Validation of Correlations Between a Number of Penetration Tests and In Situ California Bearing Ratio Tests

MOSHE LIVNEH

Previous papers have presented correlations among the dynamic cone penetrometer, the dynamic probing Type A, the standard penetration test, and the in situ California bearing ratio (CBR) test. As is known, these penetration tests are intended to determine, among other things, the bearing capacity of subgrades or of existing pavements without requiring the digging of test pits. This paper presents validation for these correlations as recently tested in four bearing capacity evaluations of subgrades and pavements on existing Israeli roads and airport runways. The analysis was made possible by simultaneously carrying out the above penetration tests in combination with the in situ CBR test after test pits had been dug. Results indicate that the existing correlations are valid for translating the values of the above penetration tests into in situ CBR values. In addition, the above investigations indicated the following: (a) the layer thicknesses obtained by means of the penetration tests plausibly correspond to the thickness obtained in the test pits, and (b) the friction that develops during penetration, or the effect due to the overburden pressure, does not significantly influence the final results. Finally, it should be noted that the experience that has accumulated until now regarding an evaluation method based entirely on the above penetration tests proves the feasibility of the method for regular use in other evaluation projects.

Previous papers (*1–5*) have presented correlations among the dynamic cone penetrometer (DCP), the dynamic probing Type A (DPA), the standard penetration test (SPT), and the in situ California bearing ratio (CBR) test.

These penetration tests are intended to determine, among other things, the bearing capacity of subgrades or of existing pavements without requiring the digging of test pits. Their ability to do away with test pits is their greatest advantage, reducing costs and minimizing traffic disturbances. Practically, these tests can be termed semi-nondestructive (semi-NDT) tests. Moreover, the direct in situ CBR test occasionally leads to considerable scatter of results, sometimes as high as a coefficient of variation of 60 percent (*4, 10*), leading to diminished predictive power. Therefore, in such cases, the above penetration tests are preferable, because their coefficient of variation is usually lower (*4, 10*).

Naturally, the correlative equations used to calculate the CBR value from the above test results are empirical ones, the validity of which must occasionally be tested. This paper presents validation of these correlations as recently tested in four investigations of subgrade and pavement bearing capacity on existing Israeli roads and airport runways. The analysis for this validation was made possible by simultaneously carrying out the above penetration tests and the direct in situ CBR tests after test pits had been dug. It was also possible to determine the subgrade DCP values by means of two methods: (1) the conventional method (i.e., penetration through the structural layers after drilling the asphalt core) and (2) inside the test pit, with penetration of the subgrade only. It thus became possible to determine the influence of friction development, or, alternatively, of the layer overburden pressure on the results.

In addition to examining the above correlations for use in calculating CBR values, it is also possible to compare the structural thickness values obtained by means of the penetration tests with those obtained through digging test pits.

Finally, the validation described in this paper is aimed at contributing to the issue of the applicability of the above penetration tests to subgrade and pavement evaluation—work whose practical value has been recently shown in Israel in a number of important site investigations, both in airfields and on urban roads.

DCP TEST

The DCP test is described in a number of works [e.g., a report by Kleyn (*6*)] and is therefore not included here. At the same time, the Israeli transformation equation from DCP to CBR values is slightly different from those presented in the technical literature (*3, 4*), and its expression for a 30° angle is

$$\log \text{CBR} = 2.20 - 0.71 (\log \text{DCP})^{1.5} \quad (1)$$

where DCP is the ratio between the depth of penetration in millimeters and the number of blows required to achieve such penetration, and CBR is the material's CBR in percent, corresponding to the depth of DCP penetration.

The above expression and other expressions have been compared in the technical literature (*3, 4*). This comparison indicates the plausible validity of Equation 1. Recently, however, an additional correlation obtained from field and laboratory studies has been published (*7, 8*), and an additional comparison with it is warranted. This correlation for a 60° cone angle is

$$\log \text{CBR} = 2.81 - 1.32 (\log \text{DCP}) \quad (2)$$

Table 1 presents the required comparisons for a number of

Transportation Research Institute, Technion-Israel Institute of Technology, Haifa, Israel.

typical DCP values. Table 1 also indicates that Equation 1 leads to CBR values that are approximately 15 percent higher than those obtained by means of Equation 2, for DCP values of approximately 15 mm/blow and upward. This increase stems from the fact, mentioned before, that the cone head angle is 30° in the test that leads to Equation 1 and 60° in the test that leads to Equation 2. The difference between the above two penetrometers, as obtained in a special investigation designed to assess it (*6*), was indeed of a similar order of magnitude. In addition, it is important to note that the advantage of Equation 1 is in the lower range of DCP values, where the CBR values calculated by means of this equation are more plausible than those calculated by means of Equation 2.

TABLE 1 COMPARISON OF CALCULATED CBR VALUES

	CBR (%)	
DCP (mm/blow)	Equation 1	Equation 2
100	1.6	1.5
50	4.2	3.7
25	10.6	9.2
15	19.7	18.1
10	30.9	30.9
5	61.0	77.2
1	158.5	645.7

SPT TEST

The SPT test is commonly used in site investigations for building foundations. The easy availability of this test makes it useful in determining pavement bearing capacity as well, especially in those cases where penetration by means of the DCP is difficult, or in cases where pavement thickness exceeds 800 mm (the maximum thickness at which the DCP test can be applied).

The equation for transforming SPT values into CBR values was presented by Livneh and Ishai in 1987 (*2*) and was then improved in 1988 (*5*). Now, after additional field data have been gathered, it is possible to determine the following recommended expression:

$$\log \text{CBR} = -5.13 + 6.55 (\log \text{SPT})^{-0.26}$$

$$N = 19$$

$$R^2 = 0.955 \qquad (3)$$

where SPT is the relationship between the depth of penetration in millimeters (300 mm) and the number of blows required for such penetration.

A description of the above equation and the results of the field tests are presented in Figure 1. The data in Figure 1 were used to formulate Equation 3. Finally, it is important to mention here that the applicability of this test is in the SPT

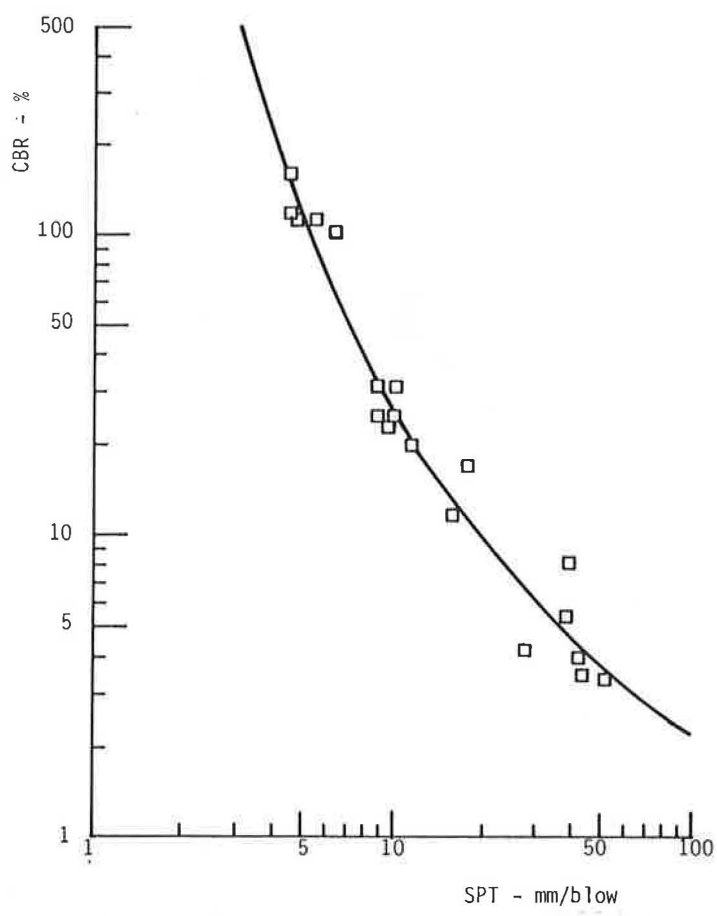


FIGURE 1 Relationship between calculated CBR from SPT-test and direct in situ CBR test.

range, corresponding to CBR ranges from approximately 15 percent to very high values.

DPA TEST

The DPA test is also used in site investigations for building foundations. A description of this test is presented by Bergdahl (9), and the recommended (5) transformation equation is

$$\log CBR = 2.20 - 0.45 [\log (3.47 \times DPA)]^{1.5} \quad (4)$$

where DPA is the relationship between the depth of penetration in millimeters (200 mm) and the number of blows required for such penetration.

It is important to note that the applicability of this test is in the DPA range corresponding to the CBR range from very low values up to approximately 20 percent (5). Its obvious advantage lies in the fact that it also allows determination of subgrade strength in existing pavements of great thickness (for example, in airfield pavement structures).

TESTING FOR CORRELATION VALIDATION

Mahanaim Airfield

In an investigation of a runway for light aircraft, which was conducted at the Northern Israeli Mahanaim Airfield, all of the above penetration tests were carried out in combination with the direct in situ CBR test after test pits had been dug in the existing pavement. The subgrade of this runway consists of clay mixed with fine gravel, and some measure of scatter is therefore expected in its characteristics. Its AASHTO classification is A-7-6 with a liquid limit of up to 70 percent.

The CBR results obtained in the direct test, with a surcharge of 409 N (90 lb), are compared with the CBR results computed from the various penetration test values using Equations 1, 3, and 4. This comparison is presented in Figure 2. It should be mentioned in this context that the CBR values appearing in Figure 2 were calculated from the DCP values and include both the DCP test conducted on the pavement surface after drilling asphalt cores and the DCP test conducted inside the test pits. Figure 2 indicates that the results of all

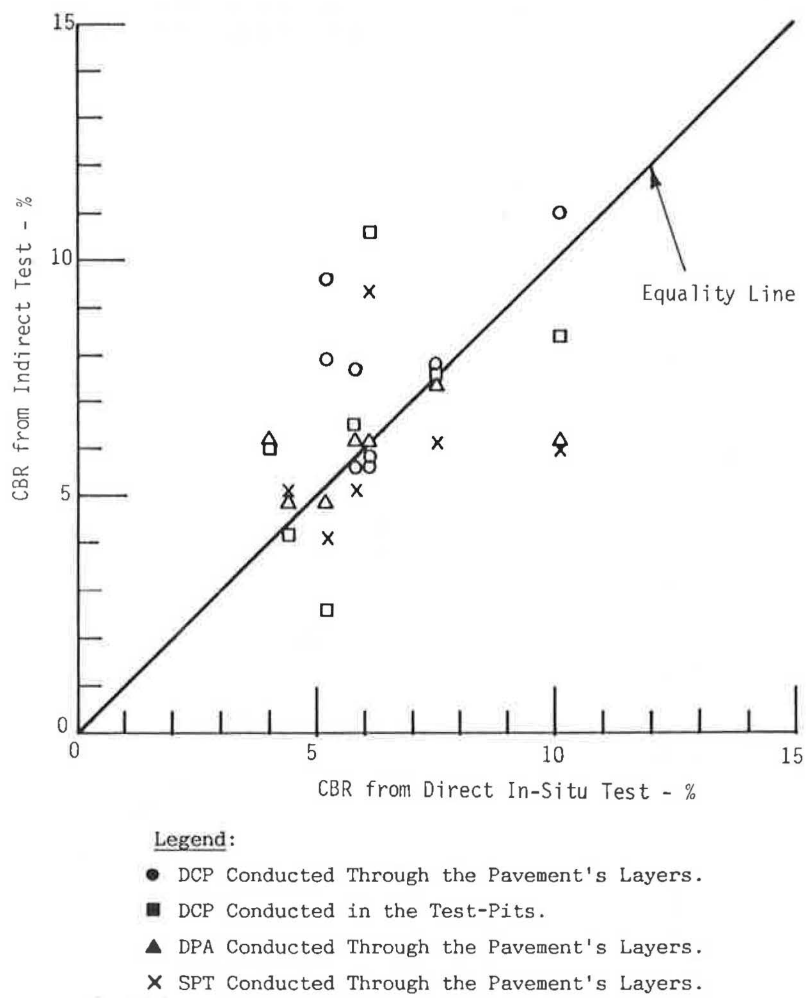
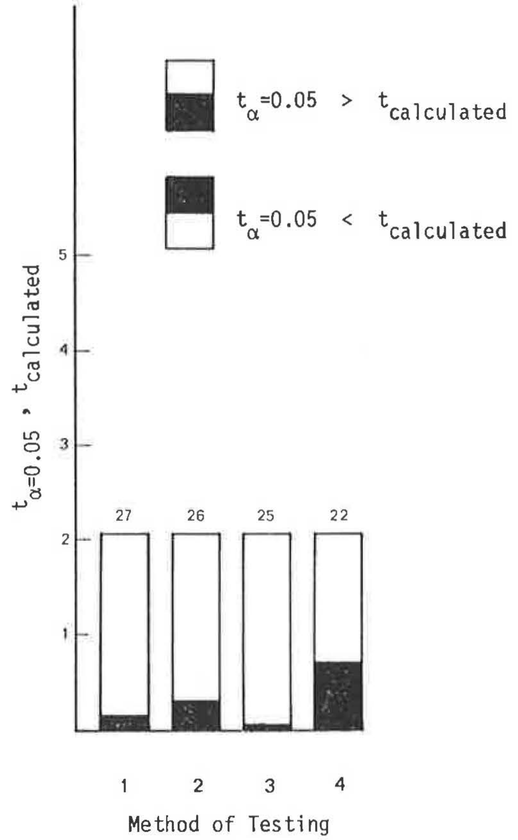


FIGURE 2 Comparison of calculated CBR values from several penetration tests and direct in situ CBR values: Mahanaim Airfield.



Legend:

1. DPA Conducted Through the Pavement's Layers.
2. DCP Conducted in the Test-Pits.
3. DCP Conducted Through the Pavement's Layers.
4. SPT Conducted Through the Pavement's Layers.

FIGURE 3 Statistical *t*-test for various penetration test results: Mahanaim Airfield. (Numbers denote degrees of freedom.)

the tests range above and below the equality line in a certain scatter, which probably stems from the natural scatter of the subgrade's characteristics. To examine this scatter, a statistical *t*-test was conducted to determine the identity or nonidentity of the various test populations. The results of this test (presented in Figure 3) indicate that it is actually possible to state, at a level of reliability of $\alpha = 0.05$, that the results population of the direct in situ CBR test is identical to the results populations of the Livneh DCP, SPT, or DPA tests.

Thus, this work has proven the validity of the above correlative equations. It should be noted in this context that the coefficient of variation obtained for the direct in situ CBR test in the test pits ranged between 5 percent and 47 percent—the upper value being a high significant value as stated in the beginning of this paper.

In addition to the above comparison, Figure 4 compares the DCP tests conducted inside the test pits and the DCP tests conducted through the structural layers of the existing pavement. Here too, the results have been found to scatter above and below the line of equality, indicating that (a) the friction developing during penetration or alternatively the effects of the overburden pressure do not constitute the only cause and (b) the natural scatter of the subgrade's characteristics also contributes its part to the difference in results. Ultimately, Figure 3, again, indicates that the results populations of the above two DCP tests do not differ statistically from the results population of the direct in situ CBR test.

Finally, it is interesting to compare the thickness of the pavement obtained in the test pits with that obtained through the analysis of the DCP test results. The thickness of the pavement obtained in the test pits was approximately 300 mm, and the DCP tests showed this thickness to range between 260 and 340 mm, with an average of 310 mm and a coefficient of variation of 12.5 percent. These results indicate the capacity of the DCP test to determine the thickness of the structural layers at an acceptable level of reliability.

Ben-Gurion Airport

In recent works of subgrade investigation, which had been carried out for purposes of designing a runway pavement for heavy aircraft at the Ben-Gurion Airport, all of the tests discussed in the preceding section were used, except for the SPT test. The in-situ CBR tests of the subgrade, which is a heavy clay subgrade (A-7-6) with a liquid limit of up to 75 percent, were carried out in test pits every half meter of depth, up to a total depth of 1.5 meters. These test pits made it possible to determine the in-situ CBR at a given depth from two DCP test measurements. One DCP measurement was taken at a level approximating the required depth (first reading) and the second measurement was taken 0.5 meter deeper than the first (second reading). Figure 5 demonstrates the variation of the results with the depth and illustrates the significance of the first and second readings.

Table 2 compares the various test results. The significance of the difference between the average values is examined by means of the statistical *t*-test. The results of the *t*-test are presented in Figures 6 and 7. According to this test, the result populations of the DPA and DCP tests are identical at any depth, apart from those DCP results that are correlated with first and second readings (all readings) or with second readings only, both for the 0.5 meter depth. In other words, at the depth of 0.5 meter, only the DCP population of the first readings is identical to the CBR population. The reason for this unique deviation in DCP results at a depth of 0.5 meter, as compared to other depths, is unclear. Yet, this deviation as compared to the other good results is insufficient in itself to alter the correlation between DCP and CBR values. Here too, the direct in situ CBR values were found to scatter greatly, starting from a coefficient of variation of 2 percent in one pit and up to 54 percent in another pit, values that might constitute the reason for the above phenomenon. Additionally, the *t*-test analysis (Figure 8), also indicates that the population of first DCP readings is identical to the population of second DCP readings. (See the scatter below and above the equality line in Figure 9.) Thus, here too, it can be shown that the friction that is developed during penetration, or alternatively, the effect of the overburden pressure, is not a significant factor.

In addition to evaluating the above subgrade, a bearing-

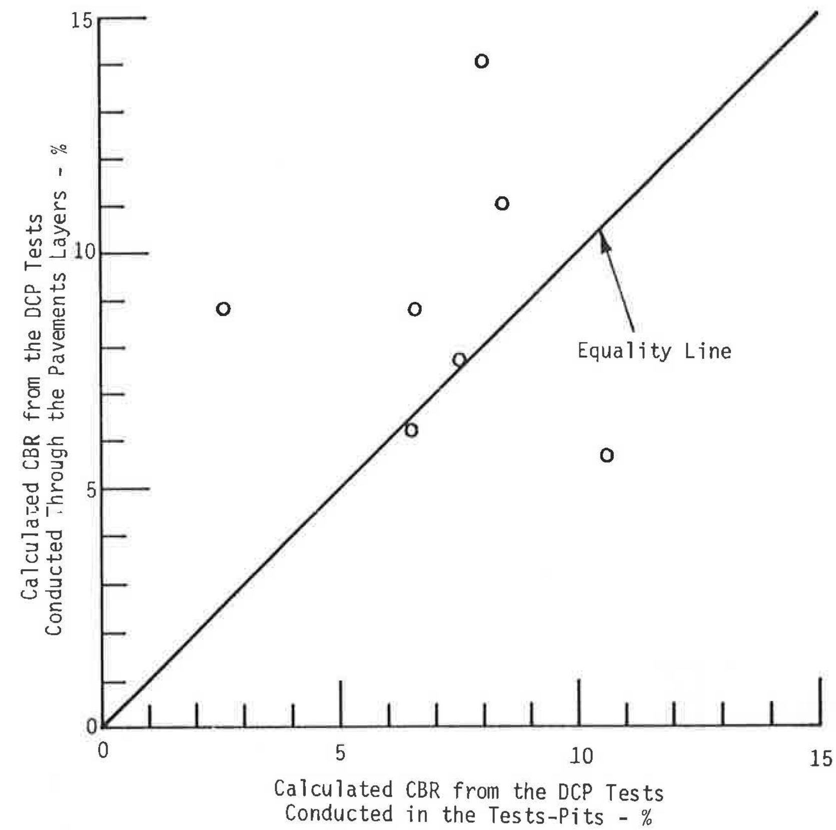


FIGURE 4 Comparison between DCP test conducted through pavement layers and DCP test conducted in test pits: Mahanaim Airfield. (CBR values are for subgrade.)

capacity evaluation of the structure of an existing pavement was also recently carried out at the Ben-Gurion Airport. Because field operating conditions made it impossible to dig test pits, only penetration tests were carried out in the pavement structure and its subgrade; vane shear tests were carried out also, in the subgrade only, of course. Translation of the vane shear strength values, S, calculated from the vane shear test results into CBR values, was carried out by means of the following expression:

$$CBR = 4.79 \times S^{0.63} \quad (5)$$

where S is the vane shear strength, expressed in kg/cm^2, and CBR is the corresponding CBR value, expressed in percentages.

The above expression is the product of a correlation study that was conducted simultaneously during previous projects at the Ben-Gurion Airport. Figure 10 presents an example of results obtained from that work. Here too, it was shown, by means of the statistical t-test, that the result populations of the DPA and the SPT tests do not differ, despite the scatter that can be seen in Figure 11. Moreover, the calculated CBR values that were obtained from these tests correspond with those obtained in the direct in-situ CBR tests that had been carried out in two test pits about two years before the present investigation. It should be noted that this latter comparison is the only one that refers to testing not done at the same time.

Finally, it is important to note that an appropriate correlation has also been found between the thicknesses of the structure as obtained through analysis of the DPA test and the thicknesses obtained through drilling for the SPT tests. These thicknesses also correspond to those obtained from the two test pits that had been dug two years earlier.

Road No. 34

A study was recently carried out to assess the pavement bearing capacity of an urban road, Road No. 34. The pavement of this road is mainly based on silty soil with medium to very high strength. Its thickness was found to average approximately 60 cm. Direct in situ CBR and DCP tests were carried out in five test pits on this pavement. In addition, near the test pits, five DCP tests were conducted on the base-course surface following drilling of asphalt cores. Comparative CBR results are presented in Figure 12. As can be seen in Figure 12, a scatter exists between the direct in situ CBR values and the calculated CBR values. However, in light of the experience gained in the preceding work described in this paper, this scatter is still within the boundaries of identity between the two results populations. In contrast to Figure 12, Figure 13 compares the CBR values calculated from the DCP tests for two cases: the test conducted inside the test pit and the test conducted beside the test pit. Here too, results are

TABLE 2 COMPARISON OF CBR RESULTS DERIVED FROM VARIOUS TESTS

Depth in meters	Value	CBR in % Calculated From the Following Tests				
		CBR	DPA	DCP	DCP 1st Readings	DCP 2nd Readings
0	$\bar{x}$	6.14	8.86	6.80	6.80	-
	σ	4.05	4.17	3.45	3.45	-
	n	14	5	11	11	-
	c.v.	0.66	0.47	0.51	0.51	-
0.5	$\bar{x}$	12.10	10.50	16.50	14.90	17.37
	σ	4.82	2.76	5.46	4.29	6.02
	n	14	5	17	6	11
	c.v.	0.40	0.26	0.33	0.29	0.35
1.0	$\bar{x}$	11.02	10.32	13.01	12.96	13.05
	σ	2.11	2.61	3.06	3.75	2.73
	n	11	5	11	5	6
	c.v.	0.21	0.25	0.24	0.29	0.21
1.5	$\bar{x}$	8.39	10.92	11.06	7.88	14.24
	σ	3.62	3.96	7.90	3.23	10.23
	n	10	5	10	5	5
	c.v.	0.42	0.36	0.71	0.41	0.72

Legend:

$\bar{x}$ - Average value. n - Number of readings.

σ - Standard deviation. c.v. - Coefficient of variation.

scattered considerably, yet the main feature of the scatter is the considerable heterogeneity of the subgrade.

Finally, Figure 14 compares the pavement thicknesses obtained from both test pits and DCP tests. Here too, the scatter is considerable, but essentially stems from the heterogeneity of the structural thickness. It is worthwhile noting that this thickness, according to the test pits, ranges between approximately 30 cm and 70 cm; and the above scatter is, therefore, only natural. Obviously, this fact also influences the decoding of the NDT tests.

SUMMARY AND CONCLUSIONS

This paper has attempted to validate empirical correlations among direct in situ CBR tests and three penetration tests (DCP, SPT, and DPA) with respect to determining the bearing capacity of subgrades and existing pavements in roadways and airport runways. After analyses of four studies recently carried out in Israel, the following three primary conclusions were reached:

1. The correlative transformation from DCP, SPT, or DPA values to direct CBR values can be used with plausible reliability. The equations of these transformations (Equations 1, 3, and 4) are presented in this paper, and it is not necessary to modify them.
2. The effect of friction or alternatively the effect of overburden pressure on the results of DCP tests is negligible. This is expressed in the reasonable correspondence that exists between the DCP results of the first readings (a test conducted on the base-course surface of the pavement following the

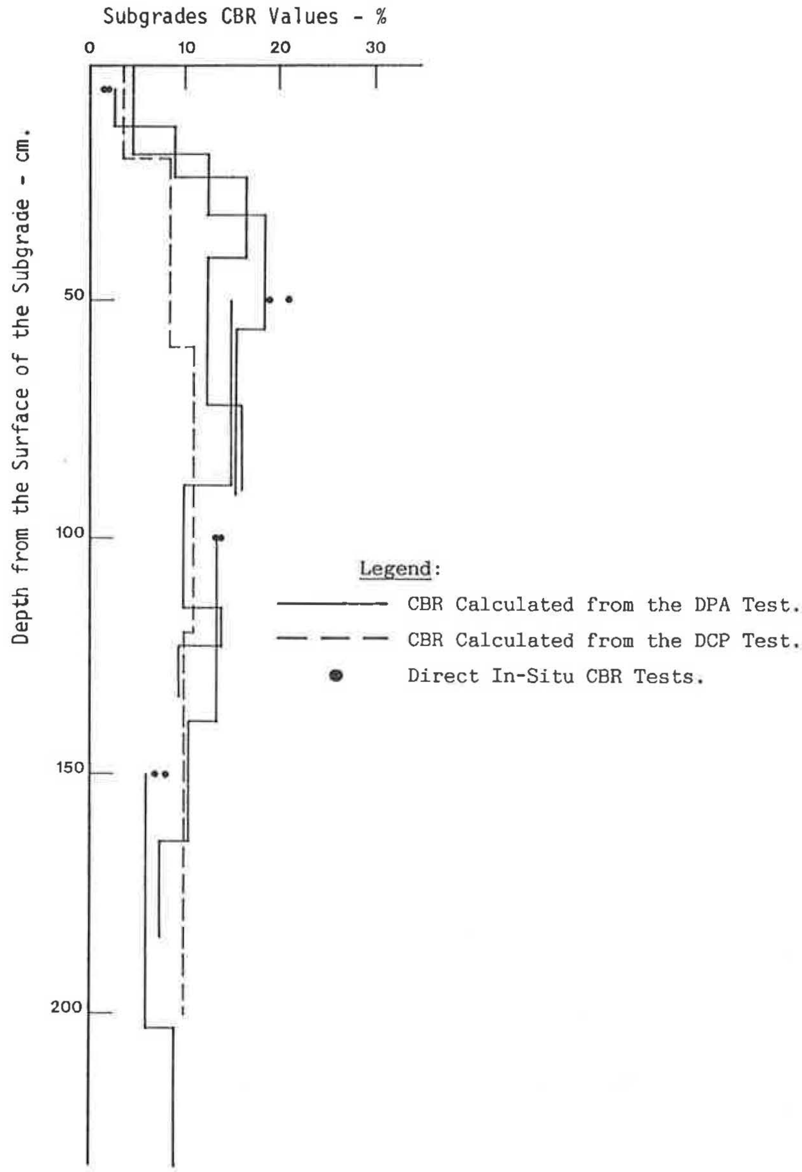


FIGURE 5 CBR distribution with depth as derived through various tests: Taxiway Y, Ben-Gurion Airport.

drilling of an asphalt core) and the DCP results of the second readings (a test conducted on the surface of the subgrade in the test pit). Similar findings have been obtained for tests carried out in pits dug in the subgrade only.

3. There is a plausible correlation between the thickness of the pavement as obtained through test pit measurements and the thickness of the pavement obtained through decoding the results of the various penetration tests.

Finally, it is important to emphasize that the DCP test permits determining the in situ CBR value of materials with any range of strength but to a limited depth of 80 cm. In contrast, the DPA test permits determining the in situ CBR of materials with a medium to low range of strength but to a greater depth. Owing to the strength limitation, this test cannot always be carried out from the existing pavement's base course; and it is therefore necessary to drill vertically through the structural layers until the DPA cone achieves the depth at which the strength values of the structural layers are appropriate to the test's ability. Similarly, the SPT test is not limited in depth but always necessitates vertical drilling. It is applicable to materials with a strength range of medium to high.

In summary, it can be stated that the in situ practical work with the above penetration tests and without digging test pits in order to determine the direct in situ CBR values has proved itself to be more efficient and faster. It is therefore recommended that this method of assessing bearing capacity of subgrades and pavements, as recently expressed in the assessment of a taxiway at the Ben-Gurion Airport, also be adopted for other evaluations.

Finally, it should be emphasized that differences in geographic areas throughout the world may lead to changes in the empirical equations presented in the paper, although the method shown here is most likely to be applicable everywhere.

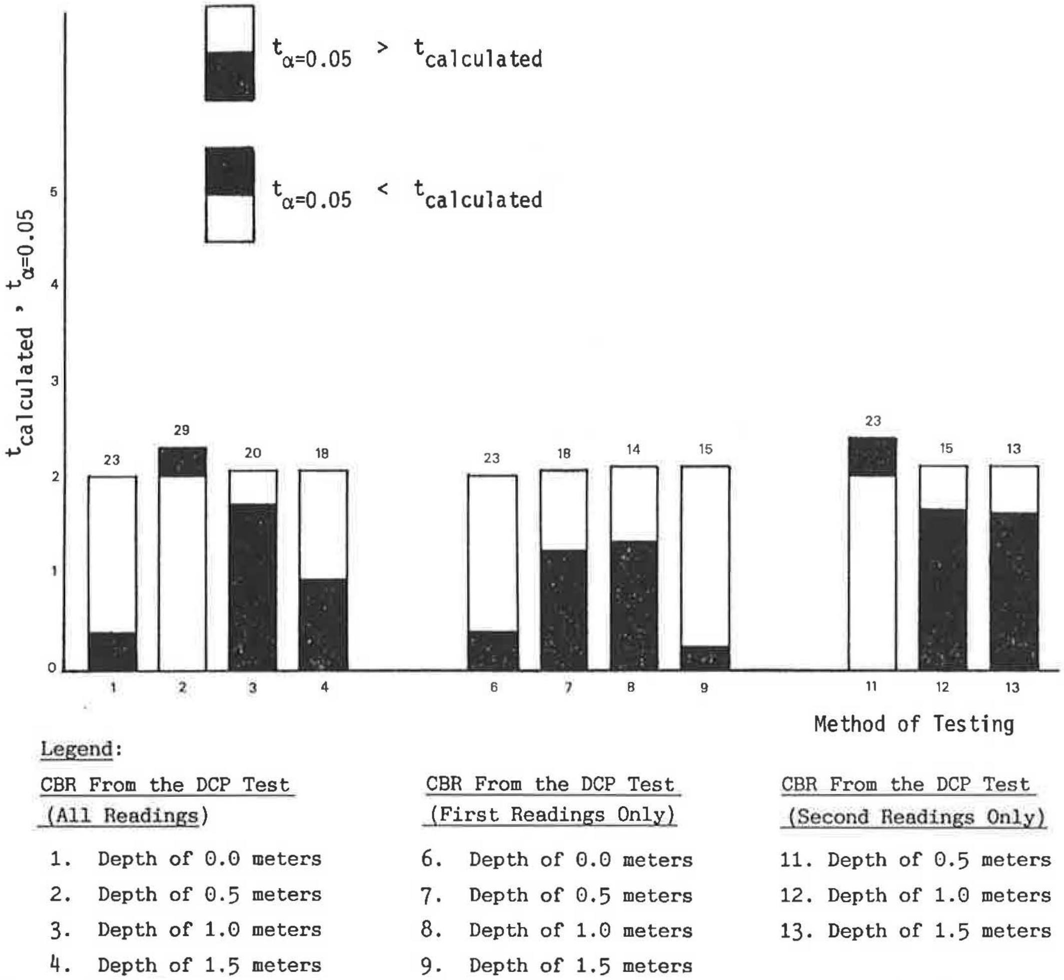


FIGURE 6 Statistical *t*-test for direct in situ CBR versus DCP test: Taxiway Y, Ben-Gurion Airport. (Numbers denote degrees of freedom.)

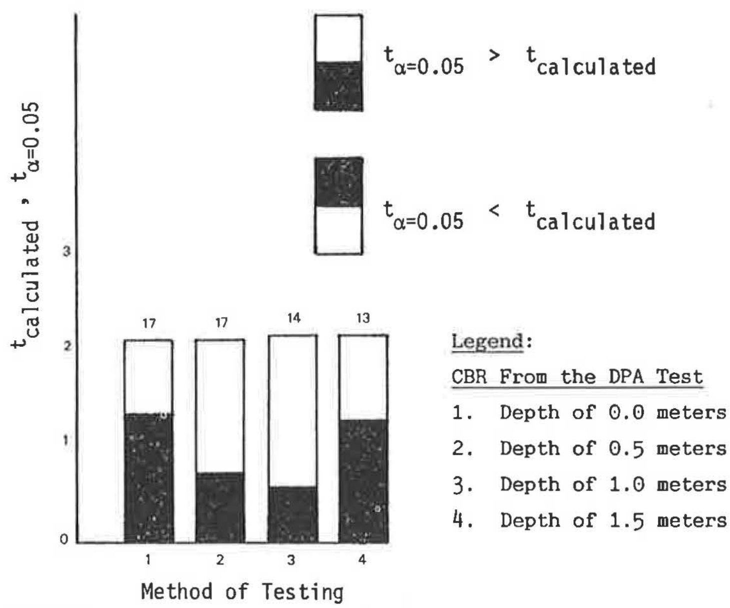


FIGURE 7 Statistical *t*-test for direct in situ CBR test versus DPA test: Taxiway Y, Ben-Gurion Airport. (Numbers denote degrees of freedom.)

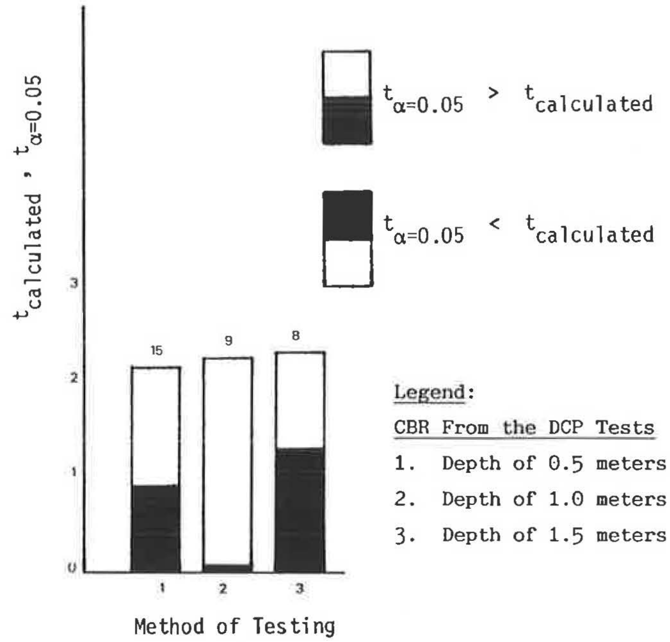


FIGURE 8 Statistical *t*-test for DCP test, first readings versus second readings: Taxiway Y, Ben-Gurion Airport. (Numbers denote degrees of freedom.)

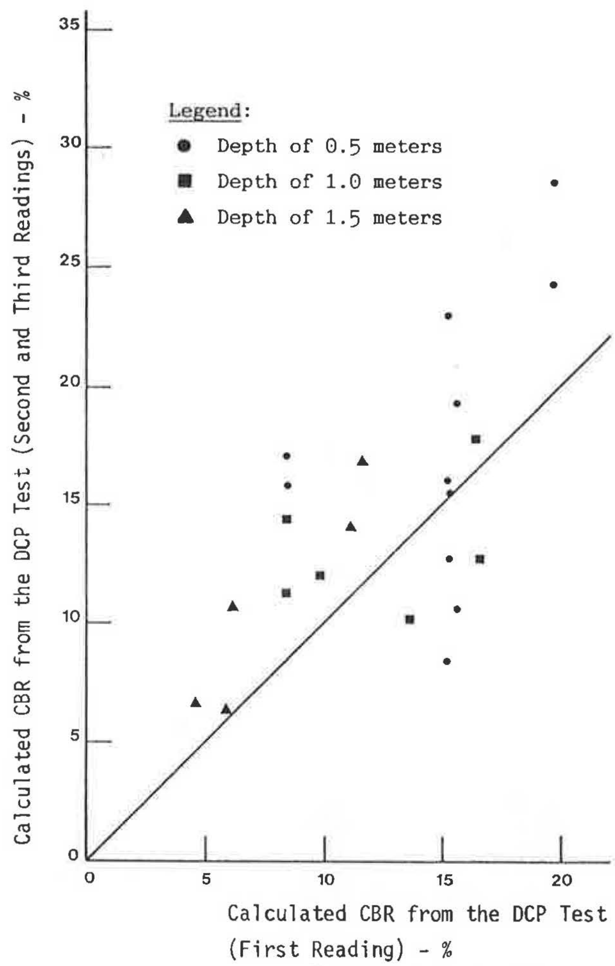


FIGURE 9 Comparison of calculated CBR for DCP tests, first readings versus second and third readings: Taxiway Y, Ben-Gurion Airport.

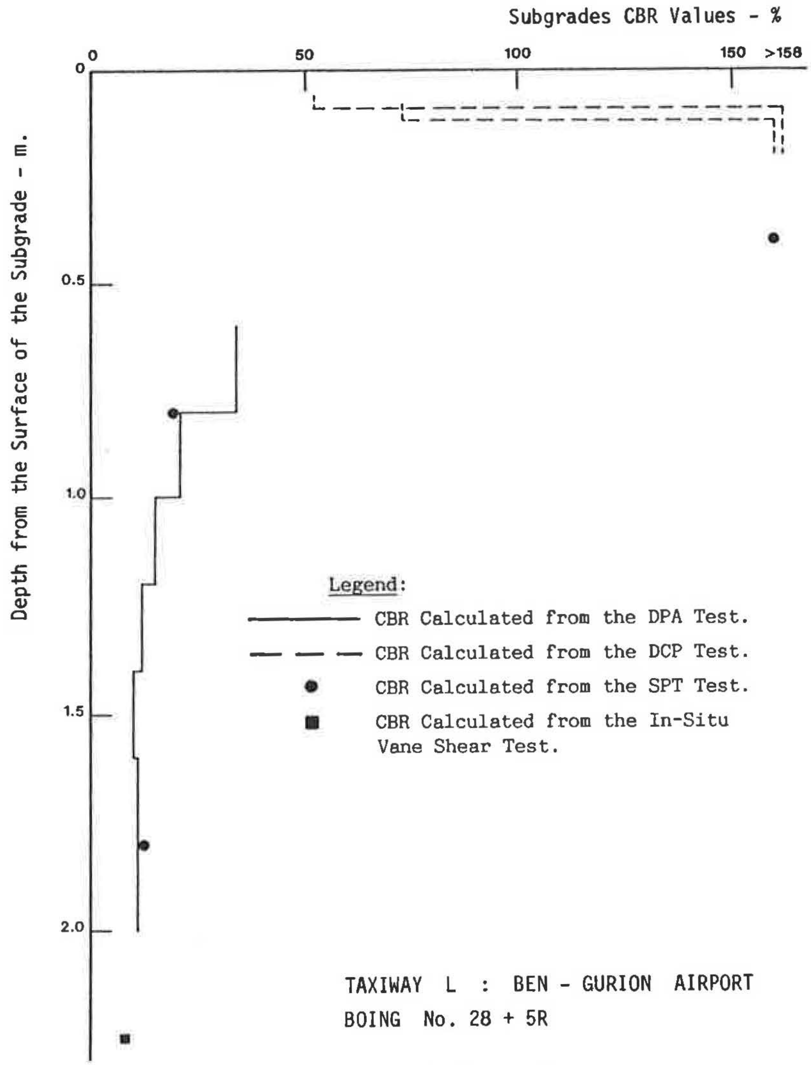


FIGURE 10 Strength distribution with depth according to various penetration and vane shear tests: Taxiway L, Ben-Gurion Airport.

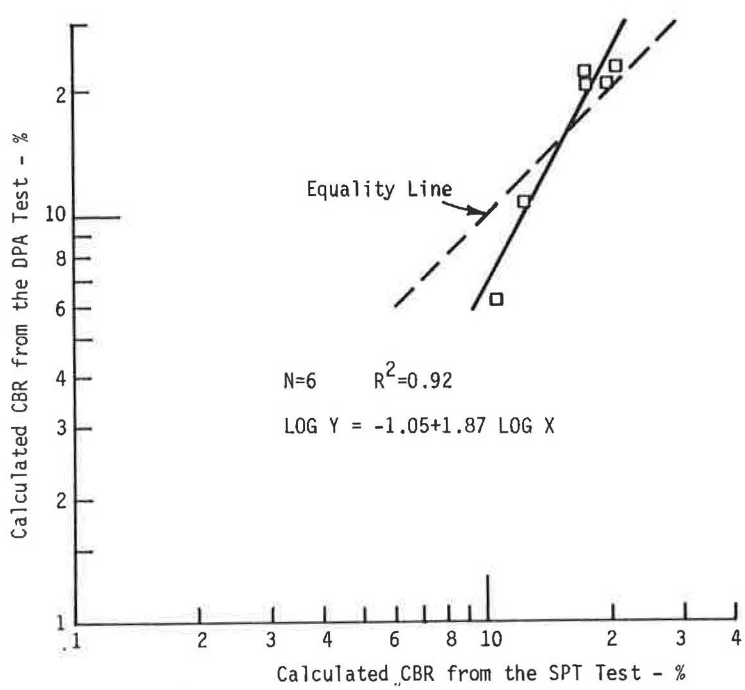


FIGURE 11 Comparison of CBR calculated from DPA and SPT tests.

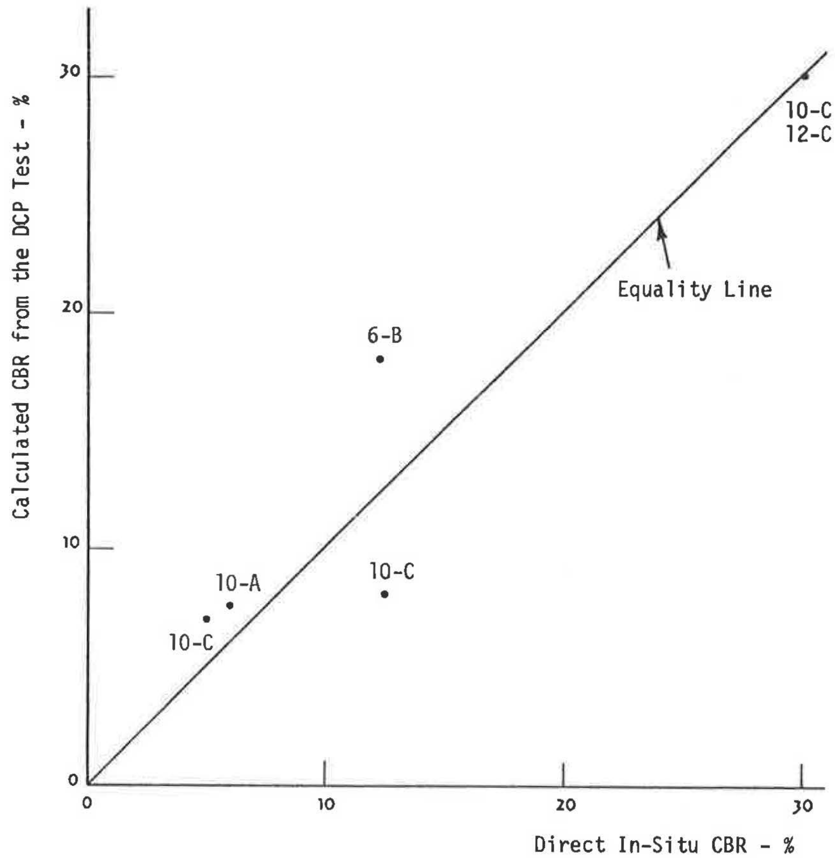


FIGURE 12 Comparison of CBR results derived from direct in situ tests and DCP tests: Road No. 34.

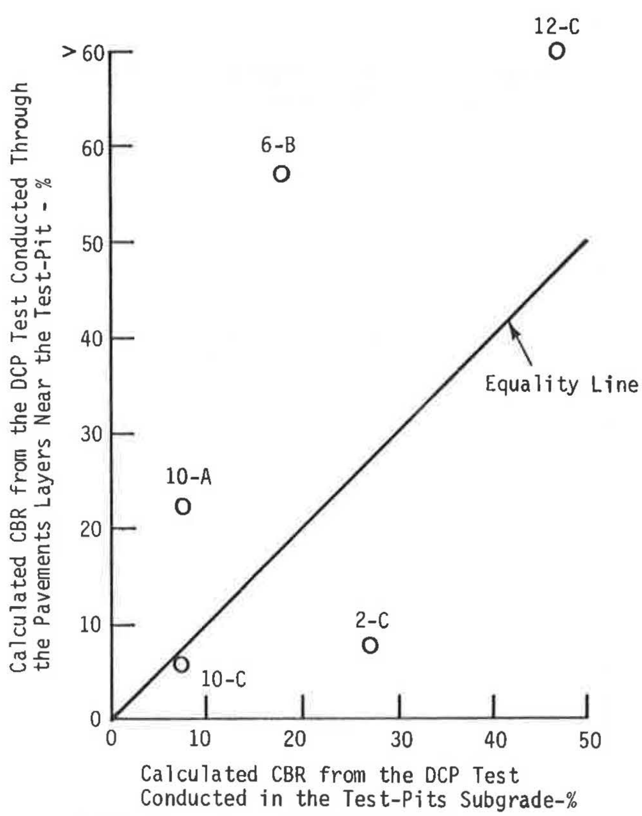


FIGURE 13 Comparison of CBR calculated from DCP tests conducted near test pits and inside test pits: Road No. 34.

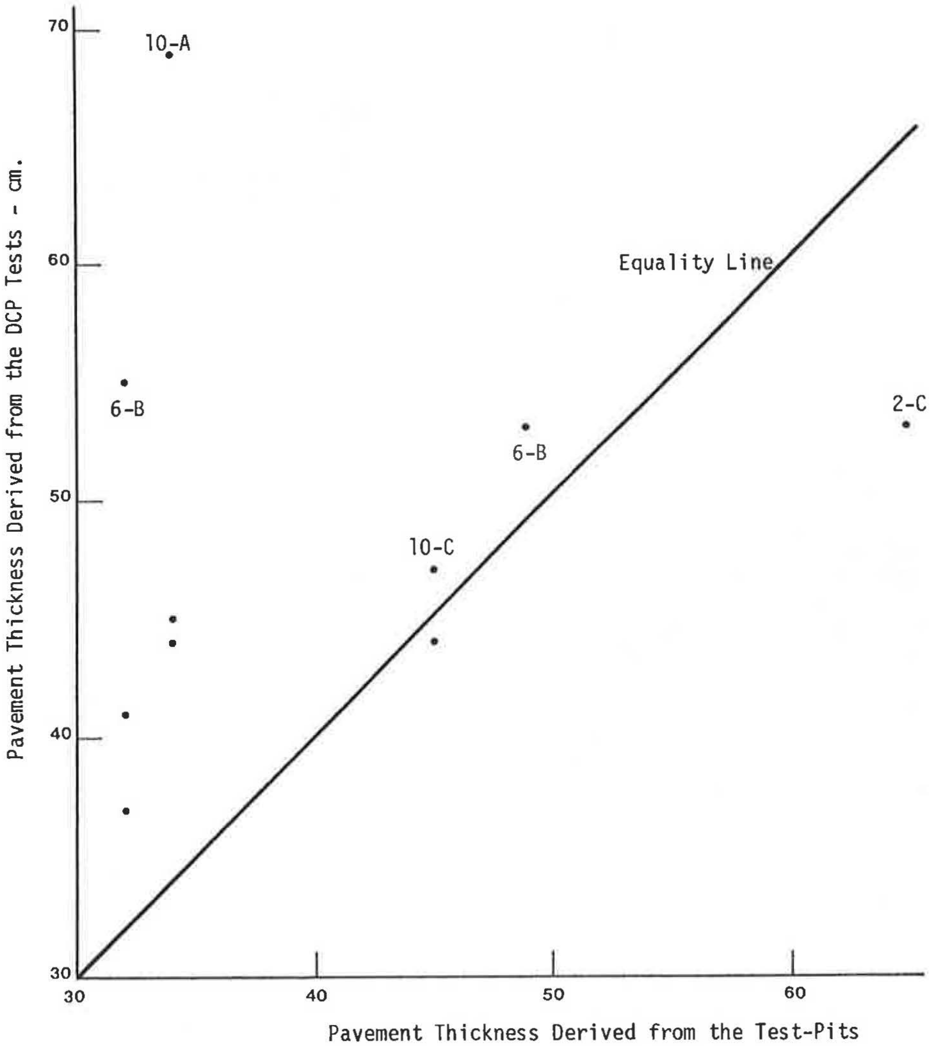


FIGURE 14 Comparison of pavement thickness derived from DCP test and test pits: Road No. 34.

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