Evaluating the Structural Strength of Flexible Pavements in Taiwan Using the Falling Weight Deflectometer

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ABSTRACT

This study involves the application of an FWD (JILS-20) on numerous test sections in Taiwan. The goal is to develop a temperature correction equation and to establish a structural evaluation system, SSI, for rapid and reliable assessment of pavement structural conditions. The SSI evaluation system will assist transportation authorities in prioritizing routine preventive maintenance and rehabilitation needs.

Temperature correction factors were established based on the 1176 FWD tests on two specific built test sections. Thus, the effects of traffic load on pavement sections can be eliminated. Comparisons of temperature correction factors with other studies were performed. It is interesting to find that although in those studies temperature correction factors for deflection were developed under different climatic conditions and pavement structures, the temperature correction factors differ, in average, by only 13%. Three significant indicators for upper and subgrade layers were identified through the comprehensive statistical analyses. Criteria were established so that a pavement engineer can repeatedly use those three indicators for cross checking and verifying the most reasonable assessment. For overall structural evaluation, the Structural Strength Index (SSI) was established, with criteria to differentiate good or poor pavement structural condition. One of the advantages of using the SSI is that after the criteria are established, no backcalculation process is required to determine whether structural conditions are good or poor. The SSI is a direct computation from the FWD deflection measurements which are first corrected for temperature. As more experience is gained using the SSI evaluation system, a revised system will provide higher reliability and accuracy.

Keywords: Flexible Pavement, Structural Strength Evaluation, Falling Weight Deflectometer, Temperature Correction

INTRODUCTION

The quality of our daily life depends greatly on the quality of the highway pavements provided by the transportation authorities. Repeated illegal (or legal) overload and frequent trenching to repair utility lines in pavements are causing rapid deterioration of Taiwan’s highway systems. Transportation authorities often adopt maintenance measures that are aimed at preventing immediate safety hazards and minimizing traffic disruption. However, those measures often do not last long, because of lack of comprehensive understanding of the existing pavement conditions.

Although laboratory testing of core samples yields much valuable information to assess pavement layer conditions, the required traffic control and time delay lowers the value of the service to the general public. With the advances in technology in recent years, the non-destructive testing (NDT) methods have been accepted worldwide for evaluation of pavement layer conditions. These methods include the Benkelman Beam, Dynaflect, Road Rator, and Falling Weight Deflectometer (FWD) [Davies and Mamlouk, 1985; Hoffman and Thompson, 1982; Stoffels and Lytton, 1987; Tholen et al., 1985; Ullidtz and Coetzee, 1995]. In the last decade, the Benkelman Beam and Dynaflect have been applied successfully to many projects all over the world [Chen, 1999; Chen et al., 1996; Newcomb, 1989; Parker, 1991; Roesset et al., 1995]. Although the FWD has many more advantages than the other devices, there is only limited FWD-related experience in Taiwan. The goal of this study is to establish a FWD testing system for highway authorities that allows engineers to monitor the changes in pavement conditions with time. Thus, this paper should be of use to other highway authorities on developing their own FWD testing programs.

FWD TECHNIQUE AND LIMITATION

Pavement structural condition is important to highway engineers for processing super-heavy load requests, selecting rehabilitation strategies and other pavement management activities. The FWD has evolved as one of the primary tools in the US and around the world for rapid in-situ pavement structural characterization. During FWD testing, a target load (at a preset drop height) is applied to the pavement surface. Surface deflections are measured through a series of geophone sensors at fixed distances from the load. With known load, deflections and pavement layer thickness, layer moduli can be computed through the mathematical and/or empirical models [Lytton, 1989; Newcomb, 1989; Ullidtz, 1987]. Models based on linear-elastic layer theory or finite element techniques have been given in references [Gomez-Achecar and Thompson, 1986; Parker, 1991]. To improve the accuracy of the analysis, an appropriate temperature correction equation has to be established and applied correspondingly.

One of the main objectives of this study is to assist the Taiwan Highway Bureau to implement FWD technology for pavement evaluation. Without this study, the implementation will be difficult, and the Bureau will lack the confidence to do so. Currently, there is no analytical/mechanistic model for FWD temperature correction and thus it has to be developed empirically. Empirical models have helped engineers for years in analyzing complex problems. The empirical equations developed in this study considered local materials, climate and commonly used pavement structures in Taiwan that provide an 'ease-of-use' benefit to local authorities and practitioners. The first step in this study was to develop the temperature correction equations for FWD measurements and to study the variables (e.g., load level, location of temperature measurement, and combination of load and temperature) that may affect deflection measurements. Numerous FWD tests were conducted in different seasons on specific constructed test sections to develop temperature correction equations for different AC thickness. The specific constructed test sections are only for temperature correction study and thus the effects of traffic load on pavement sections can be eliminated.

Comparisons of temperature correction factors with other studies were performed to assess the differences among them. The second step was to develop a Structural Strength Index (SSI) for rapid and reliable assessment of pavement structural conditions. Comprehensive statistical analyses were performed to determine which variables significantly affect the pavement structural conditions. Eight test sections, including National Freeway, Province, and County roads, were selected with assistance from several experienced pavement engineers. The SSI evaluation system will assist transportation authorities to prioritize routine preventive maintenance and rehabilitation needs. As more experience is gained from using the SSI evaluation system, a revised system will provide higher reliability and accuracy.

Equations developed in this study have been implemented in Taiwan. However, they may not be suitable for other areas. Calibration and verification may be needed in different areas. The temperature correction equations and SSI model developed in this study will be best used at the ranges the models are developed from. The data included in the study is for temperature from 20 °C to 45 °C, thickness from 200 mm to 400 mm and load from 6 kips to 12 kips. It is important to note that the temperature in Taiwan is seldom below 5 °C or above 45 °C.

FWD TESTING

Test Section

To verify the accuracy of the FWD and to derive a temperature correction equation, two test sections were built. Thus, the effects of traffic load on pavement sections can be eliminated. Figure 1 shows the two main types of pavement sections that have been used in this study for temperature correction. FWD tests were conducted parallel to (but not across) the 3.5 m pavement test sections. In addition, FWD tests were conducted at the center of the test lanes to avoid the edge effects [Chen et al, 1996]. Although it is not the most advance method to use a backcalculation program that assumes an infinite width, it is the most common, practical method used by the Highway Department.

These two types of pavement sections in Figure 1 represent the typical sections for National Freeway, and Province and County (P&C) roads. In addition, 8 test sections were selected to develop the structural evaluation system, with assistance from the Taiwan Highway Bureau. These 8 test sections consist of pavement sections in good condition, as well as some with a poor surface layer or poor subgrade. Table 1 presents the locations of the test roads and the corresponding pavement conditions. The layer thickness and other pertinent material characteristics for those 8 pavement sections are well documented [Chang, 2001].

FWD Device

The JILS-20 FWD device used in this study was supplied by Foundation Mechanics Inc., as shown in Figure 2. One of the reasons this machine was selected is because it is one of the most economical devices available in the commercial market. The sensor spacing used in this study was 0, 203, 305, 406, 610, 914, and 1524 mm (0, 8, 12, 16, 24, 36 and 60 inches). The deflections measured by each respective sensor are labeled D_1 through D_7.

Temperature Data Collection

It is well known that the stiffness values are greatly dependent on the test temperature [Ullidtz and Coetzee, 1995; Newcomb et al., 1989; Kim et al., 1995; Chen et al., 2000]. To accurately assess existing pavement conditions, pavement temperatures need to be recorded properly. In this study, several temperatures were collected:

- Ambient air temperature
- Pavement surface temperature (T_s)
- Mid-depth pavement temperature (T_m)
- Five-day average ambient temperatures (T_5)

The first two types were measured using an infrared laser gun. A thermocouple with accuracy of ± 0.1 °C was used to measure the mid-depth pavement temperature. The five-day average ambient temperature was obtained through a local weather station. FWD tests were conducted during different seasons of the year, using a consistent morning-to-evening test routine.

Variables Affecting Deflection Measurements

FWD tests were conducted on the two specific built test sections during warm and cool times of the year, generating a total of 1176 data sets. Although there are many possible variables that may affect the deflection measurements, the three major contributing factors are temperature, load and thickness of the AC layer. The variables included in the study are presented in Table 2. As shown in Figure 1, AC thickness of 200 mm and 400 mm were considered in this study. The reason only those two sections were selected is because the AC thickness of National Freeway, and Province and County (P&C) roads is rarely greater than 400 mm. Also, the AC thickness of Taiwan's roads is generally between 200 mm and 400 mm.

An effort was made, by linear regression analysis, to determine the effect of temperature measurement location on deflection. The temperature measurement with the highest correlation with the deflection measurement was selected as the effective pavement temperature. Kim et al. and Chen et al. reported that the deflection measurements are mainly related to the mid-depth AC temperature. In view of Table 3 and Figure 3, the mid-depth temperature (T_m) has the highest R^2 value for both National Freeway, and Province and County (P&C) roads. Thus, the mid-depth temperature was selected as the effective pavement temperature, and will be the temperature referred to from here on in the paper. The findings from study of those 1176 data sets are given as follows:

- At the same load level and AC thickness, the effective temperature has the greatest impact on D_1, and D_2 deflection values, as shown in Figure 4. The effect of temperature on deflection decreases as the sensor distance increases from the center of the load.
- For pavements of the same AC thickness, linear regression was applied to study the effect of load level on deflection. It was found that there is a linear relationship between load and deflections. It may due to the thick AC pavement used in this study.
- For pavement sections with 400 mm of AC, the temperature has no effect on deflections D_5, D_6, and D_7. Similarly, for pavement sections with 200 mm of

AC, there is only minimal temperature effect on deflections D_5, D_6, and D_7. This phenomenon is shown in Figure 4.

TEMPERATURE CORRECTION FACTOR FOR DEFLECTION

1986 AASHO Design Guide adopts Southgate and Deen's method to correct temperature effects as given in Equations (1) and (2).

$$(D_r)_i = F_i \times (D_o)_i \tag{1}$$

$$F_i = f_i(T, L, H),\ i = 1 \sim 7 \tag{2}$$

Where D_r: temperature adjusted deflection

D_o: measured deflection

F_i: correction factor

T: effective pavement temperature, (mid-depth temperature in this case)

L: load level, and

H: AC thickness

Before multiple regression analysis was conducted, linear transformations were conducted on the deflection values and corresponding variables. Equations (3) through (9) present the results of this analysis. It is not surprising to note that D_6 and D_7 deflections have lower R^2 values. Since D_6 and D_7 values represent subsurface layer properties, temperature has little effect on those two measurements.

$$\log D_1 = 0.137 - 1.4\times10^{-2}H + 1.029\log L + 1.15\times10^{-2}T \qquad R^2 = 0.958 \tag{3}$$

$$\log D_2 = 0.169 - 1.5\times10^{-2}H + 1.005\log L + 8.12\times10^{-3}T \qquad R^2 = 0.966 \tag{4}$$

$$\log D_3 = 0.117 - 1.4\times10^{-2}H + 1.013\log L + 5.97\times10^{-3}T \qquad R^2 = 0.969 \tag{5}$$

$$\log D_4 = -0.204 - 1.11\times10^{-2}H + 1.012\log L + 0.195\log T \qquad R^2 = 0.968 \tag{6}$$

$$\log D_5 = -0.142 - 7.77\times10^{-3}H + 1.02\log L \qquad R^2 = 0.960 \tag{7}$$

$$\log D_6 = -0.555 - 1.51\times10^{-3}H + 1.015\log L \qquad R^2 = 0.933 \tag{8}$$

$$\log D_7 = -1.111 - 3.737\times10^{-3}H + 1.021\log L \qquad R^2 = 0.891 \tag{9}$$

When the values T = 25 °C, H = 20 cm and L = 9 kips (40 kN) were substituted into equation (3) to (9), the following values were obtained: D_1 = 13.3788, D_2 = 10.7402, D_3 = 8.9722, D_4 = 6.4910, D_5 = 4.7416, D_6 = 2.4170, D_7 = 0.8671. Equations (10) through (16) were obtained by substituting those D-values back to original data sets, performing linear transformation, and conducting regression.

$$\log F_1 = 0.99 + 1.43\times10^{-2} H - 1.029\log L - 1.2\times10^{-2} T \qquad R^2 = 0.958 \qquad (10)$$

$$\log F_2 = 0.862 + 1.51\times10^{-2} H - 1.005\log L - 8.1\times10^{-3} T \qquad R^2 = 0.966 \qquad (11)$$

$$\log F_3 = 0.836 + 1.42\times10^{-2} H - 1.013\log L + 6.0\times10^{-3} T \qquad R^2 = 0.969 \qquad (12)$$

$$\log F_4 = 1.017 + 1.112\times10^{-2} H - 1.012\log L - 0.195\log T \qquad R^2 = 0.968 \qquad (13)$$

$$\log F_5 = 0.818 + 7.862\times10^{-3} H - 1.02\log L \qquad R^2 = 0.960 \qquad (14)$$

$$\log F_6 = -0.938 + 1.514\times10^{-3} H - 1.015\log L \qquad R^2 = 0.933 \qquad (15)$$

$$\log F_7 = 1.049 - 3.74\times10^{-3} H - 1.021\log L \qquad R^2 = 0.891 \qquad (16)$$

Further mathematical manipulations were made to derive correction factors (F_i). Equation (17) shows correction factor F_1. All other correction factors are given in Table 4.

$$F_1 = 10^{(0.99+0.0143H-0.012T)} / L^{1.029} \qquad (17)$$

A comparison of correction factors (F_i) among sensors for AC thickness of 200 mm and a load level of 40 kN (9 kips) is presented in Figure 5A. Similarly, AC thickness of 400 mm is given in Figure 5B. Since correction factors (F_5 through F_7) are not a function of temperature, they were not included in these comparisons. In view of Figures 5A and 5B, the effects of temperature were greater, as expected, for the sensors closer to load. The slopes of the plotted correction factors are steeper. Also, the temperature has more of an effect on thicker AC, as these correction factors are higher. This comparison is shown in Figure 5C. AC thickness of 200, 300, and 400 mm were used in the comparison via Equation (17).

COMPARISON WITH OTHER STUDIES

Temperature correction of deflections has been addressed in other literature [Kim et al. and Chen et al.]. One of the most common and important temperature corrections is for D_1 deflection (at the load center). The comparison with other studies was limited to the correction factor for D_1 deflection only. Comparison with other studies is important because it not only provides an opportunity to determine the differences from other studies, but also to check if the established correction factors are valid.

Kim et al. proposed Equation (18) to correct the D_1 surface deflection to a reference temperature of 20 °C.

$$D_{68} = D_T * \left[10^{\alpha(68-T)}\right] \tag{18}$$

Where D_{68}: deflection adjusted to a reference temperature of 20 °C (68 °F)

D_T: deflection measured at temperature T (°F)

α: $3.67*10^{-4}*t^{1.4635}$ for wheelpaths and $3.65*10^{-4}*t^{1.4241}$ for lane centers

t: thickness of the AC layer (inches), and

T: the AC layer mid-depth temperature (°F) at the time of FWD testing

In a recent study, Chen et al. proposed the generalized Equation (19) to correct the D_1 deflection to any reference temperature chosen by the user:

$$W_{T_W}^1 = W_{T_C}^1 * \left[\frac{1.0823^{-0.0098*t}}{0.8631} * T_W^{0.8316} * T_C^{-0.8419}\right] \tag{19}$$

Where $W_{T_W}^1$: the D_1 deflection adjusted to temperature T_W (mm)

t: the thickness of the pavement (mm)

T_C: mid-depth pavement temperature at the time of FWD data collection (°C)

$W_{T_C}^1$: the measured D_1 deflection at T_C (mm), and

T_W: the temperature to which the deflection is adjusted (°C)

The D_1 temperature correction factors calculated from Equations (17), (18) and (19) were computed for temperatures ranging from 10 °C to 50 °C. These factors are graphed in Figure 6 for easy comparison between studies. The temperature correction factors from Equations (18) and (19) are the bracketed portion of those formulas. A reference temperature of 20 °C and AC thickness of 200 mm were used in the computation. It is reasonable to compare the correction factors for AC thickness of 200 mm because both Equations (18) and (19) were developed from that thickness range but not for AC thickness of 400 mm. When Equation (18) was used, the difference in computation from the wheel path and the center of the lane, on average, was less than 3.5%. Since Equation (19) was derived from FWD data from a lane center, the α value for lane center was used in Equation (18). It is interesting to see that although equations (17), (18) and (19) were developed under different climatic conditions and pavement structures, the temperature correction factors differ, on average, by only about 13%. The variation among different studies can be understood, as the AC mix characteristics also affect the temperature-dependent properties.

TEMPERATURE CORRECTION FACTOR FOR MODULUS

Since the structural evaluation system given below requires input of the temperature corrected deflection, only limited discussion is presented for temperature correction on modulus value.

Although many back-calculation programs are available, MODULUS was the one used in this study. Using the MODULUS program, moduli were back-calculated using FWD data collected at different temperatures. Equation (20) was found to represent the modulus vs. temperature relation for the data collected. The temperature and modulus relation is illustrated in Figure 7A.

$$E_r = E_0 * 10^{[-0.705+0.02822T_C]} \qquad R^2 = 0.781 \tag{20}$$

Where E_r: the adjusted modulus of elasticity to 25 °C

E_0: the measured modulus of elasticity at T_C, and

T_C : the mid-depth temperature at the time of FWD data collection (°C)

Kim et al. and Chen et al. proposed equations for temperature correction of modulus value, as given in Equation (21) and (22), respectively.

$$E_{68} = E_T * 10^{0.0153(T-68)} \tag{21}$$

Where E_{68} : adjusted AC modulus to the reference temperature of 68 °F

E_T : back-calculated AC modulus from FWD testing at temperature T (°F), and

T : the AC layer mid-depth temperature (°F) at the time of FWD testing

$$E_{T_W} = E_{T_C} / \left[(1.8T_W + 32) 2.4462 * (1.8T_C + 32) - 2.4462 \right] \tag{22}$$

Where E_{T_W} : the adjusted modulus of elasticity at T_W

E_{T_C} : the measured modulus of elasticity at T_C

T_W : the temperature to which the modulus of elasticity is adjusted (°C), and

T_C : the mid-depth temperature at the time of FWD data collection (°C)

Comparison of the Equations (20), (21), and (22) is presented in Figure 7B. A reference temperature of 25 °C was applied in Equation (22). Also, for the comparison with Equations (20) and (21), the reciprocal of bracketed portion of Equation (22) was used. In view of Figure 7B, there is a close agreement between the present study (Equation (20)) and that proposed by Chen et al. (Equation (22)) for temperature less than 35 °C. It is important to note that Equation (21) proposed by Kim et al. is aimed for a reference temperature of 20 °C which may contribute some of differences from this study. It can be observed from Figures 6 and 7B that the differences among studies for temperature correction were less for deflection than for modulus values.

PROPOSED STRUCTURAL EVALUATION SYSTEM

An innovative structural evaluation system was developed to assist transportation authorities to prioritize routine preventive maintenance or rehabilitation needs. The developed system was based on numerous FWD tests and extensive pavement condition surveys on the National, Province, and County roads. Temperature correction was applied to test data using the correction factor described above. In addition, the backcalculation program MODULUS 5.1 was applied to compute the layer moduli. Using the known moduli and layer thickness, the Structural Number (SN) was subsequently computed by the method outlined in the AASHTO design guide. In the analysis, all pavement sections were treated as a 3-layer system. Furthermore, a statistical multi-variable analysis was performed to verify the indicator criteria. Figure 8 is a flowchart of the proposed method. In particular, the indicator computation and analysis in Figure 8 was aimed at remedying some of the variation in the FWD test results. Various pavement sections were monitored to improve the method's reliability and validity when applied to the other sections. It should be noted that generally, the applicability of an empirical equation is limited to the range of data from which the equation was derived.

Indicator

More than 50 indicators have been proposed in the past to assist engineers in characterizing pavement layer quality. Seven indicators were used in the analysis, including six indicators from previous literature, and one devised from this study. These seven indicators were given as follows:

- Direct deflection indicator: D_1, D_2, D_3, D_4, D_5, D_6, D_7
- Curvature index: $CI_i = D_i - D_{i+1}$, $i = 1 \sim 6$
- Shape indicator: $F_i = (D_{i-1} - D_{i+1}) / D_i$, $i = 2 \sim 6$
- Slope variance: $S_i = D_1 - D_i$, $i = 3 \sim 7$
- Reciprocal indicator: $I_i = 1 / D_i$, $i = 1 \sim 7$
- Area indicator: There are rectangular area, $RA_i = (D_1 + D_2 + D_3 + D_4 + D_5 + D_6 + D_7) / D_i$, $i = 1 \sim 7$ and trapezoid area, $TA_i = (D_1 + 2D_2 + 2D_3 + 2D_4 + 2D_5 + 2D_6 + D_7) / D_i$, $i = 1 \sim 7$

- Self prescribed indicator: $X_{i,i+1} = D_i + D_{i+1}$, $i = 1 \sim 6$,

  $Y_{i,i+1,i+2} = D_i + D_{i+1} + D_{i+2}$, $i = 1 \sim 5$

Pearson correlation analysis [Montgomery, 1991] was performed with criteria of $|r| \geq 0.80$. Note that a criterion of $|r| \geq 0.67$ means the indicator is highly correlated. The higher criteria used in this study is intended to improve the practicality and reliability of the analysis. Table 5 illustrates the summary of indicators in order of significance.

Based on the 3-layer modulus backcalculation and the corresponding correlation analysis, a few observations are noted as follows:

- There are many significant indicators for AC and subgrade layers. Also, those indicators were very sensitive to the variation in stiffness values. In contrast, there were only few indicators for base layers, and they are generally less responsive to the changes in stiffness values.
- The subgrade indicators were related to the deflection values from the sensors farthest from the load, which concurs with those reported in the literatures.
- The upper layer denotes a combination of the AC and base layer. As shown in Table 5, there are some duplications of significant indicators from the AC layer. Thus, to conduct a structural evaluation of pavement layers, the analysis can be focused on upper and subgrade layers.

Establishment of Pavement Structural Evaluation System

The discriminant analysis was applied to conduct multiple-variable analysis and establish Structural Strength Index, SSI. The SSI value will be the indicator used in the Pavement Management System (PMS) to estimate remaining life and to prioritize routine preventive maintenance and rehabilitation needs.

The three significant indicators in Table 5 for upper and subgrade layers were identified as I_1, S_7, X_{12} and I_7, X_{67}, Y_{567}, respectively. Subsequently, the discriminant analyses were performed using Group Centroid and Cutting Score values for those indicators. In the analysis, 0 and 1 were used to represent good and poor conditions, respectively. Several experienced pavement engineers from transportation authority were requested to make a decision on good and poor conditions based on the FWD backcalculation results and the condition surveys.

Subsequently, the Canonical Discriminant Function $Y = -3.079 + 35.638 I_1$ was found for indicator I_1 with Group Centroid values of 0.291 and –1.233 for values 0 and 1, respectively. This Canonical Discriminant Function provided a Cutting Score of -0.942 with a correct ratio of discrimination of 85.6%. Table 6 shows the analysis results of various indicators under good and poor conditions. Thus, a pavement engineer can use criteria in Table 6 for rapid classification of a network pavement system. Also, there are three indicators each for upper and subgrade layer evaluations. Pavement engineers can repeatedly use those three indicators for cross-checking and verifying the most reasonable assessment.

The SSI was developed using the indicators that possess the highest correct ratio of discrimination, which are X_{12} and X_{67} in Table 6 for upper and subgrade layers, respectively. Following the same aforementioned procedure, the SSI function was obtained as given in Equation (23):

$$SSI = -1.945 - 0.021 X_{12} + 0.52 X_{67} \qquad (23)$$

Where $X_{12} = D_1 + D_2$ represents upper layer indicator (mils), and

$X_{67} = D_6 + D_7$ represents subgrade layer indicator (mils)

A SSI value of less than -0.49 indicates a good pavement condition pavement, while a value higher than 0.72 represents a poor pavement condition. The cutting score in this case was 0.23. It is noted that the higher the SSI value, the poorer the pavement condition.

One of the advantages of using the SSI is that after the criteria for indicators were established, no backcalculation process is required to determine whether pavement structural conditions are good or poor. The SSI is a direct computation from the FWD deflection measurements which have been corrected for temperature. The SSI model could easily be used as a screening tool to identify potential areas for further investigation. Since no backcalculation is needed, the possibility of missing a particular/unusual result is possible. With lack of analytical/mechanistic models, empirical equations developed in this study provide an excellent alternative for the local transportation authority. As was indicated earlier, the empirical equations developed in this study are best used for temperatures from 20 °C to 45 °C, thickness from 200 mm to 400 mm and load from 6 kips to 12 kips.

CONCLUSION

This study involved the application of an FWD on numerous test sections in Taiwan to develop temperature correction equations and to establish a structural evaluation system for rapid and reliable assessment of pavement structural conditions. The findings and conclusions are given as follows:

- The measured deflections are highly correlated to mid-depth AC temperature, and this temperature was selected as the effective pavement temperature in this study.
- At the same load level and AC thickness, the effective temperature has the greatest impact on D_1 and D_2 deflection values. The effect of temperature on deflection decreases as the distance of the sensor from the center of the load increases.
- Deflections responded linearly to changes in load. In particular, sensors D_3 through D_5 were very sensitive to the variation of load applied.
- Comparisons of temperature correction factors for deflection and modulus with other studies were performed. Although in those studies temperature correction factors were developed under different climatic conditions and pavement structures, the temperature correction factors for deflection differ, on average, by only 13%. The variation among different studies can be understood, as the AC mix characteristics also affect the temperature-dependent properties. The differences among studies were higher for modulus than those for deflection correction.
- Statistical analysis indicates that the three significant indicators for upper and subgrade layers are I_1, X_{12}, S_7 and I_7, X_{67}, Y_{567}, respectively. Criteria were established for those indicators for rapid assessment of pavement structural conditions. Pavement engineers can repeatedly use those three indicators for cross checking and verifying the most reasonable assessment.

- For overall structural evaluation, the Structural Strength Index (SSI) was established as $SSI = -1.945 - 0.021X_{12} + 0.52X_{67}$. The indicators X_{12} and X_{67} are used because they possess the highest correct ratio of discrimination. An SSI value of less than -0.49 indicates a good pavement condition, and a value higher than 0.72 represents a poor pavement condition.
- One of the advantages of using the SSI is that after the criteria for indicators were established, no backcalculation process is required to determine pavement structural conditions. The SSI is a direct computation from the FWD deflection measurements after they have been corrected for temperature.

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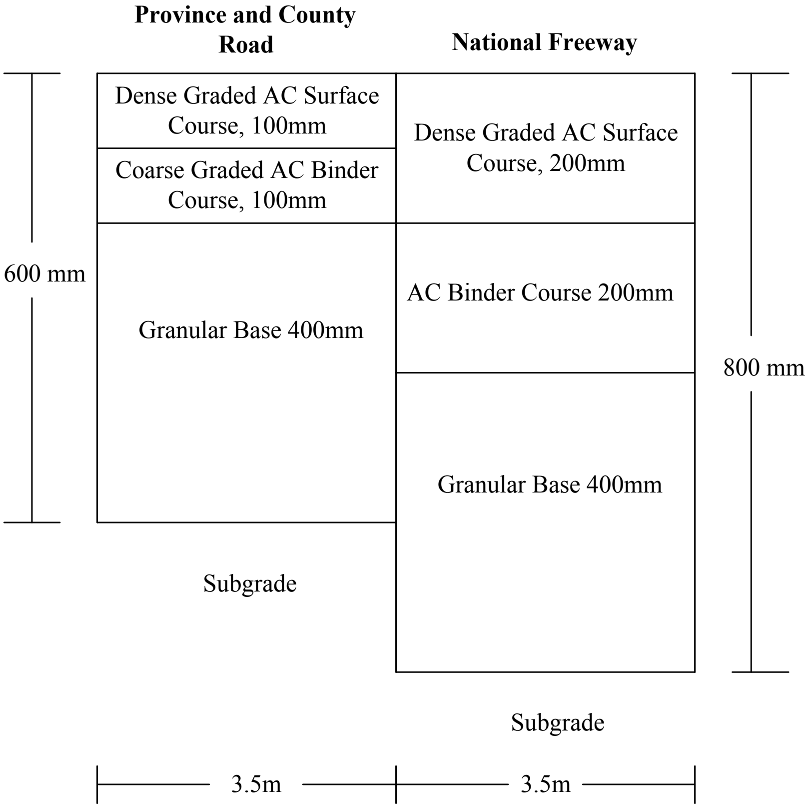

Figure 1 Test Sections for National Freeway, and Province and County (P&C) Roads

Figure 2 JILS-20 FWD Used in this Study

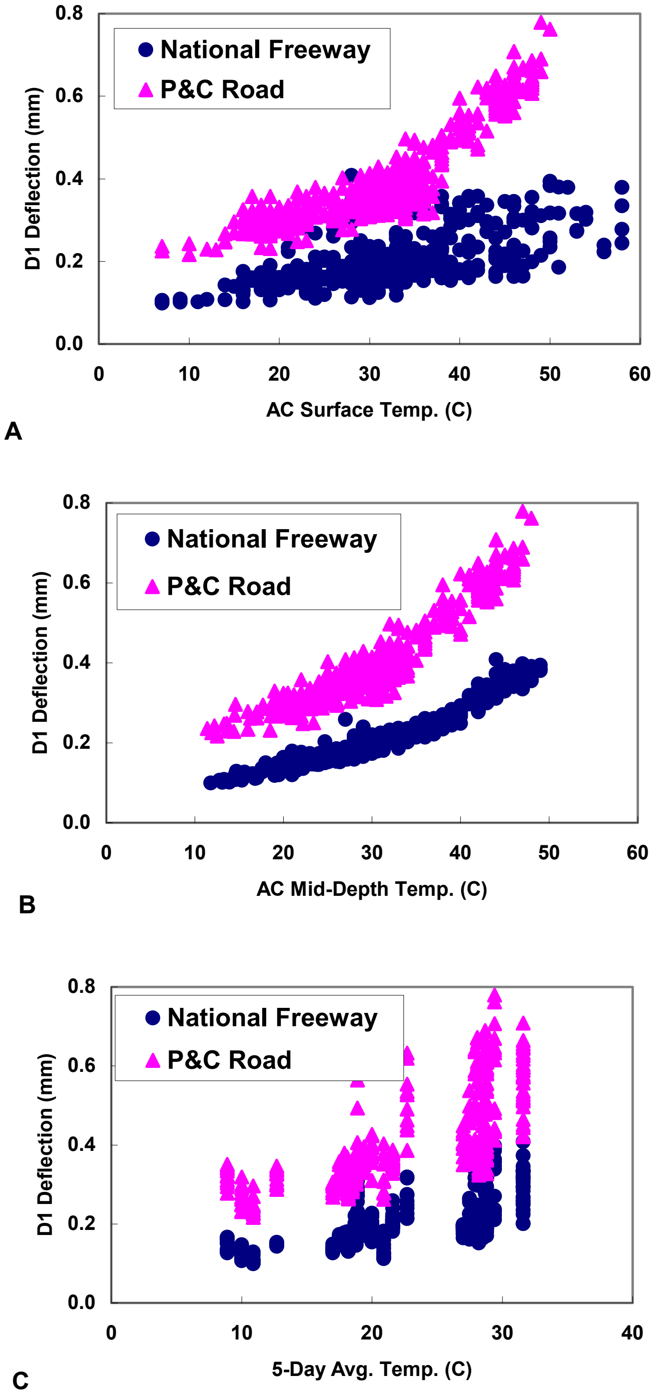

Figure 3 Effect of Temperature Measurement Location on Deflection (A) AC Surface Temperature; (B) Mid-Depth AC Temperature; (C) Five-day Average Ambient Temperatures

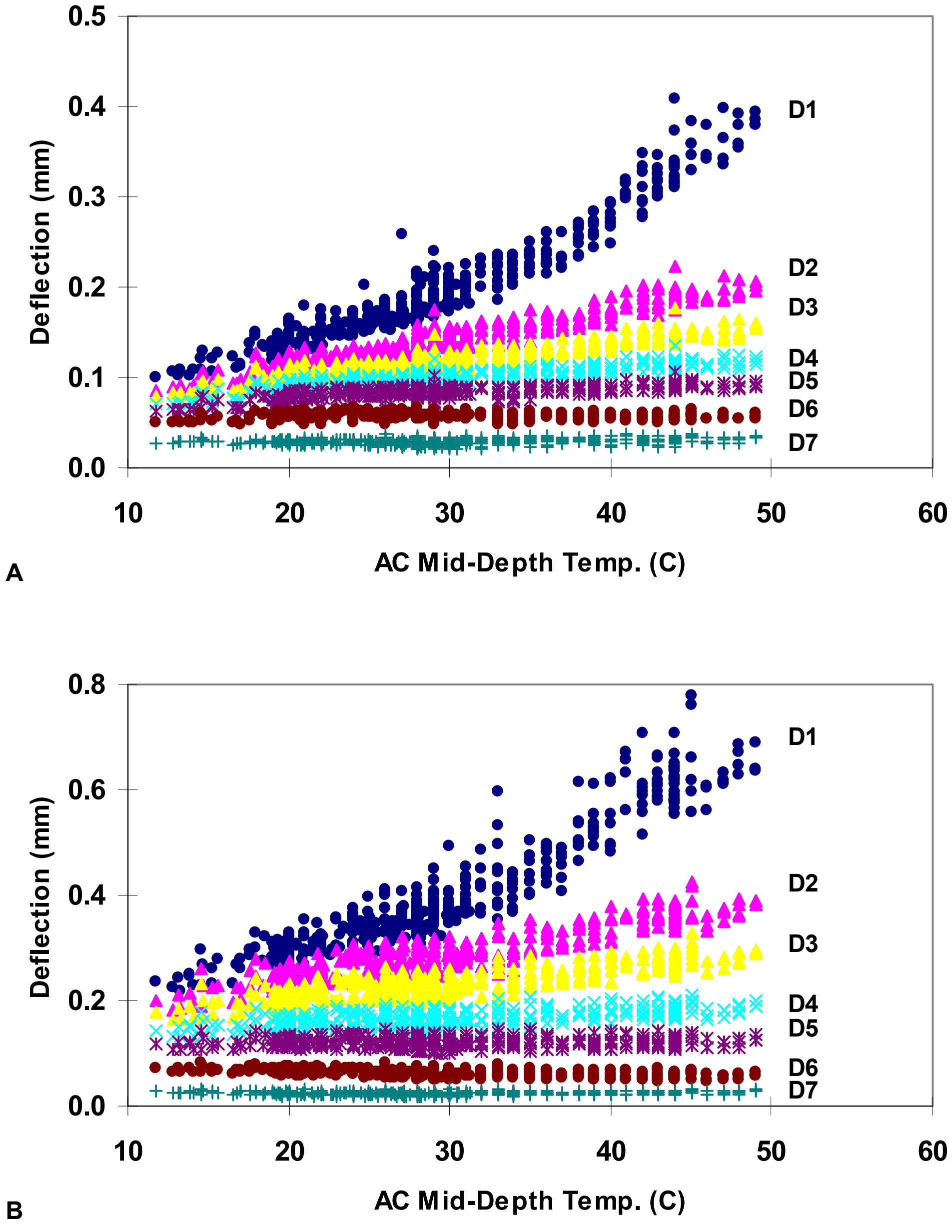

Figure 4 Effects of Temperature on Deflections (A) For National Freeway of 400 mm AC; (B) For Province and County (P&C) Road of 200 mm AC

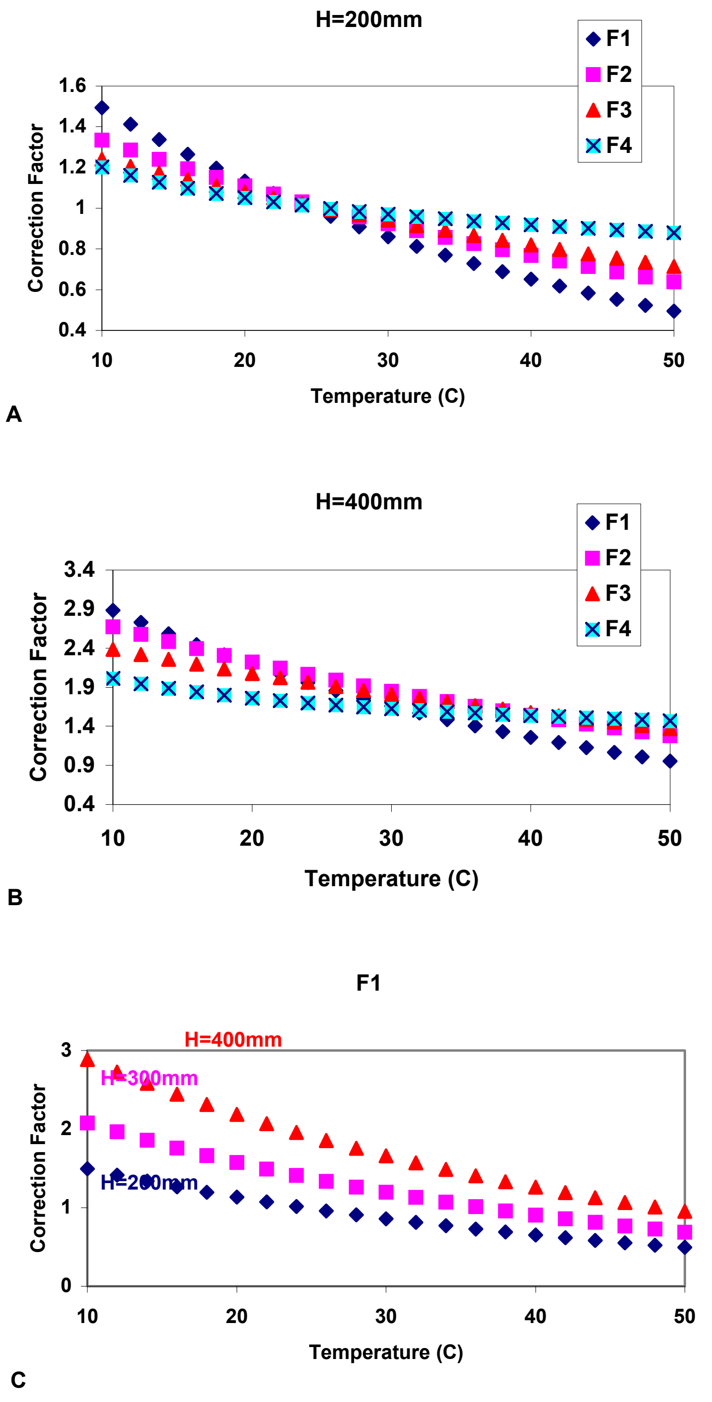

Figure 5 Comparison of Correction Factors for Deflection (A) for H = 200 mm; L = 40 kN (9 kip); (B) for H = 400 mm, L = 40 kN; (C) for F_1, L = 40 kN

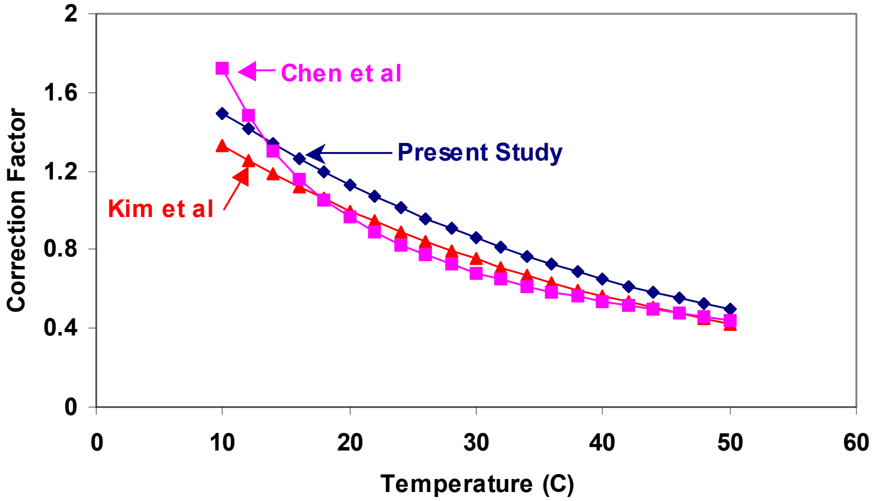

Figure 6 Comparison of Correction Factors (F_1) for Deflection with Other Studies (H = 200 mm)

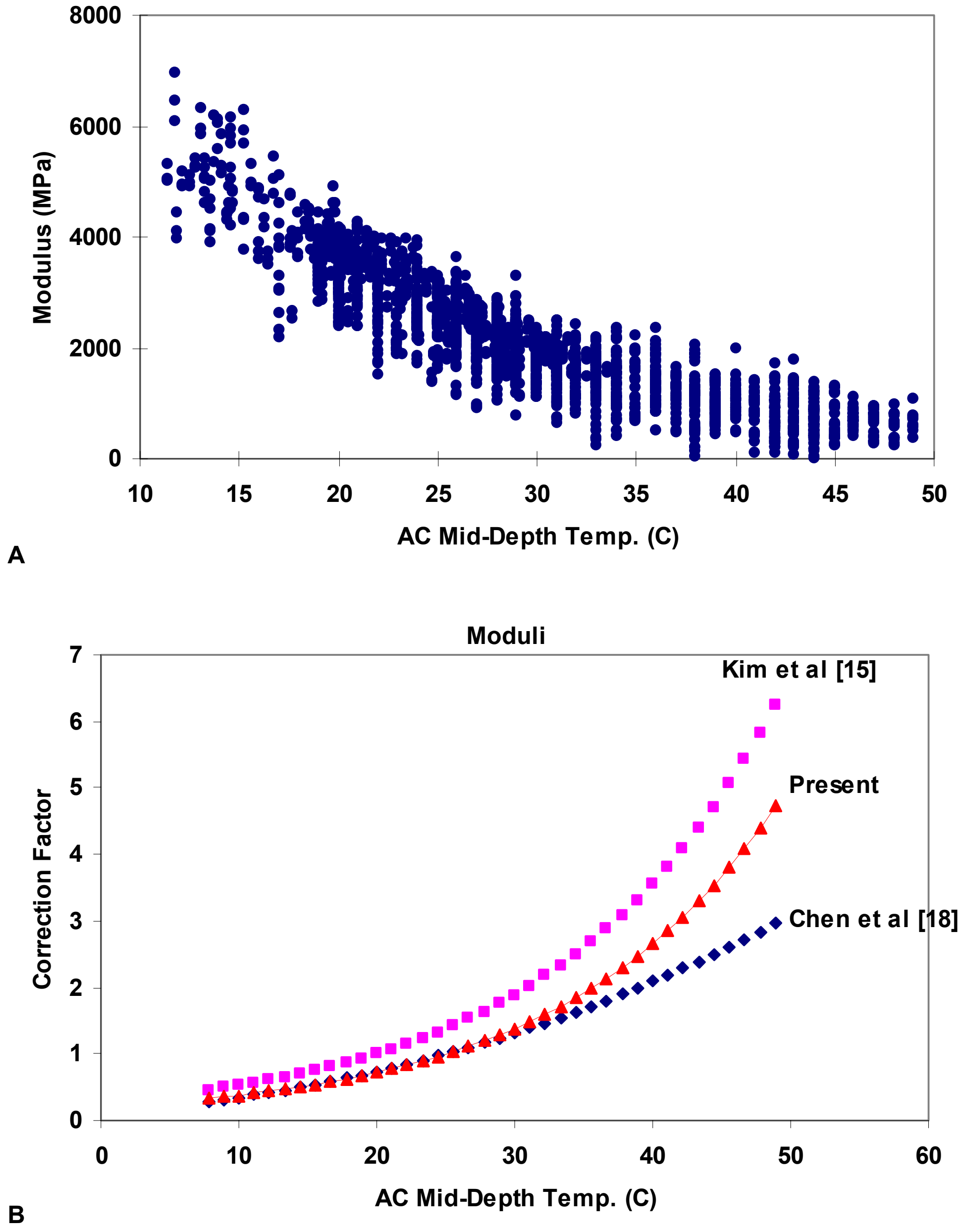

Figure 7 Temperature Correction for Modulus (A) Temperature vs. Modulus (B) Comparison with Other Studies

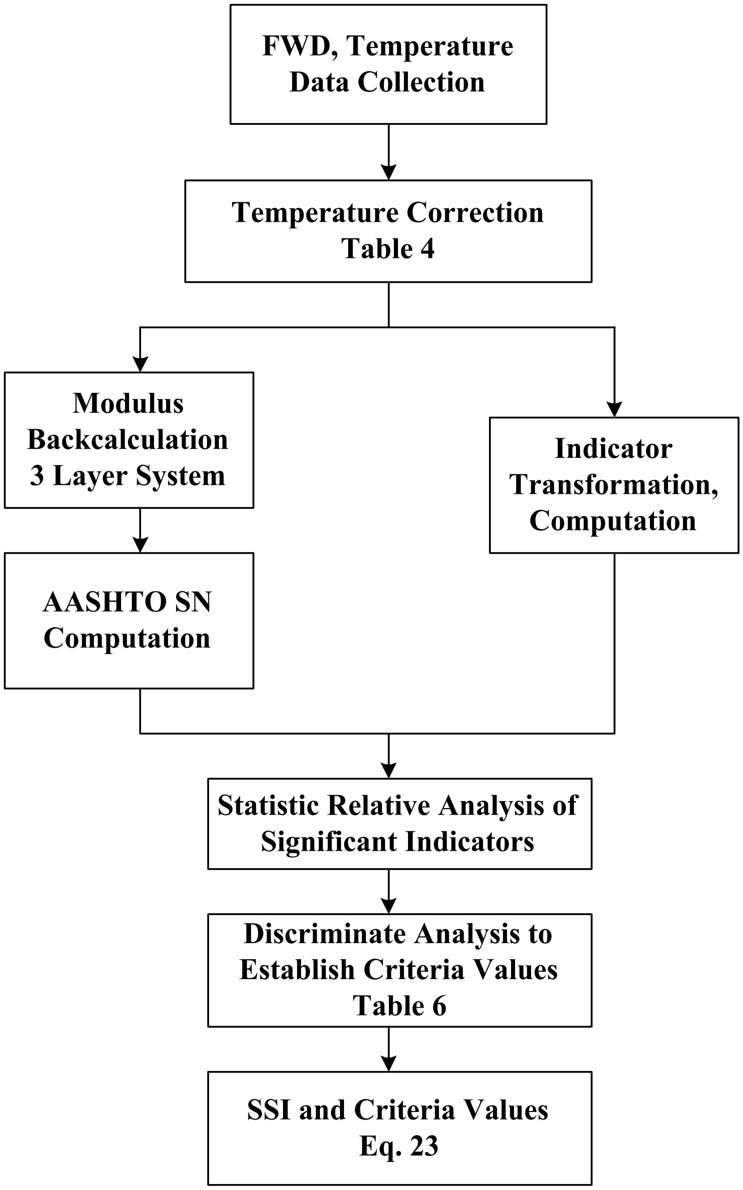

Figure 8 Flowchart of Structural Evaluation System

Table 1 Locations and Conditions of Test Roads

Road Section	Mile Post	Location	Condition
NF-1	23.6 ~ 24.0	Outside Lane (OL)	Poor Surface Layer
C-110A	2.0 ~ 1.6	West Bound, OL	Poor Surface Layer
P-1A	18.5 ~ 17.6	North Bound, OL	Poor Subgrade Layer
P-15	48.1 ~ 49.0	South Bound, OL	Poor Subgrade Layer
C-115	2.0 ~ 2.9	East Bound, OL	Poor Subgrade Layer
NF-1	28.0 ~ 30.0	North Bound, OL	Good Condition
P-1A	22.0 ~ 23.0	South Bound, OL	Good Condition
P-15	50.0 ~ 51.0	South Bound, OL	Good Condition

Table 2 Variables Included in the Study

Variables	Symbols	Total Sample
Temperature	T_s, T_m, T_5	1176
Load	L_6, L_9, L_{12}	
AC Thickness	H_{40}, H_{20}	
Temperature and AC Thickness	$T \times H$	
Load and AC Thickness	$L \times H$	

Table 3 Regression Results for D_1 Values with Different Temperature Location Measurements

Temperature	R^2	
	National Freeway, H = 400 mm	P&C Road, H = 200 mm
T_s	0.392	0.828
T_m	0.941	0.904
T_5	0.532	0.549

Table 4 Temperature Correction Factors for Sensor D_1 through D_7

$(D_r)_i = F_i \times (D_o)_i \qquad F_i = f_i(T, L, H) \qquad i = 1 \sim 7$
$F_1 = 10^{(0.99+0.0143H-0.012T)} / L^{1.029}$
$F_2 = 10^{(0.862+0.0151H-0.0081T)} / L^{1.005}$
$F_3 = 10^{(0.836+0.0142H-0.006T)} / L^{1.013}$
$F_4 = 10^{(1.017+0.0112H)} / \left(T^{0.195} \times L^{1.012}\right)$
$F_5 = 10^{(0.818+0.007862H)} / L^{1.02}$
$F_6 = 10^{(0.938+0.001514H)} / L^{1.015}$
$F_7 = 10^{(1.049-0.00374H)} / L^{1.021}$

Unit: T = °C; L = kip; H = cm

Table 5 Summary of Significant Indicators in Pavement Layers

Layer	Significant Indicator, $\lvert R \rvert \geq 0.80$
AC	S_4, S_3, C_1, C_2, S_5, TA_1, C_3, RA_1, F_2, S_6
Base	C_5, I_3, I_4
Upper (AC + Base)	C_3, C_4, I_1, S_7, S_6, D_2, X_{12}, X_{23}, D_1, D_3
Subgrade	I_7, I_6, I_5, D_7, X_{67}, X_{56}, Y_{567}, I_4, D_6, D_5

Table 6 Upper Layer Structural Evaluation

	Good Condition	Poor Condition	Cutting Score
I_1	> 0.095	< 0.052	0.06
X_{12}	< 20.820	> 38.180	34.87
S_7	< 9.450	> 18.020	16.39

Subgrade Structural Evaluation

	Good Condition	Poor Subgrade	Cutting Score
I_7	> 0.96	< 0.53	0.78
X_{67}	< 3.16	> 5.87	4.34
Y_{567}	< 7.24	> 11.88	9.19