Overlay Design Procedure for Pavement Maintenance Management Systems

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A methodology for flexible pavement rehabilitation and development of overlay thickness design curves for pavement maintenance management systems (PMMSs) is presented. The methodology is based on nondestructive testing of deflection basin measurements and on the rational approach that characterizes pavement response to major deterioration criteria, such as fatigue and rutting. Within the general framework, subgrade and pavement were classified into three categories of strength: weak, medium, and strong according to the measured deflection D_6 (at a distance of 1.80 m from the loading plate) and the surface curvature index parameter. With reference to these categories, a structural index (SI) was defined. Between the SI and overlay thickness there is a dependence that can be expressed by a design curves system related to different traffic categories and subgrade type. The present methodology can readily be incorporated as a subsystem within the general PMMS, and it enables fast solutions at the network level for economic evaluation and rehabilitation priority order determination of extensive road systems.

There are several main approaches to determining the overlay thickness of rehabilitated flexible pavements: (*a*) engineering experience and judgment, which in many cases is still being used to design overlays (*1*); (*b*) the standard overlay thickness for a given existing pavement type, traffic level, and other factors; (*c*) the empirical approach, which is based on the limited deflection criteria or correlation between the elastic deflection and pavement life (*2–6*); (*d*) the rational approach, which is based on the major deterioration criteria, such as fatigue and rutting [in this approach the pavement performance and its load response is expressed in terms of strains and stresses (*7–9*)]; and (*e*) the mechanistic approach, which is based on principles of fracture mechanics, to which the Paris law (*10*) is being applied that associates crack propagation with the stress intensity factor (*11–15*). The first two methods do not require evaluation tests of pavement materials and therefore are faster but not reliable. By contrast, the other methods demand destructive and nondestructive testing (NDT) for the evaluation of the properties and the performance of the pavement being rehabilitated.

The use of NDT is more common and widespread and nowadays is an integral part of the overlay design procedures applied in many institutions in the world (*4,6–9,16–19*). The design process carried out by these methods usually includes the following stages: (*a*) deflection basin measurements and their correction according to standards of load level, temperature, load frequency, and so forth (*1,2,16–18*); (*b*) properties derivation of the pavement layers by empirical analysis, using maximum deflection (DMD), surface curvature index (SCI), and base curvature index (BCI) (*5*) or structural analysis, based on the multilayer theory, which includes elastic moduli derivation by backcalculation programs (*7–9*); and (*c*) determining the relation between layer material properties and pavement performance in terms of pavement life by means of empirical deflection models (*2–6,16,19*) or semimechanistic models to predict pavement response and its resistance to deterioration criteria such as fatigue and rutting (*7–9*).

In pavement maintenance management systems (PMMSs) the rehabilitation solutions are subsystems within the whole system where additional indices exist, such as visual deterioration, pavement condition index (PCI), distress rating (DR), and roughness, for the purpose of economic evaluation and rehabilitation priority determination. Such a systems application for road system management of hundreds of kilometers requires fast and reliable representation of rehabilitation solutions at the network level. In this case the rational approaches, although reliable and advantageous, do not apply, because of the amount of work required by the tests to determine layer thickness, layer moduli derivation, and stresses and strains calculation to determine the rehabilitated pavement resistance to deterioration criteria.

This paper presents a methodology for the design of flexible pavement rehabilitation and development of overlay thickness design curves for PMMS. The methodology is based on NDT deflection basin measurements and on the rational approach for predicting the main deterioration criteria of fatigue and rutting. The rationale behind this methodology is that it is possible to characterize and express structural strength of the rehabilitated pavements by means of an index called structural index (SI), which is determined according to the measured deflection basins. Between this index and the required overlay thickness there is a mutual dependence, which can be expressed by curve systems for traffic categories and different subgrade types. The advantage of this method is that it can readily be incorporated as a subsystem within the overall PMMS to furnish reliable and fast solutions at the network level of extensive road systems for economic evaluation and rehabilitation priority order determination as shown elsewhere (*20,21*).

EVALUATION PARAMETERS AS INPUT DATA

The rehabilitation design methodology and overlay thickness design curves development are based on a data base of deflection basin measurements in different rehabilitated roads in Israel totaling 450 km in length and moduli derivation of

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the layers by means of backcalculation programs. The measured sections represent a wide range of pavement thicknesses and subgrade types. The deflection basins were measured at 100-m intervals by a Dynatest FWD 8002 model, which delivers an impulse load of 7 to 110 kN (1.15 to 24.2 kips). In each basin seven deflections were measured under an average load of about 75 kN (within the range of 70 to 80 kN) distributed uniformly on a circular load plate 300 mm in diameter. The deflections were measured at a distance of 0, 0.30, 0.60, 0.90, 1.20, 1.50, and 1.80 m (D_0, D_1, ..., D_6, respectively) from the center of the load plate. At the same time the asphalt layer temperature of each section was measured. Since measurements were performed at the end of the winter, temperatures ranged between 9°C and 22°C.

The moduli derivation of the pavement layers and the subgrade (the three-layer model) was carried out by a backcalculation program, DEFMOD (*20*). This program derives the moduli according to the data base approach (*22*) similar to MODULUS (*23*). The evaluation results of this software were compared with results of BISDEF (*23,24*), MODULUS (*23,24*) and ELMOD (*22*) and were found to be correct and reliable. The modulus of the asphalt layer, which was derived from the deflection basin, was corrected to fit the standard temperature of 30°C (86°F), according to the relationship proposed by Uzan et al. (*25*).

The measured deflections and layer moduli derived from them were used as input to develop a structural index for the pavement and overlay thickness design curves according to this index.

PROPOSED APPROACH FOR OVERLAY DESIGN PROCEDURE

NDT Correction to Fit Standard Conditions

The development of overlay design curves according to the proposed approach must be based on standard condition measurements. Therefore, the deflections were corrected by two factors for load level and temperature.

All the FWD measurements were performed within the load range 70 to 80 kN. Therefore, all the deflection basins were corrected according to the standard load of 75 kN in a linear manner as follows:

$$D_i^{cor} = D_i^m \times \frac{75}{P_m} \qquad (1)$$

where

- D_i^{cor} = corrected deflection for the standard load of 75 kN for the *i*th sensor,
- D_i^m = measured deflection at P_m load for the *i*th sensor, and
- P_m = load at the measurement time.

Because of the nonlinear behavior of the pavement layers, the measured deflection versus load level is also nonlinear. However, since most measurements were performed within the narrow load range and close to the reference load, the linear relation adopted in Equation 1 is precise.

The correction function of the central deflection, D_0 according to standard temperature of 30°C, was based on numerical analysis in which the modulus of the asphalt layer was determined in the temperature range 10°C to 50°C according to the relationship recommended by Uzan et al. (*25*). This function was corrected according to the temperature range 10°C to 20°C (the temperature range in which the deflection basins were measured) by means of the measured deflection basin and moduli derivation of the pavement layers. The regression function for the central deflection correction, $F_T(D_o)$, is expressed as follows:

$$F_T(D_o) = 1.694 - 3.155 \times 10^{-2}\, T_p + 3.286 \times 10^{-4}\, T_p^2 - 1.667 \times 10^{-6}\, T_p^3 \qquad (2)$$

where T_p is the asphalt layer temperature at the time of measurement in degrees Celsius.

This correction was carried out only on the central deflection D_o (in addition to the load correction) of all the deflection basins as follows:

$$D_o(30°C) = F_T \times D_o(T_p) \qquad (3)$$

The central deflection is highly sensitive to variations of temperature, whereas the other deflections are not affected by the temperature or the effect is negligible (*25*).

Subgrade Characterization and Classification

One approach to subgrade quantitative and qualitative evaluation from NDT measurements is by means of empirical indices, such as spreadability (*18*), SCI (*5*), BCI (*5*), and basin area (*8*). Figure 1 shows the relation between the modulus of the subgrade E_s derived by DEFMOD backcalculation and the measured deflection D_6, corrected to standard load of 75 kN (see Equation 1). The figure shows that irrespective of the subgrade type or pavement thickness, there is a correlation between the subgrade modulus and D_6 that allows the characterization and classification of the subgrade by that deflection. This fact is well known and is commonly used for subgrade modulus derivation (*19*). The regression that fits the relationship shown in Figure 1 is as follows:

$$D_6 = 8.588 \times 10^3\, E_s^{-1.055} \qquad (R^2 = 0.961) \qquad (4)$$

where E_s is expressed in MPa and D_6 in μm.

On the basis of local experience, the variety of subgrade materials, and Equation 4, the subgrade was classified according to the recommended methodology into three quantitative and qualitative categories—weak, medium, and strong subgrade, as indicated in Table 1. Categories and values similar to those given in Table 1 were proposed by Scullion (*26*). Linear modification of Scullion's results for standard load of 75 kN leads to 93 μm and above for weak subgrade, 56 to 93 μm for medium subgrade, and below 56 μm for a strong subgrade.

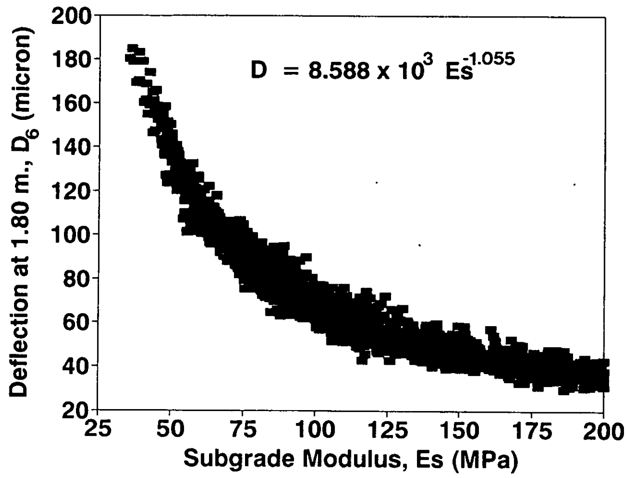

FIGURE 1 D_6 **deflection versus subgrade modulus** E_s**.**

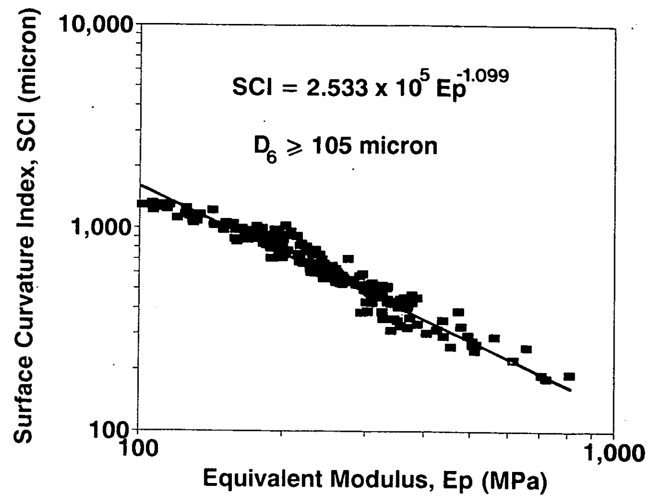

FIGURE 2 SCI versus equivalent modulus E_p **for weak subgrade.**

Pavement Characterization and Classification

The structural condition of the pavement is a combination of the thickness and strength of its layers. Therefore, a quantitative and qualitative characterization of the pavement according to NDT measurements requires the presentation of the above factors by means of a single index. For that purpose the SCI parameter and equivalent pavement modulus E_p expressed by the following equations were adopted:

$$SCI = D_0 - D_1 \tag{5}$$

$$E_p = \left(\frac{\sqrt[3]{E_A}\, h_A + \sqrt[3]{E_G}\, h_G}{h_A + h_G} \right)^3 \tag{6}$$

where

- D_0 = central deflection corrected to standard load of 75 kN and temperature of 30°C;
- D_1 = measured deflection at 0.3 m from the loading plate corrected to the standard load of 75 kN;
- E_A, E_G = moduli of the asphalt (at standard temperature of 30°C) and the granular layers, respectively; and
- h_A, h_G = thicknesses of the asphalt and granular layers, respectively.

Figures 2 through 4 show the relation between the equivalent modulus E_p derived from the deflection basin analysis and the SCI values for the three subgrade types, characterized respectively. The figures show that there is a correlation between E_p and SCI expressed by means of the following equations:

For a weak subgrade ($D_6 \geq 105$ μm),

$$SCI = 2.533 \times 10^5\, E_p^{-1.055} \qquad (R^2 = 0.936) \tag{7}$$

For a medium subgrade ($55 \leq D_6 < 105$ μm),

$$SCI = 3.425 \times 10^5\, E_p^{-1.152} \qquad (R^2 = 0.902) \tag{8}$$

For a strong subgrade ($D_6 < 55$ μm),

$$SCI = 1.974 \times 10^5\, E_p^{-1.052} \qquad (R^2 = 0.890) \tag{9}$$

where E_p is expressed in MPa and SCI in μm.

On the basis of local experience and a variety of materials, the pavement was classified according to the following three categories: weak pavement, $E_p \leq 200$ MPa; medium pave-

TABLE 1 Subgrade Classification Based on NDT

Subgrade Classification	Elastic Modulus (MPa)	C.B.R [a] (%)	D_6 [b] (micron)
Weak	⩽ 65	⩽ 4	⩾ 105
Medium	65 - 120	4 - 8	55 - 105
Strong	> 120	> 8	< 55

[a] Based on the correlation Es=(15-16)CBR.
[b] According to Eq. 4.

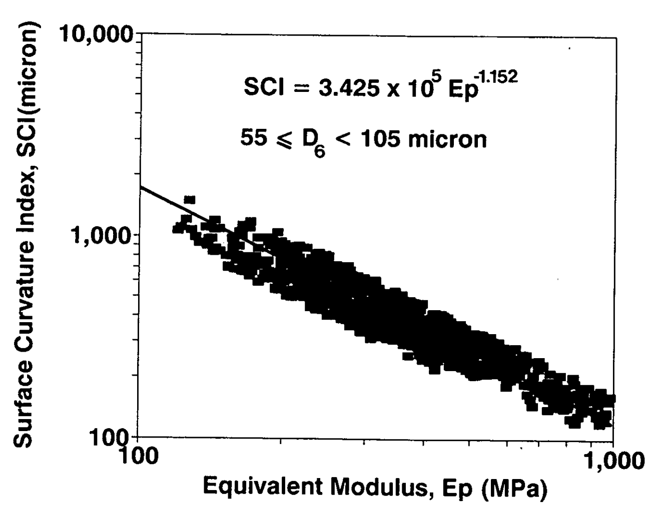

FIGURE 3 SCI versus equivalent modulus E_p **for medium subgrade.**

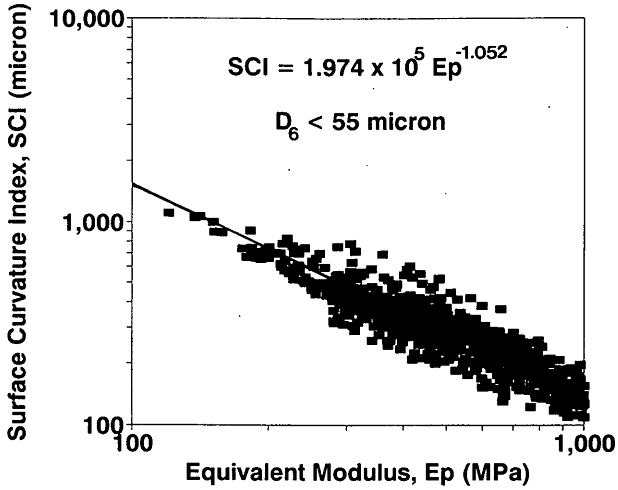

FIGURE 4 SCI versus equivalent modulus E_p for strong subgrade.

ment, 200 MPa < E_p ≤ 400 MPa; and strong pavement, E_p > 400 MPa.

Classification of the pavement according to the measured SCI determined by Equations 7 through 9 leads to identical results irrespective of the subgrade classification. Therefore, uniform criteria for pavement classification were determined as follows: weak pavement, SCI ≥ 750 μm; medium pavement, 350 μm ≤ SCI < 750 μm; and strong pavement, SCI < 350 μm.

Table 2 gives the criterion values for both subgrade and pavement classification according to the correction deflection basin measurements.

Structural Index

To express the pavement classification in a quantitative manner, SI was adopted. This is an index within the range 0 to 1.0 that expresses the performance condition of the rehabilitated pavement in terms of remaining life. SI determination for any subgrade type was based on the following assumptions:

1. For any pavement in the strong category (SCI ≤ 350 μm), SI is equal to 1.0.
2. The SI of a pavement in the other categories expresses its remaining life relative to identical pavement with an SI of 1.0. For instance, an SI of 0.3 means that the pavement's

TABLE 2 Subgrade and Pavement Classification Based on NDT (micron)

Pavement Classification	Subgrade Classification: Weak	Medium	Strong
Weak	D_6 ≥105 SCI ≥750	55≤ D_6<105 SCI≥750	D_6<55 SCI ≥750
Medium	D_6 ≥105 350≤ SCI <750	55≤ D_6<105 350≤ SCI <750	D_6<55 350≤ SCI <750
Strong	D_6 ≥105 SCI <350	55≤ D_6<105 SCI <350	D_6<55 SCI <350

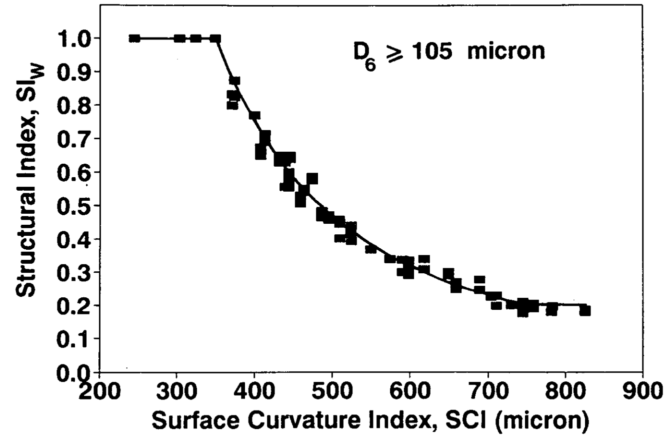

FIGURE 5 SI_W as a function of SCI for weak subgrade.

remaining life in terms of number of load application to failure, N_f according to the proposed criterion, is 30 percent relative to pavement of identical thickness with an SI of 1.0.

3. The remaining life of the actual pavement layers (the three-layer model) is determined according to the criterion of compressive strain at the top of the subgrade. For that purpose, the model of Verstraten et al. (*27*) was adopted. Since the SI refers to the measured deflection basin, the load that served for calculation was 75 kN distributed on a circular plate with a diameter of 300 mm. Accordingly, the SI is used as follows:

$$SI = \frac{N_f(SCI > 350\ \mu m)}{N_f(SCI = 350\ \mu m)} \qquad (10)$$

In Figures 5 through 7 the relationship between the SCI parameter and the SI for different subgrade categories is shown. The SCI of any pavement is determined according to Equations 7 through 9. These figures show that it is possible to define the structural index depending on SCI by three distinct ranges as follows:

1. For SCI values smaller than 350 μm (strong pavement), the SI value equals 1.0. This range was determined by the assumption.

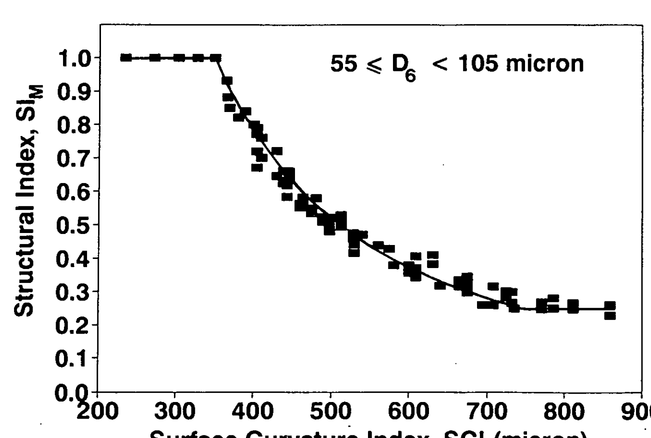

FIGURE 6 SI_M as a function of SCI for medium subgrade.

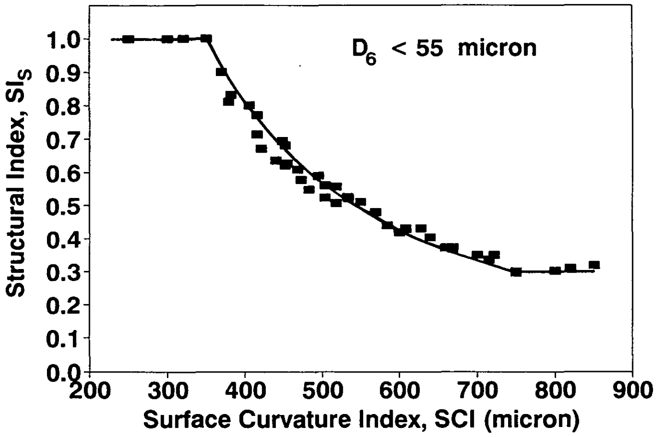

FIGURE 7 SI_S as a function of SCI for strong subgrade.

2. For SCI values between 350 and 750 μm (medium pavement), the SI values decrease in a nonlinear manner as the SCI parameter increases.

3. For SCI values greater than 750 μm (weak pavement), the SI value is constant.

The range definitions for all the subgrade types were expressed by the following regression equations.

For a weak subgrade ($D_6 \geq 105$ μm),

$$SI_W = \begin{cases} 0.2 & SCI \geq 750\,\mu m \\ 2.361 \times 10^5 SCI^{-2.112} \quad (R^2 = 0.987) & 350 \leq SCI < 750\,\mu m \\ 1.0 & SCI < 350\,\mu m \end{cases} \tag{11}$$

For a medium subgrade ($55 \leq D_6 < 105$ μm),

$$SI_M = \begin{cases} 0.25 & SCI \geq 750\,\mu m \\ 4.243 \times 10^4 SCI^{-1.819} \quad (R^2 = 0.975) & 350 \leq SCI < 750\,\mu m \\ 1.0 & SCI < 350\,\mu m \end{cases} \tag{12}$$

For a strong subgrade ($D_6 < 55$ μm),

$$SI_S = \begin{cases} 0.3 & SCI \geq 750\,\mu m \\ 1.046 \times 10^4 SCI^{-1.580} \quad (R^2 = 0.988) & 350 \leq SCI < 750\,\mu m \\ 1.0 & SCI < 350\,\mu m \end{cases} \tag{13}$$

There is no relation between the numerical value of SI in the different subgrade categories. Identical SI values in different subgrade categories are not equivalent and do not express identical strength of the pavement. The reason for this lies in the definition and determination of this index according to Equation 10.

A similar index for subgrade and pavement categories identical to those shown was developed by Scullion (*26*), who assigned each subgrade category six separate structure strength index groups for all the pavement categories.

Overlay Thickness as a Function of SI

The rational approach (*7–9*) for overlay thickness design relies on the resistance of the rehabilitated pavement to the main deterioration criteria such as fatigue and rutting. The SI indicates the strength of the pavement and provides evaluation about the structural performance of the pavement. It is therefore possible to present rehabilitation curves on the basis of the rational approach depending on the SI index. The development of overlay thickness design curves was based on the following principles:

1. Several dozen structures within the weak, medium, and strong pavement categories with a wide range of SI were adopted. The total pavement thickness was between 300 and 600 mm with asphalt thickness of 60 to 200 mm.

2. The subgrade modulus (E_S) representing the weak subgrade groups ($E_S \leq 65$ MPa) was determined as 650 MPa ($D_6 = 115$ μm according to Equation 4). The modulus representing the medium subgrade groups (65 μm $< E_S \leq$ 120 μm) was determined as 90 MPa ($D_6 = 75$ μm). For the strong subgrade groups ($E_s > 120$ MPa) the representative modulus was determined as 120 MPa ($D_6 = 55$ μm).

3. For each case the pavement and subgrade were classified according to D_6, and SCI and SI were calculated according to the principles demonstrated in previous sections.

4. A constant load distribution representing the rural mixed traffic in Israel was adopted. The load range is between 20 and 180 kN for a single axle (*20*). The effect of that mixed traffic to determine overlay thickness was taken into account according to the Miner hypothesis (*28*). After having calculated the overlay thickness and to express the mixed traffic levels in the overlay design curves (Figures 8 through 10) by means of a single traffic number (for easier utilization), the various load levels were transformed to a number of equivalent applications of a 130-kN single-axle load, which is the design axle load in Israel. The transformation was performed by means of the load equivalency factor of the AASHO method (*1*).

5. Two deterioration criteria were adopted, fatigue and compressive strain at the top of the subgrade, used as rutting criteria. The fatigue criterion was adopted according to the model proposed by Finn et al. (*29*) with some modification referred to by Uzan and Gur (*30*). As a rutting criterion, the model of Verstraten et al. (*27*) was adopted. The overlay thickness for each rehabilitated pavement according to Miner's law is the thickness that fits the critical criterion between the two.

Figures 8 through 10 show overlay thickness design curves depending on SI for a weak, medium, and strong subgrade, respectively. The overlay thickness is presented for various equivalent 130-kN load applications. The required overlay thickness of 20 mm was defined as the surface treatment classification and the 10 mm as distress repair.

APPLICATION AND LIMITATION OF THE PROPOSED METHOD

The proposed methodology including all its principles and fundamental assumptions can be incorporated within PMMS

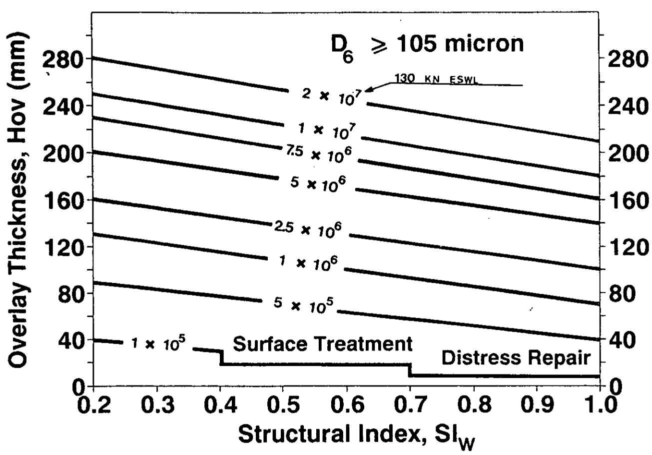

FIGURE 8 Overlay thickness versus SI_W for weak subgrade.

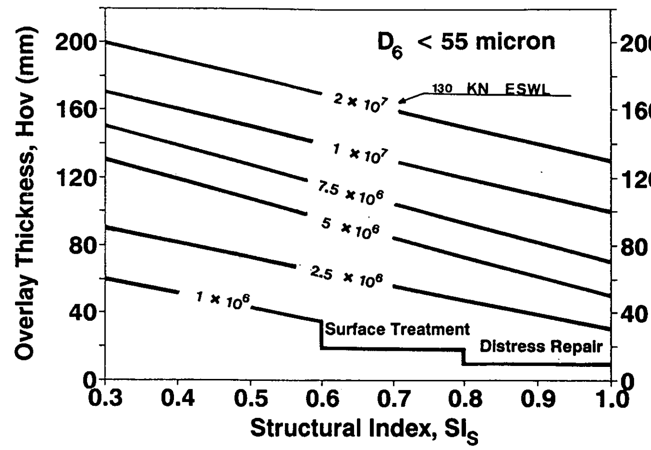

FIGURE 10 Overlay thickness versus SI_S for strong subgrade.

to provide fast rehabilitation solutions at the network level. The system was successfully applied to a road system totaling 900 km in length (*20,21*).

Figure 11 shows a general flowchart of the process for overlay thickness determination. The process stages may be summarized as follows:

1. Choose the rehabilitated section, measuring the deflection basin at suitable distances and asphalt layer temperatures.
2. Correct the central deflection D_0 for standard load of 75 kN (Equation 1) and standard temperature of 30°C (Equations 2 and 3).
3. Correct D_1 and D_6 for standard load of 75 kN.
4. Calculate the SCI parameter according to corrected deflections D_0 and D_1.
5. Determine the representative D_6 and SCI parameters of the section by statistical analysis.
6. Classify subgrade and pavement by D_6 and SCI parameters (Table 2).
7. Calculate the SI according to the subgrade and pavement classification (Equations 11 through 13).
8. Do traffic analysis for a design period.

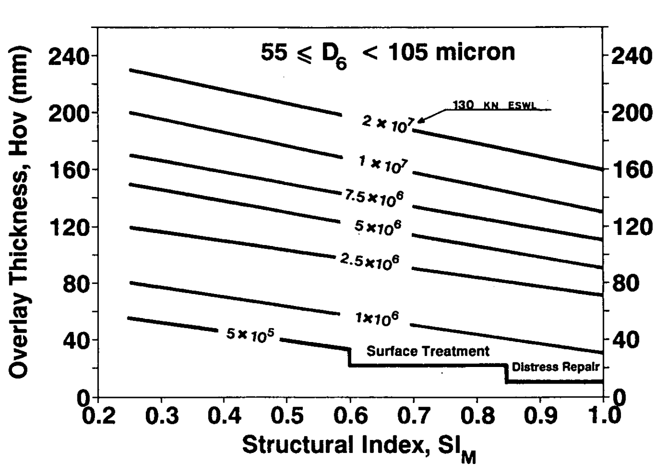

FIGURE 9 Overlay thickness versus SI_M for medium subgrade.

9. Determine the required overlay thickness according to subgrade type, SI, and traffic analysis (Figures 8 through 10).

The design curves shown in Figures 8 through 10 have two main limitations, which under certain circumstances may lead to conservative results or overdesign with reference to the rational approach. The two limitations mentioned in the fundamental assumptions may be summarized as follows:

- The curves were developed to different structure thicknesses up to 600 mm. The overlay thickness is affected considerably by the pavement thickness in the case where the critical criterion is rutting. In instances where the thickness is above 600 mm and the deterioration criterion is rutting, one must expect overdesign. These instances are characteristic of pavements based on weak subgrade.
- The subgrade modulus E_s representing the different subgrade categories was constant at 60, 90, and 120 MPa for a weak, medium, and strong subgrade, respectively (D_6 of 115, 75, and 55 μm, respectively). Therefore in cases where the subgrade modulus presented by the deflection value D_6 (see Equation 4) was radically different from the representative values, one must expect conservative results or overdesign.

These limitations are partially solved by statistical analysis for determining the representative basin properties or by calculating the overlay thickness for every single point within the section and choosing the required overlay thickness on the basis of statistically homogeneous units (*1*).

For the validation of the proposed procedure, a comparison of the overlay thickness calculated by the proposed procedure and by the rational approach was carried out. The results of the analysis showed good correlation between the solutions. The deviation of the results were in the range 0 to 20 mm, which is acceptable for solutions at network level.

The proposed method is not intended to replace the rational approach for pavement rehabilitation. To establish the approach it is necessary to develop modification factors to the said limitations and calibrate the method with extensive laboratory and field tests. However, its advantage lies in providing fast rehabilitation solutions at the network level in

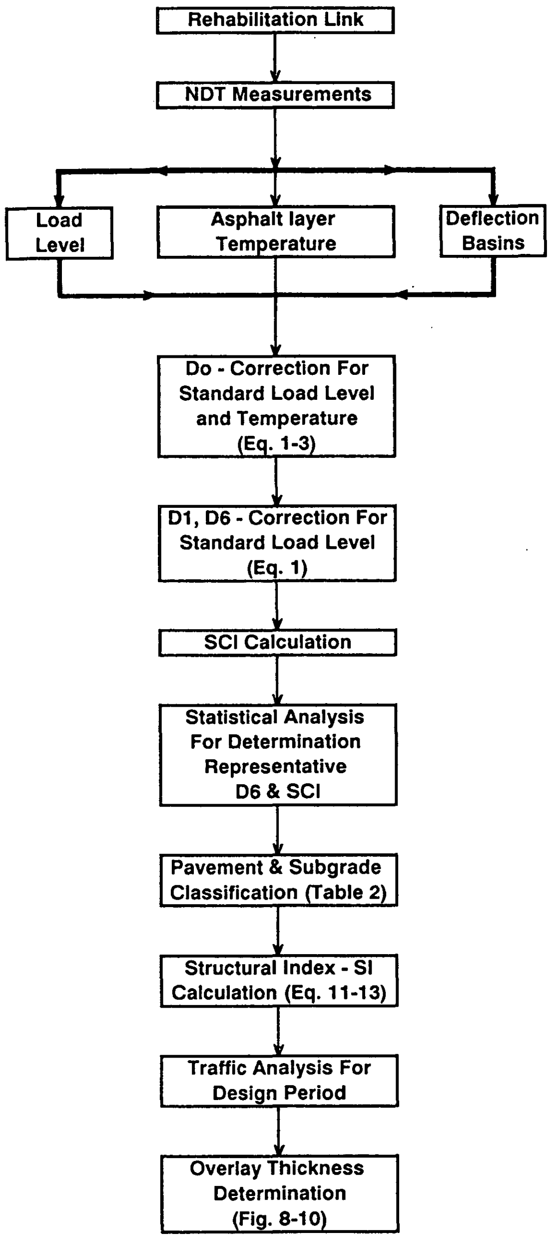

FIGURE 11 Flowchart of the overlay design procedure.

PMMS for economic evaluation and rehabilitation priority order determination of extensive road systems (*20,21*). The fast solutions at the network level save a lot of work required by the field tests in the determination of layer thickness, layer moduli derivations, and stress and strain calculations to predict pavement response.

SUMMARY

This paper presents a methodology for flexible pavement rehabilitation design and development of curves to determine the overlay thickness in flexible pavements. The methodology is based on NDT measurements and the rational approach for predicting the main deterioration criteria such as fatigue and rutting. The findings indicate that it is possible to classify the subgrade and pavement by the seventh deflection, D_6, and the SCI parameter and to express the structural pavement condition by the structural index, SI. Between this index and the overlay thickness there is a dependence, which makes itself evident in the overlay curves presented here. The advantage of the proposed procedure is in its application possibility as a subsystem within a general PMMS. This enables fast and reliable solutions at the network level of extensive road systems. Such solutions are decisive for economic evaluation and rehabilitation priority order determination.

ACKNOWLEDGMENTS

The methodology reported in this paper was developed under a project financed by the Public Work Department of Israel. Special thanks are extended to the departments of Road Maintenance and Material and Road Research, which participated in the steering committee of the project.

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