCP and FWD were conducted to assess the subgrade CBR of the eleven pavement test sections selected from the road network in Brisbane City. Thirty DCP test points were carried out at thirty FWD test locations along the test sections. From pavement coring, the thickness of the asphalt layers was found to be between 20 to 50mm. The granular base layers vary from 160 to 200 mm in thickness. For the pavements, FWD deflection basins were measured and reported at distances of 0, 200, 300, 450, 600, 900 and 1500 mm from the centre of the test load. These deflections are denoted as D_0, D_{200}, D_{300}, D_{450}, D_{600}, D_{900} and D_{1500} respectively. The deflections as far as possible from the centre of the applied load are recommended and preferably up to 1500 mm offset distance. The deflections at large offsets would allow a good presentation of a full extent of the deflection basin. In this study, deflection D_{900} was used in estimating the subgrade CBR by using the three models specified in Eqs. (1), (2), and (3). A new predictive model was developed utilising the FWD D_{450} deflection data at 450 mm from centre of loading plate. The rationale of using deflection at D_{450} in the predictive model will be explained in the following section.

Three repeat 'drops' were conducted at each test point, with the data from the third 'drop' was used for reporting and analysis purposes. The measured deflections were then 'normalised' to the appropriate surface stress, to correspond with operating tyre pressures. Deflections from FWD testing were 'normalised' to the relevant target load by multiplying the measured deflections by the ratio of the target load to the actual load. With a standard 300 mm diameter loading plate, each target load corresponds to a specific surface stress, as shown in Table 1.

The Queensland Department of Transport and Main Roads (QTMR) Pavement Rehabilitation Manual [12] specifies that deflection and back-analysis results must be corrected to the average working temperature of the pavement for the particular location. This average working temperature is referred to as the Weighted

Mean Annual Pavement Temperature (WMAPT). For design expediency, WMAPT zones have been derived for the Queensland state. The Manual stipulates that for pavements with asphalt with a total thickness of less than 50 mm no temperature correction is required.

Dynamic Cone Penetrometer (DCP) is the direct field method used to estimate the subgrade CBR for cohesive soils in accordance with Australian Standard AS 1289.6.3.2 (1997) [13]. As the penetration cone is driven through the subgrade layer of pavement, for each drop of the standard weight and the penetration is measured in mm/blow. Austroads (2008) [14] presented the correlation between CBR value and DCP test for fine-grained cohesive soils as shown in Fig. 1.

Brisbane City Council (BCC) has developed an empirical correlation between DCP penetration and subgrade CBR specifically for use within Brisbane area. The correlation is shown in the following equation [15]:

$$CBR_{subgrade} = 83.048(DCP)^{-0.7191} \quad (4)$$

where CBR = subgrade CBR value (%) and DCP = DCP penetration (mm/blow).

A comparison of subgrade CBR predictions obtained from the three deflection based models and the in-situ CBR values derived from DCP was then carried out.

Discussion of Results

Thirty boreholes were drilled at the FWD test point locations in the eleven test sections. Soil profiles from the boreholes indicate the pavements consist of 30 to 50 mm asphalt over 165 to 250 mm granular base layer. The subgrade layers for eight test sites consist predominantly of clay with traces of sand. According to the AASHTO Soil Classification System [16], the soil is classified as A-2-7 and is described as clayey sand. The Liquid Limits (LL) in the sites ranging from 48 to 68, Plastic Limits (PL) range from 22 to 27 and Plastic Index (PI) from 26 to 41. The moisture content of the subgrade ranges from 10.8 to 18.8%. The subgrade soil at Test Site No. 11 consists of high plasticity clay with PL, PI and LL of 15, 60 and 75 respectively. The soil is classified as A-7-5. Test sites No.5 and 9 consist of silty sand with the AASHTO Soil Classification as A-2-4. The in-situ subgrade CBR values of the test sites were determined using the BCC's CBR-DCP model as shown in Eq. (4). The CBR values were determined to be between 3 to 23 percent (see Table 2). The subgrade CBR values are consistent with the subgrade soil types with CBR vary from 8 to 23% for clayey sand soil and 3% for clayey soil.

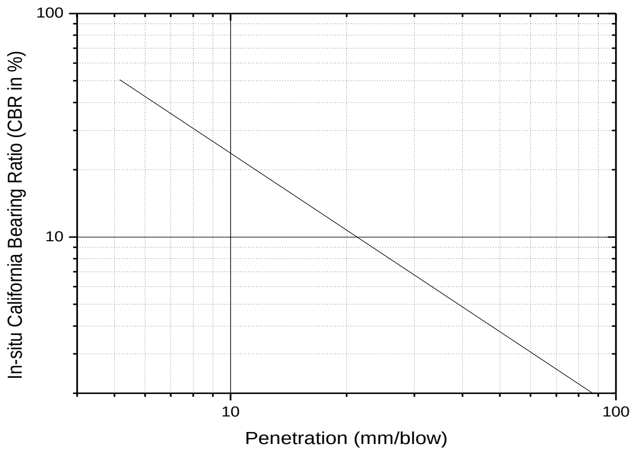

Fig. 1. Correlation between DCP and Subgrade CBR [14].

The deflection data generated by the FWD device at the eleven Test Sections (TS) are presented in Table 3 and the deflection basins for TS2, TS3, TS6 and TS10 are depicted in Figs. 2 to 5. The D_0 deflection varies from 465 micron (0.465 mm) to 2,515 microns (2.515 mm). For D_{450}, the deflection is reported to be between 110 (0.110 mm) to 734 microns (0.734 mm). Relatively small deflections were recorded at the D_{900} sensors. At this sensor location, the deflection varies from 11 (0.011 mm) to 118 microns (0.118 mm) and is nearly identical despite the increase in the deflection in D_0. These are particularly obvious for Test Sites No.1 to 6. The same trends were also observed for deflections at sensors D_{600} and D_{1500}. One reason for these consistently small deflections is the dynamic affect of the FWD load which influences mainly the pavement materials near the impact load at the time of contact. The deflection basins show that the radius of influence zone for the thin granular pavements (with bituminous layer less than 50 mm) is about 450 mm from the impact load. This distance is between 1.5 to 2.0 times

Table 2. Comparison of the Subgrade CBR with Different Deflection Based Models.

Test Sections	Subgrade CBR (%) derived from the deflection based models					AASHTO Soil Classification
	TMR(1993)	Jameson (1996)	Robert (2006)	New Model	In-situ CBR from DCP	
1	165	83	41	17	16	A-2-7
2	423	160	77	24	23	A-2-7
3	177	87	42	10	12	A-2-7
4	103	60	29	19	20	A-2-7
5	73	47	23	20	20	A-2-4
6	69	45	22	15	15	A-2-7
7	22	20	10	8	8	A-2-7
8	50	36	18	14	13	A-2-7
9	56	39	19	16	16	A-2-4
10	42	32	16	11	13	A-2-7
11	13	14	7	4	3	A-7-5

Table 3. FWD Deflections at the Test Sites.

Test Sections	FWD Deflection (Micron or mm x 10^{-3})						
	D_0	D_{200}	D_{300}	D_{450}	D_{600}	D_{900}	D_{1500}
1	642	472	291	155	79	21	8
2	681	479	310	110	51	11	10
3	1044	719	515	264	70	20	17
4	523	383	259	145	83	29	13
5	465	320	222	132	81	37	21
6	653	464	322	179	77	38	23
7	1876	1278	786	314	116	84	69
8	476	350	274	189	126	48	18
9	704	467	317	170	93	44	27
10	743	573	403	233	136	54	25
11	2515	1902	1363	734	348	118	88

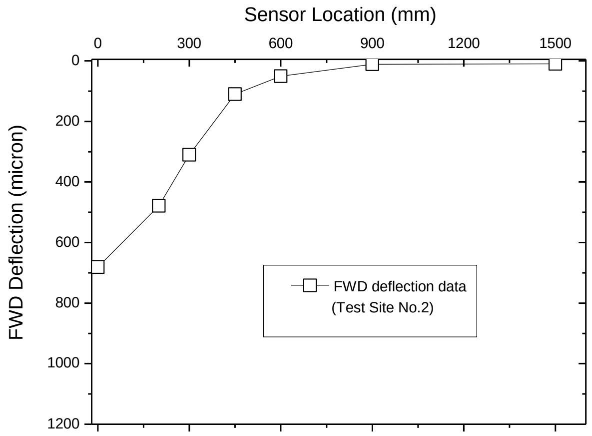

Figure 2: Deflection basin at Test Site No.2

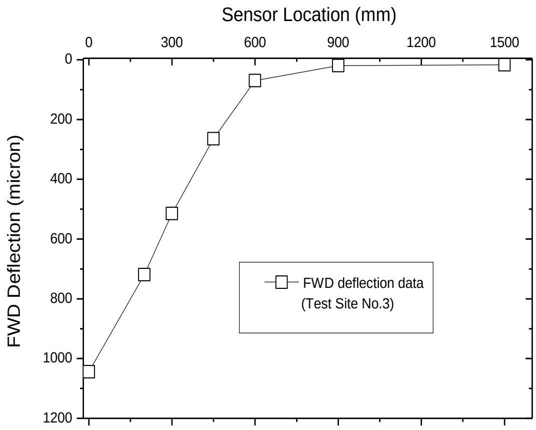

Figure 3: Deflection basin at Test Site No.3

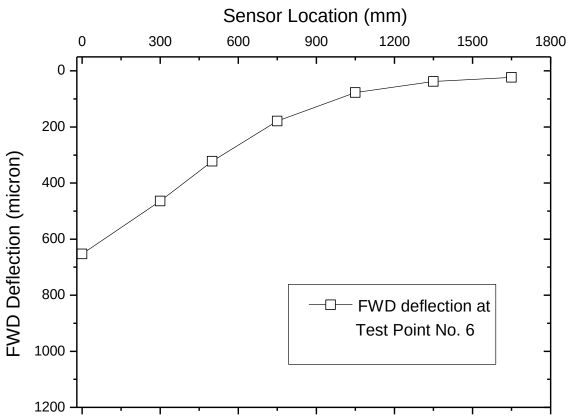

Figure 4: Deflection basin at Test Site No.6

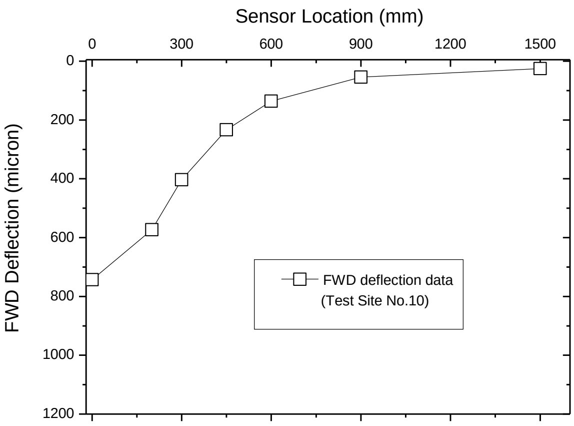

Figure 5: Deflection basin at Test Site No.10

the total thicknesses of pavement layers. This is evidenced from the deflections at D_{200}, D_{300}, and D_{450} which show an increase of deflection as the D_0 deflection increases. The deflections at D_{600}, D_{900} and D_{1500} do not show a similar pattern of response.

It is also observed that deflection basins from D_0 to D_{300} exhibit linear behaviour because the Deflection Ratios (DR) for D_0/D_{200} and D_{200}/D_{300} are nearly identical. The average deflection ratios are calculated to be 1.40 to 1.46 respectively. In the study of the FWD deflection characteristics of composite and sandwich pavements [17], it was found that when the DR values for D_0/D_{200}, D_{200}/D_{300}, D_{450}/D_{600} and D_{600}/D_{900} are nearly identical, linearity of the subgrade materials were observed. However, if the DR values were highly variable the subgrade material is said to be non-linear. The average DR for D_{450}/D_{600} and D_{600}/D_{900} are 2.13 and 2.78 (see Table 4). These variable DR values indicate that the deflection basins for sensor locations D_{600} and D_{900} are non-linear. The main observation from these deflection characteristics is that the deflection basins recorded at sensors beyond D_{450} exhibit non-linearity behaviour.

The non-linearity behaviour of the subgrade materials were analyzed by computing the Surface Modulus using Boussinesq's

Table 4. FWD Deflection Ratio (DR).

Test Sections	FWD Deflection Ratio (D_i/D_j)				
	D_0/ D_{200}	D_{200}/ D_{300}	D_{300}/ D_{450}	D_{450}/ D_{600}	D_{600}/ D_{900}
1	1.360	1.622	1.877	1.962	3.762
2	1.422	1.545	2.818	2.157	4.636
3	1.452	1.396	1.951	3.771	3.500
4	1.366	1.479	1.786	1.747	2.862
5	1.453	1.441	1.682	1.630	2.189
6	1.407	1.441	1.799	2.325	2.026
7	1.468	1.626	2.503	2.707	1.381
8	1.360	1.277	1.450	1.500	2.625
9	1.507	1.473	1.865	1.828	2.114
10	1.297	1.422	1.730	1.713	2.519
11	1.322	1.395	1.857	2.109	2.949
Average	1.401	1.465	1.938	2.132	2.778

equations [18] as shown below. The maximum deflection (D_0) underneath the centre of the load was used to compute the subgrade Surface Modulus as shown in Eq. (5) and the deflection recorded at sensors D_{200} D_{300}, D_{450}, D_{600}, D_{900} and D_{1500} were used for calculating the Surface Modulus as in Eq. (6).

$$E_0(0) = \frac{2\times(1-\nu^2)\times R\times\sigma_0}{D_0} \tag{5}$$

$$E_0(r) = \frac{(1-\nu^2)\times R^2\times\sigma_0}{r\times D_r} \tag{6}$$

where,

$E_0(0)$	=	Subgrade Surface Modulus at the center of the load (MPa)
$E_0(r)$	=	Subgrade Surface Modulus at a distance r (MPa)
ν	=	Poison ratio (0.35)
R	=	Radius of the plate (mm)
σ_0	=	Contact pressure (kPa)
r	=	Distance from the center of the loading plate (mm)
D_0	=	Deflection underneath the centre of the load (mm)
D_r	=	Deflection at the distance *r* (mm)

The Surface Modulus for Test Sections 2, 3, 6 and 10 are shown in Fig. 6. In all cases, the Surface Modulus decreases up to D_{300} sensor location and the graphs show an increasing trend beyond D_{450}. An explanation for this observation is that the subgrade material is linear elastic up to D_{450} sensor location. This is evidenced from the Surface Modulus which decreases as the stress level decreases at a distance about 450 mm from the the center of the loading plate. Beyond D_{450}, the Surface Modulus increases as the stress level decreases confirming non-linearity behaviour of the subgrade materials.

In view of the inherent characteristics of the deflection basins exhibited by the thin bituminous pavements, D_{900} deflection would not be a reliable data for use in predicting the subgrade CBR. If D_{900} deflection is used in the modeling the subgrade CBR, the model would over predict the CBR values because very small deflection data (<0.100 mm) are recorded by the D_{900} sensor. The new model developed in the current study using the deflection at sensor D_{450} is presented in Eq. (7).

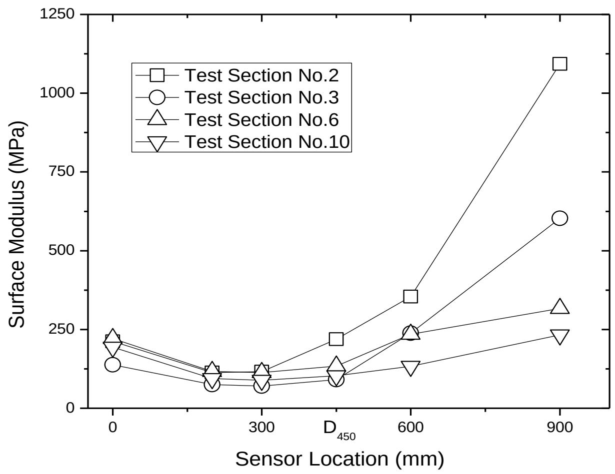

Fig. 6. Surface Modulus at Sensor Locations.

$$CBR_{subgrade} = 2.6523\ (D450) - 1.001 \tag{7}$$

where, $CBR_{subgrade}$ = California Bearing Ratio (%) and D_{450} = FWD deflection recorded by sensor located at 450 mm from the impact load (mm). Fig. 7 to 10 show the relationships between the subgrade CBR derived from FWD D_{900} deflection versus the CBR obtained from DCP test. The graphs in Figs. 7 and 8 show that Jameson and Robert's models yielded the R^2 values of 0.50 and Root Mean Square Error (RMSE) of 55.4 percent and 20.5 percent respectively. These statistical data indicate a moderate correlation. QDMR model yielded an R^2 value of 0.40 and relatively high RMSE value of 143.4 percent (Fig. 9). The study shows that Jameson (1993) [8] and Roberts et al (2006) [9] generated CBR predictions with moderate R^2 values and RMSE. Reasonably good predictions were achieved by Robert's model for Test Sites 5 and 7. QDMR (1992) models provided CBR predictions with moderate R^2 values and high RMSE. In comparison, the new model has an R^2 value of 0.88 and a low RMSE value of 1.0 percent (Fig. 10) indicating a good correlation between the subgrade CBR obtained from FWD deflection D_{450} and that obtained from DCP test.

The study shows that Jameson and QDMR models over predicted the CBR values by a sizable margin of errors because the deflection at D_{900} are consistently small which ranges from 11 to 54 micron (0.011 to 0.054 mm) in most of the test sites. One reason for these consistently small deflections is the dynamic effect of the FWD load which influences mainly the materials of the thin asphalt pavement near the impact load (at distance equal or less than 450 mm) at the time of contact. On an average, the two models over predict the in-situ CBR by a factor of 2.6 and 3.6 respectively. Robert's model over predicts the CBR values by a factor of 1.30 on an average. When the D_{900} recorded a deflection of 11 micron (0.011 mm), the error in the prediction become large and the model over predicts by a factor of 3.35. As such, the three models which use D_{900} deflection data were found to be not suitable for predicting the subgrade CBR for thin bituminous pavements. The study shows that the deflection data at D_{450} yielded more reliable results and provided an enhanced prediction of subgrade CBR for this pavement type.

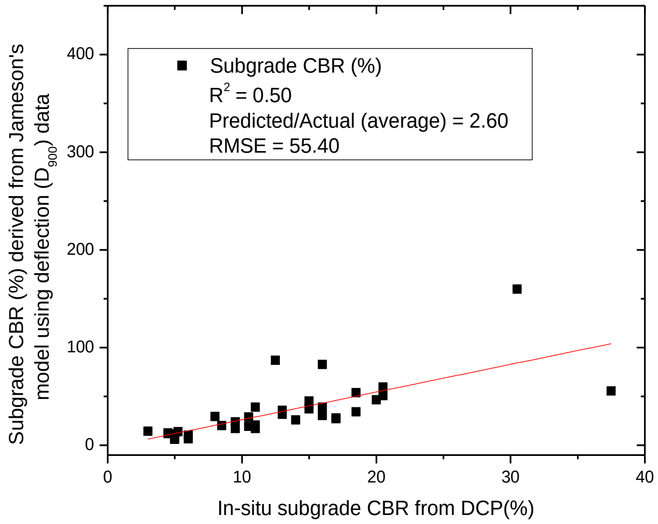

Fig. 7. Comparison of Jameson Model's Prediction with DCP Results.

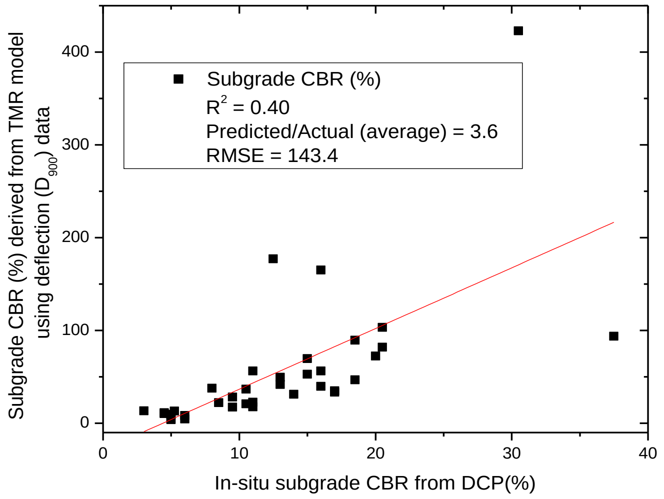

Fig. 9. Comparison of QDMR Model's Prediction with DCP Results.

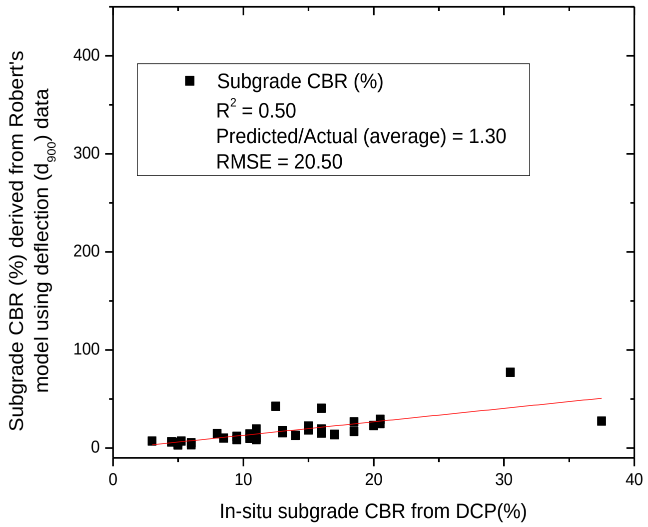

Fig. 8. Comparison of Robert Model's Prediction with DCP Results.

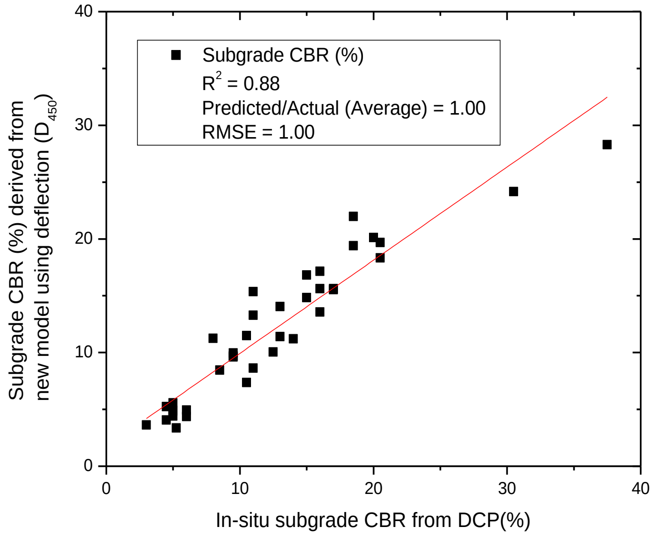

Fig. 10. Comparison of Newly Developed Model's Prediction with DCP Results.

Conclusion

The characteristics of the FWD deflection basins for thin granular pavements with bituminous layer less than 50 mm have been examined and the inherent properties of the deflection basins have been discussed. The assessment of the three deflection based models (Jameson, Robert and QDMR) has been carried out specifically for the thin granular pavements. The findings from the study are summarised as follows:

- The study shows that relatively small deflections were recorded at the D_{900} sensors. This is due to the dynamic affect of the FWD load which influences mainly the pavement materials near the impact load at the time of contact;
- The deflection basins show that the radius of influence zone for the thin granular pavements (with bituminous layer less than 50 mm) is about 450 mm from the impact load. This distance is between 1.5 to 2.0 times the total thickness of pavement layers;
- It is observed that deflection basins from D_0 to D_{300} exhibit linear behaviour because the Deflection Ratios for D_0/D_{200} and D_{200}/D_{300} are nearly identical. Whereas, the average Deflection Ratios for D_{450}/D_{600} and D_{600}/D_{900} are variable indicating non-linear behaviour at sensor locations D_{600} and D_{900};
- The non-linearity behaviour of the subgrade material was analyzed by computing the Surface Modulus using Boussinesq's equation. The results obtained from the Surface

Modulus plot show that the subgrade materials of the pavement sections exhibits non-linear elastic behaviour.

- The study shows that the three deflection based models over predict the subgrade CBR because of the relatively small deflections are recorded at sensor $D_{900;}$ As such, the three models which use D_{900} deflection data were found to be not suitable for use in predicting the subgrade CBR for thin bituminous pavements when small deflection (< 0.100 mm) is recorded at D_{900}.
- Utilising the D_{450} deflection data, the study shows that the deflection data at D_{450} yielded more reliable results and provided an enhanced prediction of subgrade CBR for thin bituminous pavements with asphalt layers less than 50 mm.

The new deflection model was developed for sites with predominantly silty sand, clayey sand and clayey soil with AASHTO Soil Classification types (A-2-4, A-2-7 and A-7-5). It is recommended that validation of the model be carried out when FWD deflection data are collected on pavement sites with different subgrade soils. In this manner, the model developed in the current study can further be refined through the various stages of the development.

Acknowledgement

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