HIGHWAYS DEPARTMENT

GUIDANCE NOTES
ON
BACKCALCULATION OF LAYER MODULI
AND
ESTIMATION OF RESIDUAL LIFE
USING
FALLING WEIGHT DEFLECTOMETER
TEST DATA

Research & Development Division

RD/GN/027A
June 2009

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

These Guidance Notes (GN) describe the standard procedures for estimating pavement layer effective modulus and residual life using data acquired with the Dynatest 8002 Falling Weight Deflectometer (FWD) and the accompanying Evaluation of Layer Moduli and Overlay Design (ELMOD) software. This GN is written in close relation with the ELMOD software. Hence, these GN are not intended for other evaluation software. By following these standard procedures, the data is analysed in a consistent manner and can be used to compare the relative conditions of pavement sections in the road network. It is expected that as more experience are gained in FWD testing and analysis, the Benkelman Beam (BB) test will be phased out. This GN is to be read in conjunction with the accompanying 'RD/GN/026 - Guidance Notes on Falling Weight Deflectometer Field Survey' that stipulates the FWD deflection data collection procedures.

Highways Department (HyD) has been using the BB test to evaluate the structural condition of pavements. However, the BB test has the following limitations:

(a) It cannot be used for rigid pavements.

(b) The loading time for the BB test is longer than normal traffic loading times and the deflection may be different under actual loading conditions.

(c) It cannot measure the shape of the deflection basin.

(d) It cannot analyse individual pavement layers.

(e) The BB test results are analysed according to TRRL Laboratory Report No. 833, which is based on empirical results in the UK and may not be appropriate for local conditions.

(f) The BB test is time consuming, requiring road closure and traffic diversion.

The FWD test is considered more suitable to evaluate the structural condition of the pavement for the following reasons:

(a) It can be used to test both flexible and rigid pavements.

(b) The loading time is comparable to that of normal traffic load, and the resulting stress, strain and deflection correspond well with those under normal traffic.

(c) It can measure the shape of the deflection basin.

(d) It can analyse the condition of individual pavement layers.

(e) The FWD test and analysis parameters can be tailored for local materials.

(f) The FWD testing times are relatively short, road closures are usually not necessary except for high speed roads.

In view of the limitations of the BB test, the more advanced Falling Weight Deflectometer (FWD) test was introduced under the Road Testing Programmes consultancy in 1991 to test around 600 km of roads in the territory. In this study, both flexible and rigid pavements were tested by FWD and structural analysis of the data were carried out. Coring and laboratory tests were carried out to ascertain the pavement thicknesses and material properties. Fatigue characteristics of flexible material were obtained from indirect 4-point bending tests for two mixes available at the time of the study. Data from these material properties are included in these GN for the establishment of the parameter file of ELMOD software.

In 1994, a Highway Maintenance Management System Pilot Scheme consultancy Study was commissioned to develop a pilot pavement management system for the Shatin District. A DYNATEST FWD, together with the ELMOD analysis program, was acquired by HyD in association with project. The FWD has been used experimentally to test the pavement. By the end of 1998, R&D Division conducted a study with a view to promulgate the use of the FWD as a standard pavement structural evaluation test and to phase out the BB test.

The FWD test to be conducted at the project level. The results should be considered at the project level. The results should be considered in conjunction with other inspection and test data in order to determine the most appropriate treatment method. Selection of the treatment method requires engineering judgement. The overlay thickness automatically calculated by ELMOD4 should not be directly used for rehabilitation design purposes. Overlays, if deemed to be most appropriate, should be designed in accordance with the HyD Pavement Design Manual when it is published.

The procedures are illustrated with the use of ELMOD Version 4.4 (ELMOD4) and may need to be updated when there is a major change in ELMOD. Periodical updates are required when the properties of local pavement materials are better known and more analysis results are obtained to expand our database.

Section 2 of these notes covers briefly the basic theory used by ELMOD in FWD data analysis. Section 3 explains the preparation work required before carrying out the analysis. Section 4 describes the detailed analysis steps in using ELMOD4. Section 5 illustrates the analysis steps for flexible pavements with an example. Section 6 illustrates the analysis steps for rigid pavements with an example. Appendix A is a list of references for further information.

2 BASIC THEORY

2.1 PAVEMENT STRUCTURE

The general principle in pavement modelling is that layers of similar properties should be combined into one layer. The thickness of individual layers should be determined in accordance with Section 4.2. The pavement model to be used for analysis should be determined as outlined below.

A flexible pavement is normally modelled as a 3-layer structure with all asphalt materials combined into one top layer, the sub-base as the second layer, and the subgrade as the third layer. A rigid pavement is normally modelled as a 2-layer structure with the concrete slab as the top layer and the sub-base combined with the subgrade to form the second layer.

Sometimes the above standard models may not give reasonable results, e.g., the sub-base modulus is lower than the subgrade modulus. The reason may be due to a non-linear subgrade modulus, normally increasing with depth. The subgrade modulus may also be stress dependent, usually the modulus increases as the deviator stress on the subgrade decreases. Hence the subgrade modulus measured under the load centre is smaller than that measured at some distance away from the load. A third reason may be the presence of an effective rigid layer at a certain depth in the subgrade. To achieve a more reasonable backcalculation result, the subgrade may be further divided into 2 layers, with a layer just beneath formation level of thickness 500 – 1000 mm on top of a semi-infinite bottom layer.

Overseas experiences indicate that the critical conditions in the flexible pavement structure are the horizontal tensile strains at the bottom of the top layer and the vertical strains at the top of the subgrade. A typical flexible pavement model is shown in Figure 2.1. The critical conditions in a rigid pavement structure are more difficult to determine because of the presence of discontinuities at slab joints. A typical rigid pavement model is shown in Figure 2.2. The modelling rules for the different pavement layers are described in further details in Section 4.2.

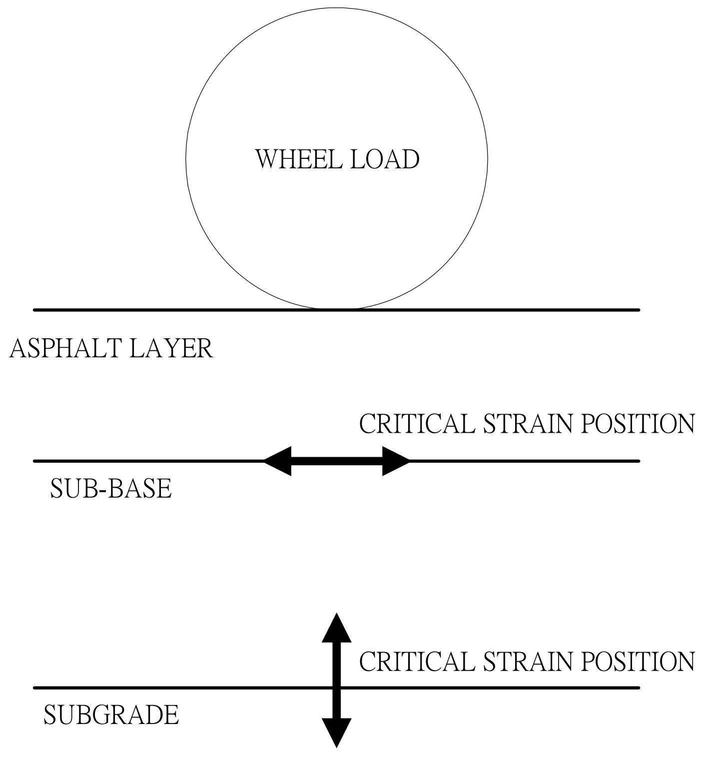

Figure 2.1 – Typical Flexible Pavement Model

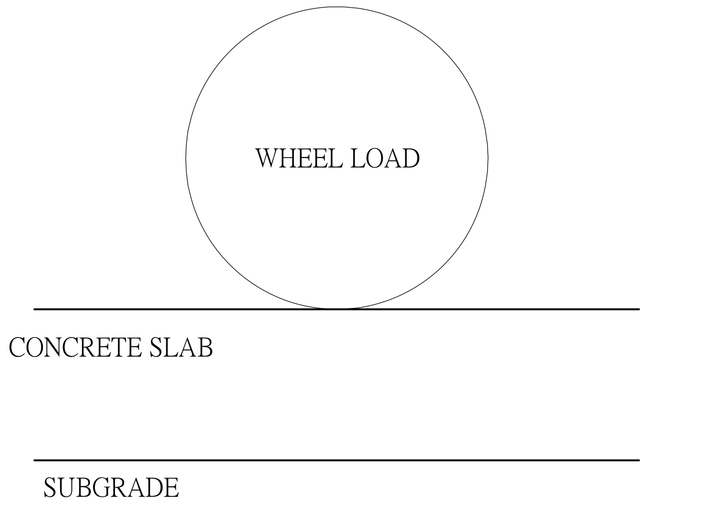

Figure 2.2 – Typical Rigid Pavement Model

2.1.1 TOP LAYER

For flexible pavement, all asphalt layers are combined into one layer. Note that non-structural surfacing layers such as friction courses should be excluded from the total thickness.

For rigid pavement, the concrete slab is modelled as the top layer. For a composite pavement where a thin asphalt friction course covers a concrete slab, the asphalt layer should not be considered as a structural layer and only the thickness of the concrete slab should be used.

The top layer is designated as Layer 1, with thickness H_1 and modulus E_1.

2.1.2 SUB-BASE

For flexible pavement, the granular sub-base is modelled as a separate layer. This is designated as Layer 2, with thickness H_2 and modulus E_2.

For rigid pavement with a granular sub-base, the difference in magnitude between the concrete slab modulus and the underlying layers is sufficiently large such that the difference in modulus between the granular sub-base and subgrade becomes insignificant. The sub-base should be combined with the semi-infinite subgrade into one layer and designated as Layer 2 with modulus E_2.

If a lean concrete sub-base is used, it is assumed that the lean concrete has cracked into pieces of size 300mm or above. This size is equal to or larger than the size of the FWD loading plate and the deflections in the neighbourhood of the loading plate cannot be correctly evaluated with elastic theory. Therefore the sub-base should also be combined with the semi-infinite subgrade into one layer and designated as Layer 2 with modulus E_2.

2.1.3 SUBGRADE

The subgrade is normally modelled as one semi-infinite layer. In the 2-layer model, the sub-base is combined with the subgrade and designated as Layer 2, with modulus E_2. In the 3-layer model, the subgrade is designated as Layer 3, with modulus E_3.

In a 4-layer model, the additional subgrade layer of thickness 500mm to 1000mm just below formation level is designated as Layer 3, with thickness H_3 and modulus E_3 and the underlying subgrade is designated as Layer 4, with modulus E_4. However, ELMOD requires that a ratio E_2/E_3 be fixed for a 4-layer model. For granular materials, ELMOD assumes the ratio $E_2/E_3 = 0.2 * H_2^{0.45}$ by default.

The use of a 5-layer model is normally not recommended. At some locations, a rigid layer, e.g. rock head, may exist at a known depth below the pavement structure. In such cases, the depth to the rigid layer should be entered into ELMOD.

2.2 BACKCALCULATION OF PAVEMENT LAYER MODULI

There are various software programs available for estimating the stiffness moduli of the pavement layers. Different programs may apply different principles. ELMOD uses an approximate method based on Boussinesq’s equations and Odemark’s method of equivalent thickness to estimate the layer moduli. This Section outlines the basic theories used.

2.2.1 BOUSSINESQ'S EQUATIONS

The 'Radius of curvature' method adopted by ELMOD makes use of the Boussinesq's equations. Boussinesq developed a set of equations to calculate the stress, strain and displacement conditions in a homogeneous, isotropic, linear elastic semi-infinite space under a point load[9]. The stress, strain and displacement conditions under a uniform load can be found by integration. At the depth 'z' below the centreline of a uniform circular load 'σ_0' with radius 'a', the stress, strain and displacement are given by the following:

$\sigma_z = \sigma_0 \text{ x } \{1 - 1/[1+(a/z)^2]^{3/2}\}$

$\sigma_r = \sigma_t = \sigma_0 \text{ x } \{(1+2\mu)/2 - (1+\mu) / [1+(a/z)^2]^{1/2} + (1/2) / [1+(a/z)^2]^{3/2}\}$

$\varepsilon_z = (1+\mu) \text{ x } \sigma_0/E \text{ x } \{(z/a) / [1+(z/a)^2]^{3/2} - (1-2\mu) \{(z/a) / [1+(z/a)^2]^{1/2} - 1\}\}$

$d_z = (1+\mu) \text{ x } \sigma_0 \text{ x } a/E \text{ x } \{1 / [1+ (z/a)^2]^{1/2} + (1-2\mu) \text{ x } \{[1+(z/a)^2]^{1/2} - z/a\}\}$

$R = E \text{ x } a/[(1-\mu^2) \text{ x } \sigma_0] / \{1+[1+ 3/2/(1-\mu)] \text{ x } (z/a)^2\} \text{ x } [1+(z/a)^2]^{5/2}$

$\varepsilon_r = z / 2 / R$

where σ_z = vertical stress;

σ_r = radial stress;

σ_t = tangential stress;

ε_z = vertical strain;

ε_r = horizontal strain;

d_z = vertical displacement;

R = radius of curvature;

E = modulus;

and μ = Poisson ratio.

Note that the horizontal strain at the bottom of a bituminous layer, often the critical strain in the pavement structure, can be found by first calculating the radius of curvature of the plane at the bottom of Layer 1.

2.2.2 ODEMARK'S METHOD OF EQUIVALENT THICKNESS

Boussinesq's equations are only applicable to a homogeneous layer. In practice, most pavement structures are not homogeneous but are layered systems. Odemark developed an approximate method to transform a system consisting of layers with different moduli into an equivalent system where the thicknesses of the layers are altered but all layers have the same modulus. This is known as the Method of Equivalent Thickness. The transformation assumes that the stiffness of the layer remains the same, i.e.

$I \times E / (1 - \mu^2)$ remains constant

where I = moment of inertia;

E = layer modulus;

and μ = Poisson ratio.

Since I is a function of the cube of the layer thickness, the equivalent thickness transformation for a layer with thickness = h_1, modulus = E_1, and Poisson ratio μ_1 into a layer with equivalent thickness = h_e, modulus E_2, and Poisson ration μ_2 may be expressed as follows:

$$h_1^3 \times E_1 / (1 - \mu_1^2) = h_e^3 \times E_2 / (1 - \mu_2^2); \quad \text{or}$$

$$h_e = h_1 \times [E_1 / E_2 \times (1 - \mu_2^2) / (1 - \mu_1^2)]^{1/3}.$$

Since this is an approximate method, an adjustment factor 'f' is applied to the right hand side of the above equation to obtain a better agreement with elastic theory. The value of 'f' depends on the layer thicknesses, modular ratios, Poisson ratios and the number of layers in the pavement structure. Furthermore, the Poisson ratio for all pavement materials can be assumed to be the same, usually equal to 0.35. The equivalent thickness equation can therefore be expressed as:

$$h_e = f \times h_1 \times [E_1 / E_2]^{1/3}.$$

To analyse a multi-layer pavement structure with known layer moduli, the layers can be successively transformed into an equivalent system with a homogeneous layer modulus equal to the modulus of the semi-infinite subgrade layer by applying Odemark's method. Boussinesq's equations can then be applied to calculate the stress, strain and displacement conditions within the equivalent layered system. In analysing FWD data, the process is reversed by using the surface displacements measured at varying distances under a plate load to 'backcalculate' the moduli of individual pavement layers.

The backcalculated modulus is often called the effective modulus because the value represents the effect of the layer within the whole pavement structure. This may be different from the modulus obtained if the layer is evaluated in isolation, such as in the case of testing a cored sample in the laboratory.

2.2.3 SURFACE MODULUS

The surface modulus is the ‘weighted mean modulus’ of the semi-infinite space calculated from the surface deflection using Boussinesq’s equations. The surface modulus at a distance ‘r’ roughly reflects the surface modulus at the same equivalent depth z = r. If the subgrade is a linear elastic semi-infinite space, the surface modulus should be the same at varying distances. If a stiff layer is present, the surface modulus at some distance should become very large.

ELMOD begins the process by estimating the subgrade modulus using the outer deflections since these are almost entirely controlled by the subgrade. The change in moduli with varying distances from the load centre is used to check whether a stiff layer is present at some depth. This can be checked by calculating the ‘surface modulus’ as follows:

$$E_0(0) = 2 \times (1 - \mu^2) \times \sigma_0 \times a / d_0(0) \text{ and}$$

$$E_0(r) = (1 - \mu^2) \times \sigma_0 \times a^2 / [\, r \times d_0(r) \,] \quad \text{(valid for } r > 2a\text{)}$$

where $E_0(r)$ = surface modulus at distance r;

μ = Poisson ratio of the subgrade (normally = 0.35);

σ_0 = uniform stress on the plate;

a = radius of the loading plate;

r = distance from the centre of load;

and $d_0(r)$ = surface deflection at distance r.

Note that the equation for $E_0(r)$ is only valid for $r > 2a$.

2.2.4 SUBGRADE NON-LINEARITY

If a stiff layer is not detected, ELMOD calculates the subgrade non-linearity coefficients 'C' and 'n' using the following equation:

$$E_0 = C \times (\sigma_1 / \sigma)^{n}$$

where E_0 = surface modulus;

σ_1 = major principal stress;

σ = reference stress, normally 160 MPa;

C = constant;

and n = negative constant.

Normally 'C' decreases almost linearly with the increase in moisture content. 'n' may be taken as a measure of the non-linearity. If n is zero, the subgrade is linear elastic and as n decreases, the non-linearity becomes more and more pronounced.

2.2.5 ITERATION

With the 'Radius of Curvature' method, ELMOD uses the centre deflection and the curvature of the deflection basin under the loading plate to determine the moduli of the top layer, and the intermediate layers if they are present. The subgrade modulus under the load centre is adjusted according to the estimated stress level, and the outer deflections are checked. If adjustments are necessary, the layer moduli are then recalculated.

The 'Deflection Basin Fit' method goes one step further by closely matching the calculated deflection profile and the measured deflection profile. The percentage difference between the calculated value and the measured value can be specified as the convergence criteria in the iteration.

2.2.6 WESTERGAARD'S EQUATIONS FOR RIGID PAVEMENT

For rigid pavement, a special problem occurs due to the discontinuities at the concrete slab joints. Elastic theory may be used for the slab centre but is not applicable close to a slab joint or corner. Westergaard developed an approximate method based on the assumption that the subgrade does not transfer shear stress[10]. This implies that the reaction of the subgrade on the slab is equal to the deflection multiplied by a constant 'k' called the modulus of subgrade reaction. 'k' can be calculated as follows:

$$k = 0.54 \times Es / h_e$$

where Es = modulus of subgrade;

and h_e = equivalent thickness of the concrete slab with respect to the subgrade.

Based on the above, Westergaard developed equations that were later modified by Ioannides, Thompson and Barenberg[11] to calculate the stresses and deflections for a concrete slab as follows:

$$\sigma_I = \{3P \times (1 + \mu) / 2h^2\} \times \{ [\ln (2L / B) + 0.5 - \tau] / \pi + 1 / 32 \times (B / L)^2\}$$

$$d_I = [P / (8kL^2)] \times \{1 + (1 / 2\pi) \times [\ln (a / 2L) + \tau - 1.25] \times (a / L)^2\}$$

$$\sigma_E = \{3P \times (1 + \mu) / [(3 + \mu) \times \pi h^2] \} \times \{\ln (E \times h^3 / 100ka^4) + 1.84 - 4\mu / 3 + (1 - \mu) / 2 + 1.18 \times (1 + 2\mu) \times (a / L)\}$$

$$d_E = [P \times (2 + 1.2\mu)^{0.5}] / \{ (Ekh^3)^{0.5} \} \times [1 - (0.76 + 0.4\mu] \times (a / L) \}$$

$$\sigma_C = (3P / h^2) \times [1 - (C / L)^{0.72}]$$

$$d_C = P/kL^2 \times (1.205 - 0.69C / L)$$

where σ_I = maximum bending stress when load is in interior position;

d_I = deflection at centre of slab;

σ_E = maximum bending stress when load is at edge position;

d_E = deflection when load is at edge position;

σ_C = bending stress when load is at corner position;

d_C = deflection at corner position;

P = uniformly distributed single wheel load;

h = concrete slab thickness;

E = concrete modulus;

μ = Poisson ratio of concrete;

k = modulus of subgrade reaction;

a = radius of loaded area;

C = side length of a square loaded area;

$B = (1.6a^2 + h^2)^{0.5} - 0.675h$ for $a < 1.724h$;

$B = a$ for $a > 1.724h$;

$L = \{Eh^3 / [12k \times (1 - \mu^2)]\}^{0.25}$;

and τ = Euler's constant (= 0.5772).

In the above equations, 'interior position' means the load is at a considerable distance from the edges and 'edge position' means the load is at the edge but at considerable distance from any corner. While the equations for 'interior position' are reasonably accurate when the smallest slab dimension is greater than 3L, Westergaard's equations are most useful for edge and corner loadings.

2.2.7 LOAD TRANSFER ACROSS JOINT FOR RIGID PAVEMENT

ELMOD uses the Odemark-Boussinesq method to calculate the layer moduli at the centre of the slab. The layer moduli are then used with Westergaard's equations to calculate the load transfer across joints. The load transfer efficiency factor 'j" is defined as follows:

$$j = 1 - (d_j - d_j') / (d_e - d_e')$$

where d_j and d_j' are deflections of adjacent slabs at any point across the joint;

and d_e and d_e' are deflections at the same point if the joint transferred no load.

ELMOD can plot on screen the graphs of moduli of each layer, the non-linear properties of the subgrade material 'C' and 'n', the modulus of concrete slab 'E_1' and modulus of subgrade reaction 'k', the differential deflection 'Dd', and the percentage load transfer efficiency 'LT%' across a joint. A small 'Dd' and a high 'LT%' indicates better joint integrity.

2.3 ESTIMATION OF RESIDUAL LIFE

2.3.1 SEASON AND TRAFFIC

Design traffic load in standard axles are required for the estimation of residual life. They can be calculated in accordance with RD/GN/017 or the HyD Pavement Design Manual when it is published. For ELMOD input, Section 3.5 shall be referred.

2.3.2 TEMPERATURE EFFECTS

Seasonal variation in traffic load affects the estimated traffic load used for estimation of residual life. The moduli determined by ELMOD for a given test point naturally correspond to the climatic conditions that happen to prevail during the testing. These conditions are not likely to be representative of design conditions and the moduli must therefore be adjusted.

Asphalt material is sensitive to temperature changes. Pavement temperature at the time of collecting the deflection data varies with time and season. Hence, a reference temperature shall be adopted for comparsion and design purpose. The backcalculated asphalt moduli has to be corrected to this reference pavement temperature before estimating the pavement residual life. Besides, unbound material (granular sub-base and subgrade) is also sensitive to seasonal and annual temperature variations.

2.3.3 MATERIALS

The general equation relating traffic loading to pavement deterioration, called the Transfer Function, is as follows:

$$\text{Permissible stress/strain} = a \times N^{-b} \times (E / E_{ref})^{c}$$

where a, b and c = constants;

N = allowable stress/strain repetitions to fatigue/rutting failure;

E = modulus of the material; and

E_{ref} = a reference modulus that converts the transfer function to proper units.

Details of the values of constants a, b and c for different material are available in Section 3.2.2.

2.3.4 LOAD

The 80kN standard axle load is adopted. All design traffic loads are expressed in terms of equivalent standard axle load. For ELMOD input, Section 3.2.3 shall be referred.

2.3.5 ESTIMATION

Backcalculated effective layer moduli are corrected for seasonal and temperature effect. Critical strains / stresses are determined based on the design load and the assumed theory adopted by each individual program. These critical strains / stresses at locations described in Section 2.1 are compared with the failure characteristics of each material and a set of allowable strain / stress repetitions of each material is obtained. Based on this data set, critical load repetition values for layers are obtained. With the past and estimated future traffic load, a set of estimated residual life of each individual pavement layer can be obtained for review. Based on this data set, different maintenance options can be considered to restore the pavement sections to desirable condition.

2.4 SECTIONING

2.4.1 SECTIONING OF PAVEMENT

The deflection data obtained from the FWD test should be reviewed to see if there are large fluctuations or inconsistencies. The cumulative sums of the centre deflection can be used to assist in deciding whether the length of the test run should be divided into different sections for design purposes. In order to help observe if there are significant changes in trend along the test run, method of cumulative sum can be adopted.

2.4.2 CUMULATIVE SUMS OF DEFLECTION

The cumulative sum A.d. at the i^{th} station is defined as follows:

$$A.d. = \sum \delta_i - i\,\mu$$

where $\sum \delta_i$ = sum of deflections from the 1^{st} station to the i^{th} station inclusively;

i = number of stations from δ_1 to δ_i inclusively;

and μ = mean deflection of the test run

From the cumulative sum, check if there are significant changes in trend (from upward to downward or vice versa). A homogeneous section is one in which the cumulative sums continue in the same upward or downward trend. A significant change in the upward or downward trend indicates a change in section. Divide the test run into homogeneous sections such that the trend is reasonably consistent within each section. This step is illustrated in Section 5.7. If a former analysis has been carried out before the sectioning, the homogeneous sections shall be re-backcalculated and analysed again. These steps are illustrated in Sections 5.8 and 5.9.

2.4.3 CHARACTERISTIC DEFLECTION

For design purposes, a set of characteristic values representative of the section has to be selected. This is done statistically by choosing the set of values at the test station where the centre deflection is at the 85 percentile of all the centre deflections in the section.

The effective moduli and residual life calculated for this test station can be used in the subsequent rehabilitation design.

3 PREPARING FOR THE ANALYSIS

To get started in analysing the FWD data, the following are required:

a. A PC installed with the ELMOD program;
b. The customised HK042009.WPR parameter file and the OLD200.TEM and NEW200.TEM temperature correction files for the old and new mix bituminous materials respectively;
c. The FWD raw data files acquired with the Dynatest equipment;
d. The pavement model and thickness of individual pavement layers of the pavement structure being evaluated; and
e. The estimated average annual traffic loading for the road section being analysed.

3.1 ELMOD INSTALLATION

The current version of ELMOD is Version 4.5.35. Copies of ELMOD licences will be provided to relevant offices to perform the analysis. Relevant offices are required to provide a PC with minimum 32MB RAM and running Windows 98/2000/Me/NT/XP (English or Chinese) to install and run the program[4].

3.2 PARAMETER AND TEMPERATURE FILES

A variety of tests have been conducted on samples of two different bituminous mixes in 1991 Road Testing Programmes consultancy. Based on test results and the recommendations in the consultancy reports, the **HK042009.WPR** parameter file and the **OLD200.TEM** and **NEW200.TEM** temperature correction files are compiled and are available in R&D Division.

ELMOD uses 3 sets of parameters: seasons, materials and loads to estimate the residual life of the pavement structure. Use ‘Parameter’ from the pull down menu to open the ‘HK042009.WPR’ parameter file. The ‘HK’ in the filename implies this parameter file is tailored for use under Hong Kong conditions and the ‘042009’ in the filename implies the parameters are prepared in April 2009. This file needs to be updated as new materials are introduced or knowledge on the properties of existing materials and environmental effects is improved. The specific settings in HK042009.WPR are described below.

3.2.1 SEASONS

ELMOD allows the user to set up seasonal variations in traffic loads. Currently, there is no local data available for this variation and hence a single season of 52 weeks, with characteristic week set at mid-year, is adopted. This setting needs to be reviewed in the future.

The ‘number of seasons’ is set to 1, the ‘No. of weeks in season’ is 52, the ‘Characteristic week in season’ is 26, the ‘Date’ is entered in ELMOD as Jun 26, and the ‘% loads in season’ is 100.

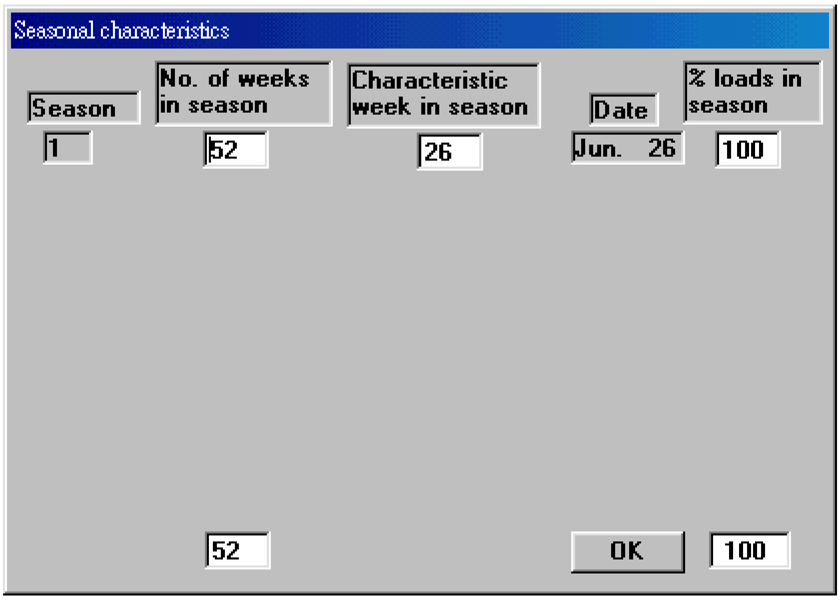

Figure 3.1 – Seasonal Characteristics

Seasonal variations of unbound layers are also not set in Section 3.2.2.

3.2.2 MATERIALS

ELMOD uses the deterioration properties of pavement materials to estimate the damage under traffic load. Default settings of ELMOD4 are changed to suit local conditions. Six types of commonly used pavement materials are set in the parameter file HK042009.WPR:

Asphalt New Mix, Asphalt Old Mix, Concrete, Granular Sub-base, Lean Concrete Sub-base and Subgrade.

They shall be amended when updated information on material is obtained. Besides, new material properties can be added if new material or asphalt mix is adopted.

Asphalt New Mix refers to mixes designed to the new bituminous materials specifications after the November 1988 Road Note 2 and Asphalt Old Mix refers to mixes designed to the old specifications before this. The Road Testing Programme Consultants determined their fatigue characteristics by carrying out laboratory tests on in-situ asphalt pavement materials.

The fatigue lines for the asphalt mixes are shown in Figure 3.2 below, where Flex New = Asphalt New Mix and Flex Old = Asphalt Old Mix:

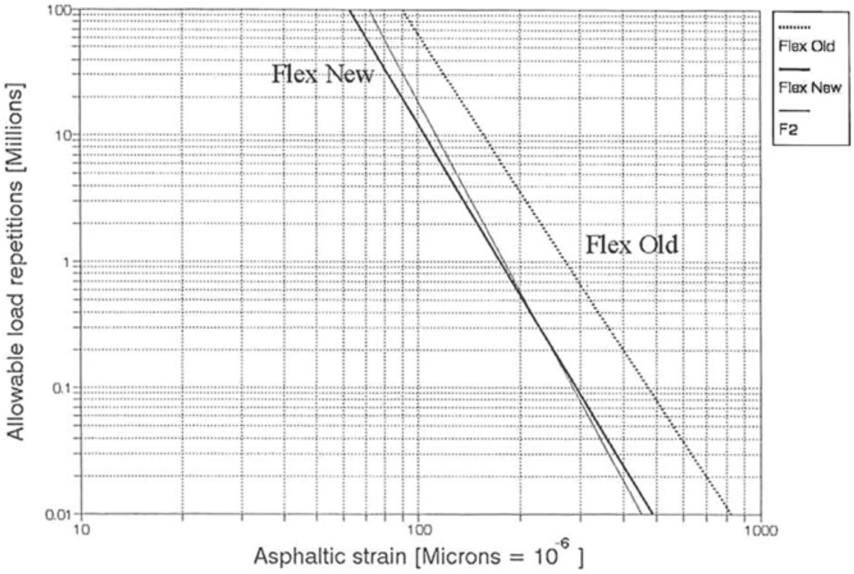

Figure 3.2 – Asphalt Fatigue Lines

The variation of the Asphalt New Mix modulus with temperature is given by the data in the NEW200.TEM file and the variation of the Asphalt Old Mix modulus with temperature is given by the data in the OLD200.TEM file. The temperature files are for an average layer thickness of 200 mm. For average layer thickness exceeding 200mm, the variation of the asphalt modulus with temperature does not deviate much as revealed from temperature files for average layer thickness of 50, 100 and 400 mm. Hence, they are not included.

The variation of asphalt moduli with temperature is shown in Figure 3.3 below, where Flex_new = Asphalt New Mix and Flex_old = Asphalt Old Mix:

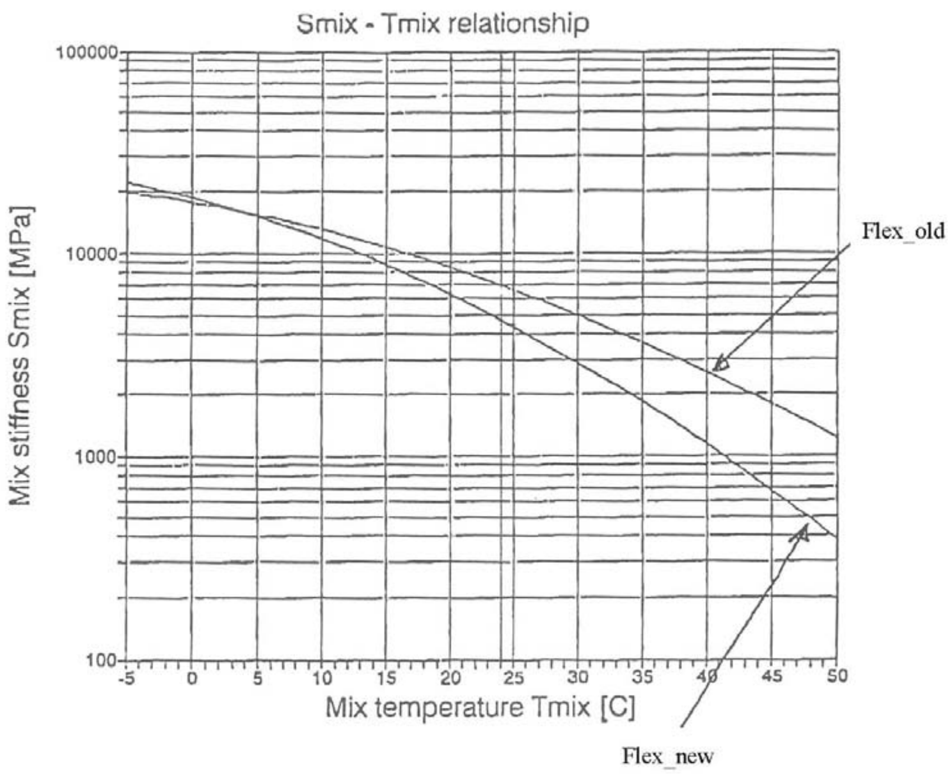

Figure 3.3 – Variation of Asphalt Moduli with Temperature

The failure criteria for Asphalt New Mix is as follows:

Permissible strain = 175.44 µstrain * $N^{-0.223}$ * $(E / E_{ref})^{C}$

where N = number of load repetition;

E = modulus of Asphalt New Mix material;

E_{ref} = 2100 MPa at 33.8° C;

and C = 0.

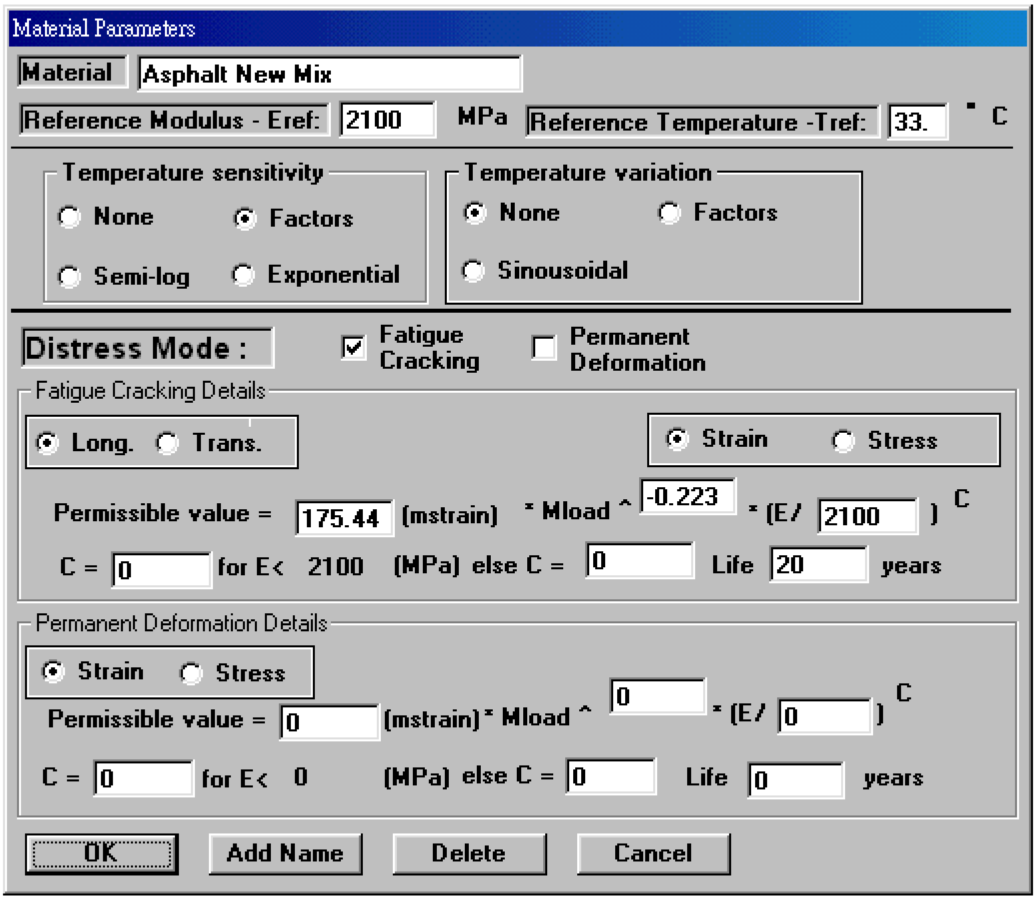

Figure 3.4 – Asphalt New Mix Properties

The failure criteria for Asphalt Old Mix is as follows:

Permissible strain = 272.85 μstrain * $N^{-0.241}$ * $(E / E_{ref})^{C}$

where N = number of load repetition;

E = modulus of the Asphalt Old Mix material;

E_{ref} = 4000 MPa at 33.8° C;

and C = 0.

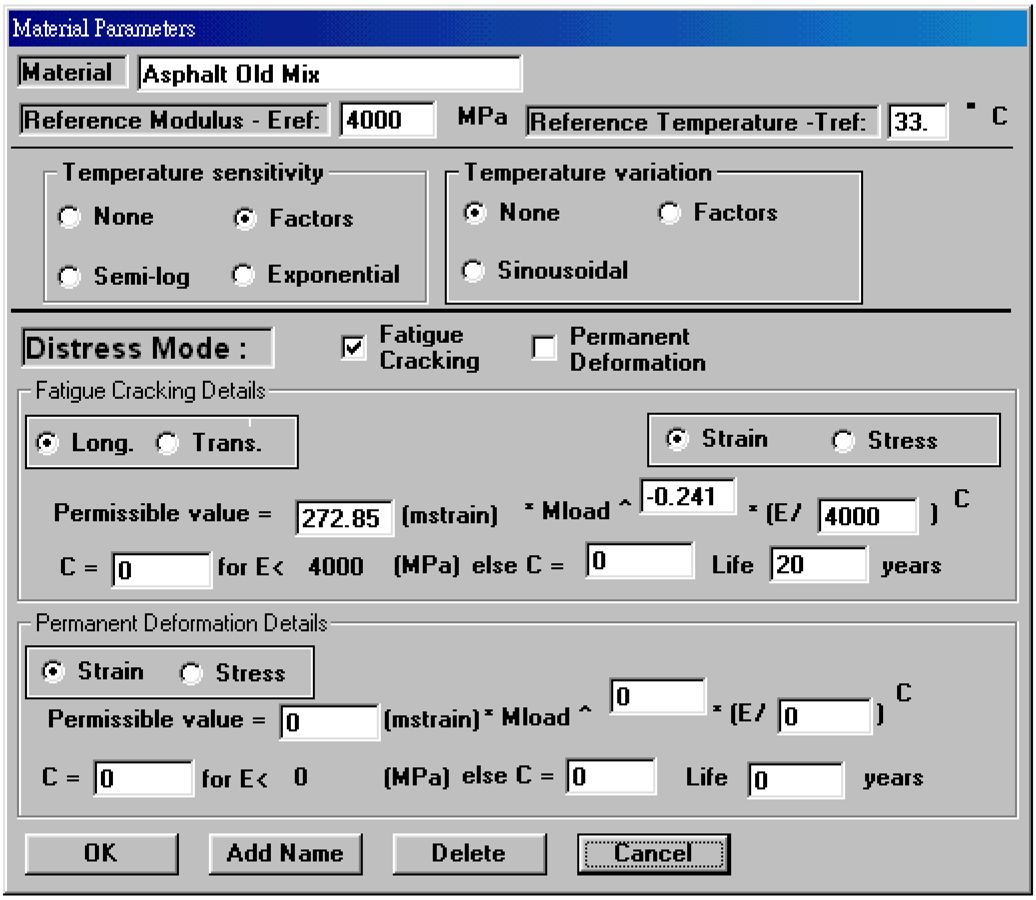

Figure 3.5 – Asphalt Old Mix Properties

The Concrete properties are based on those adopted by the Highway Maintenance Management Pilot Scheme Consultants. The failure criteria is as follows:

Permissible stress = 195 MPa * $N^{-0.333}$ * $(E / E_{ref})^{C}$

where N = number of load repetition;

E = modulus of Concrete material;

E_{ref} = 35000 MPa at 34° C;

and C = 1.

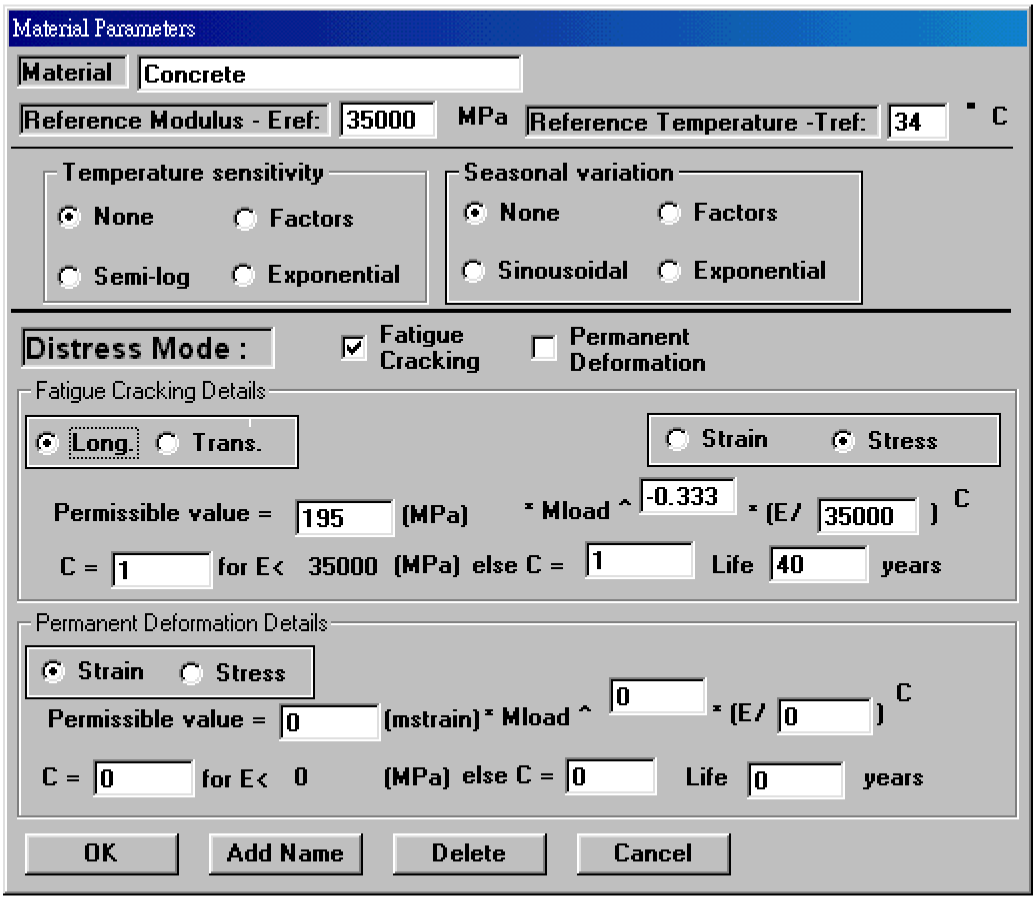

Figure 3.6 – Concrete Properties

The Subgrade properties are based on the Shell Pavement Design Manual[8]. Both the Road Testing Program Consultants and the Highway Maintenance Management Pilot Scheme Consultants adopted these properties. The fatigue line for the Subgrade is shown in Figure 3.7 below:

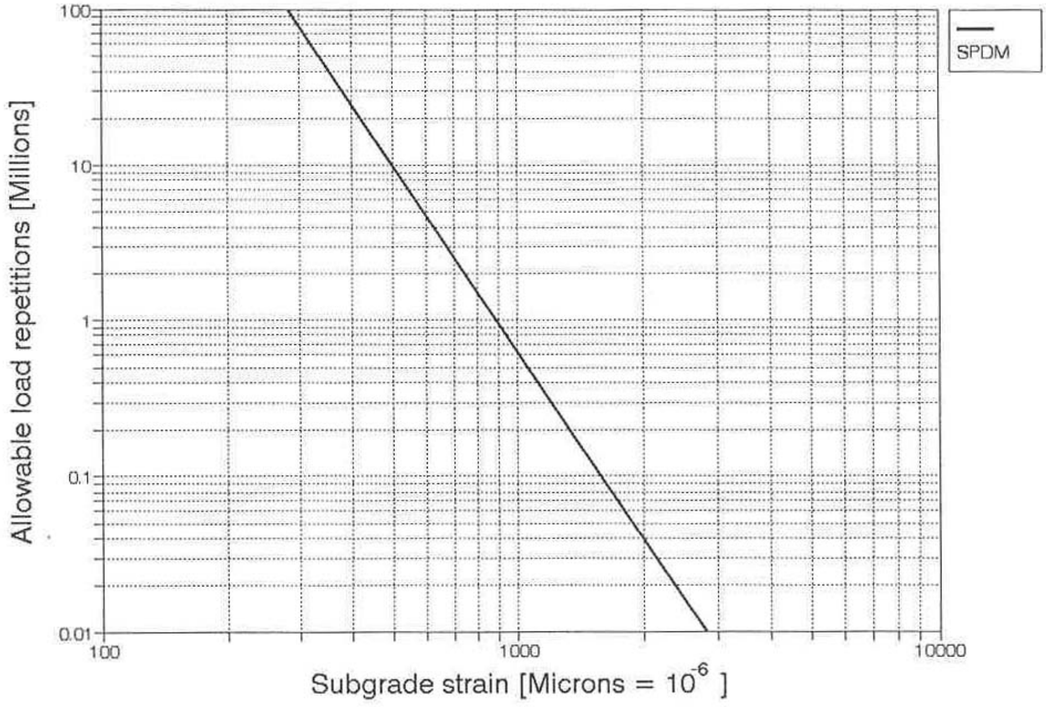

Figure 3.7 – Subgrade Fatigue Line

The failure criteria is as follows:

Permissible strain = 885 μstrain * $N^{-0.25}$ * $(E / E_{ref})^{C}$

where N = number of load repetition;

E = modulus of the Subgrade material;

E_{ref} = 160 MPa at 24° C;

and C = 0.

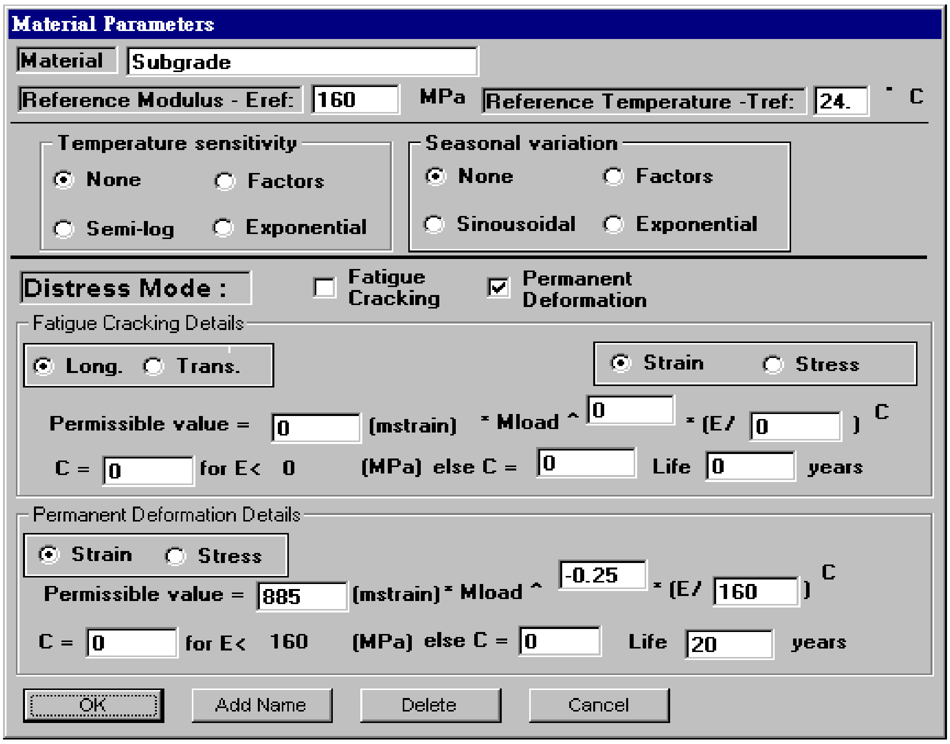

Figure 3.8 – Subgrade Properties

The Granular Sub-base properties and the Lean Concrete Sub-base properties are not well known and are not entered. Since overseas experiences indicate that the conditions in the sub-base layer are not critical, the residual life of the sub-base layer is not analysed.

3.2.3 LOADS

The 80kN standard axle load is adopted since all traffic loads are expressed in terms of equivalent standard axle load. The load configuration parameters are as follows:

Name = Dual

Total load on gear = 40000 N

Dynamic / static load ratio = 1.0

Tyre pressure = 0.577 MPa

Wheel type = Dual

Wheel distance = 330 mm

% of loads = 100%

% total = 100%

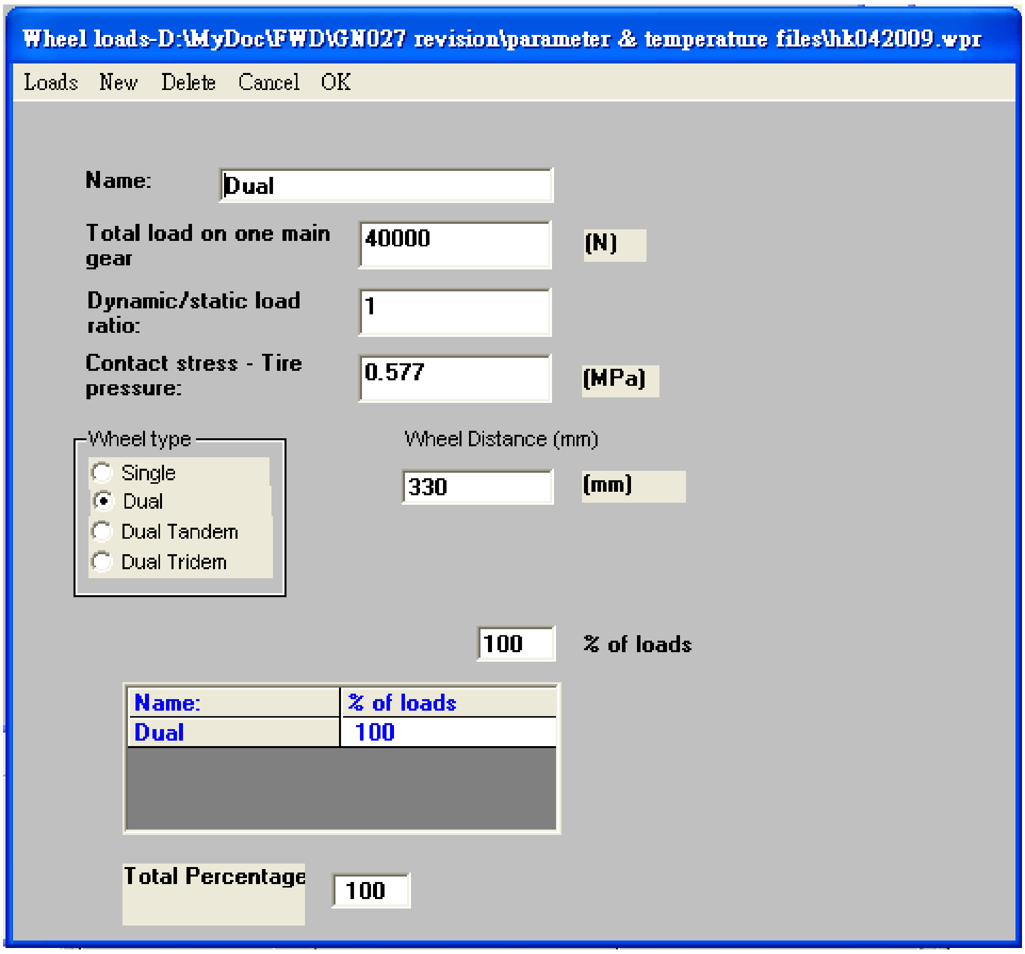

Figure 3.9 – Standard Axle Load Configuration

3.3 FWD RAW DEFLECTION DATA FILES

The FWD raw data files are to be acquired according to RD/GN/026. The raw deflection data file is to be transferred from the field laptop computer to a floppy disk, and in turn copied to the PC with ELMOD installed.

3.4 PAVEMENT MODEL AND LAYER THICKNESS

The material and thickness of the individual pavement layer has to be known, normally by referring to construction and maintenance records. If in-situ data is desirable, the thickness of the bituminous or concrete layers can be measured by taking cored samples at selected locations. The thickness of the granular sub-base layer can be assessed by conducting a dynamic cone penetrometer (DCP) test through a cored hole. For more detailed information, trial pits may be excavated to facilitate visual inspection of the layer thicknesses and pavement materials used. Alternatively, the use of ground penetrating radar for non-destructive detection of layer thicknesses may be investigated in future.

Where coring and DCP tests are performed, the cored samples may be sent for laboratory tests to determine their stiffness. The DCP test blows per mm penetration may also be related to the California Bearing Ratio (CBR) to give an indication of the strength of the layers tested. The Consultants of the Highway Maintenance Management Pilot Scheme[2] have adopted the equation developed by Harrison[4] :

$$\text{Log CBR} = 2.55 - 1.14 \text{ Log (mm/Blow)}.$$

A similar equation was developed by Kleyn and Van Heerden and adopted by the TRRL:

$$\text{Log CBR} = 2.78 - 1.59 \text{ Log (mm/Blow)}.$$

The first equation is recommended by the consultant for local conditions.

3.5 ANNUAL AVERAGE TRAFFIC LOADING

The annual average traffic loading is the design traffic load (C_n) in standard axles calculated in accordance with RD/GN/017 or the HyD Pavement Design Manual when it is published, divided by the design life (n) in years of the road. In order to estimate the average traffic load in future, the $AADT_d$ is to be taken as the annual average daily traffic from the Annual Traffic Census for the year the FWD test is carried out. If the figure is not yet available, the figure from the previous year may be used.

Quite often traffic data is not readily available for small roads. In such cases, the following $AADT_d$ values may be assumed [1]:

Road Type	Land Use	$AADT_d$
Minor Road	-	100 – 1,800
Local Distributor	Industrial	1,500
Local Distributor	Residential / Mixed	5,600
District Distributor	All	18,000

4 ANALYSIS STEPS

The FWD data analysis steps using ELMOD and the underlying theories are summarised in the Sections below. The detailed operations for analysing a flexible pavement structure are illustrated with an example in Section 5 and the detailed operations for analysing a rigid pavement structure are illustrated with an example in Section 6.

4.1 OPEN FWD RAW DATA FILE

Copy the raw FWD test deflection data file from the field portable computer onto a floppy disk and transfer the file to the analysis computer with ELMOD properly installed. Currently, data are acquired with the Field Program Version 25 and the raw data files have a '.F25' extension. Older data files collected before the upgrade of the field program have a '.FWD' extension. Either file can be opened by ELMOD as a single file or a group of files can be processed by batch. Refer to the ELMOD On-line Help File[4] for batch processing procedures.

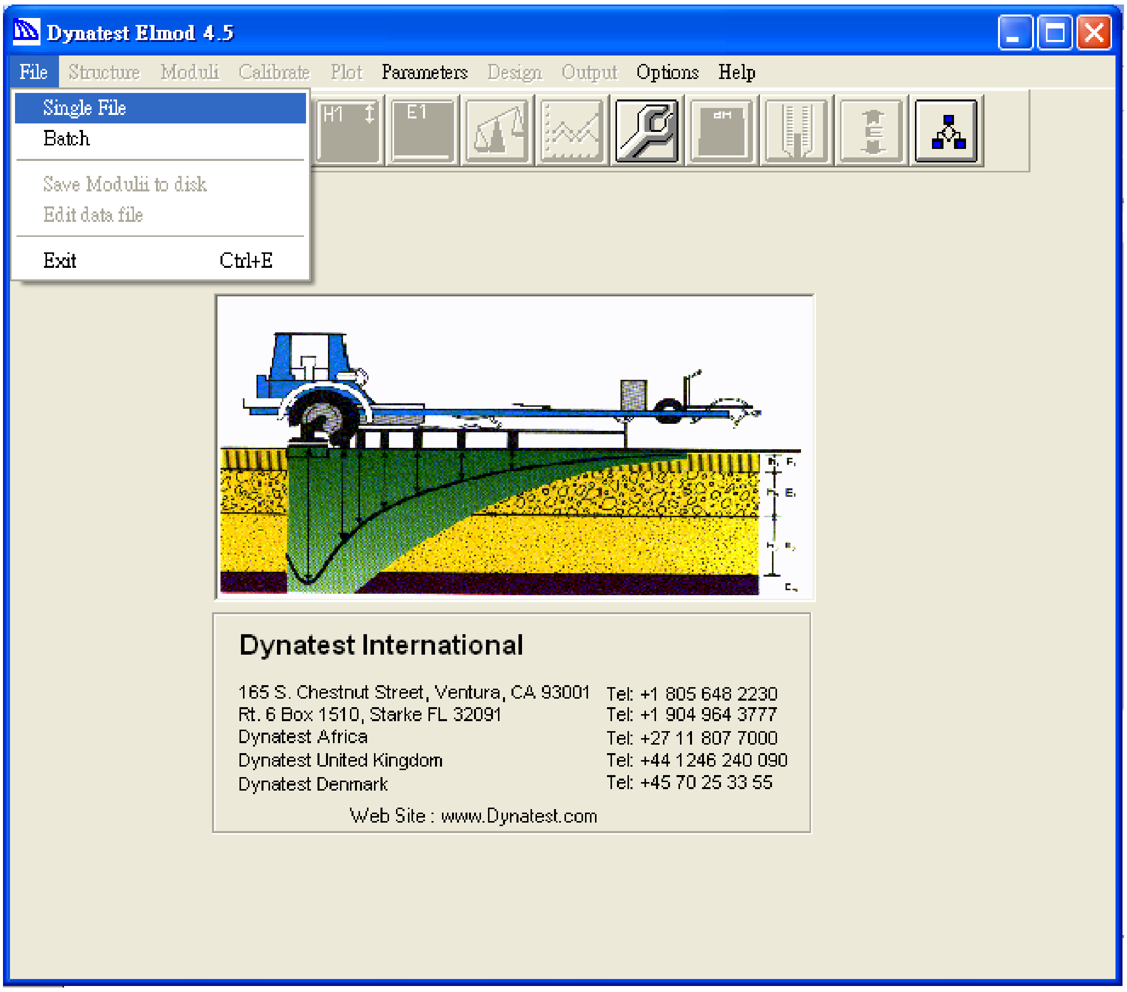

FIGURE 4.1 – OPEN SINGLE FILE

4.2 INPUT PAVEMENT STRUCTURE

With the pavement model determined according to Section 2.2, the thickness of each layer can be assessed and entered into the ELMOD. If a rigid pavement with tests across slab joints is being analysed, check the 'Use PCC Joint ID Numbers' box such that load transfer across joints is analysed. Refer to RD/GN/026, Appendix 1 for the testing method and test station naming convention.

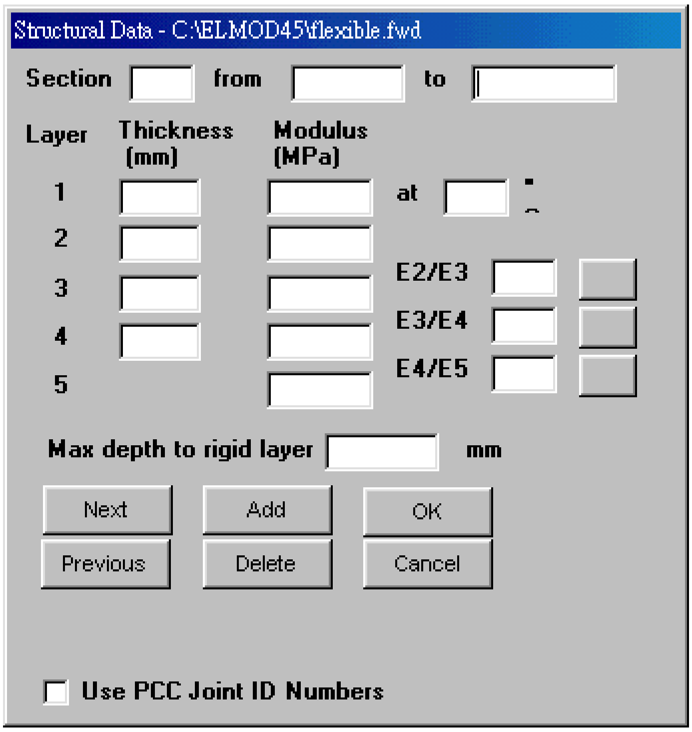

Figure 4.2 – ELMOD Structure Window

ELMOD automatically assigns one section for the whole test run with the default values for 'Section' being '1', 'from' being the chainage of the first test station, and 'to' being the chainage of the last test station. The number of sections can be added or deleted with the buttons at the lower part of the window.

ELMOD requires the layer thicknesses be entered and allows the moduli of individual layers to be fixed. For Layer 1, the modulus can be manually entered together with a temperature so that the program can adjust the stiffness of the layer at test temperature to a reference temperature.

For a 4-layer model, ELMOD requires a E2/E3 ratio to be fixed. This can be entered manually or a default value = 0.2 x $H_2^{0.45}$ can be entered by clicking the blank button to the right of the box.

If a rigid layer is known to exist at a certain depth, this can be entered in the 'Max depth to rigid layer' box. If a concrete pavement is tested at the joints, check the 'Use PCC Joint ID Number' box.

4.3 BACKCALCULATE EFFECTIVE MODULI

More detailed references to the theories adopted by ELMOD are given by Ullidtz[7]. The ELMOD Help File[3] provides some additional but incomplete information on the internal operation of ELMOD. Some of the information described below is obtained through numerous trials with the ELMOD program. Sometimes the meaning of the program steps are not clearly documented and therefore the internal operation is not known. Such information may have to be updated when more details are available.

ELMOD provides two approaches of backcalculating the effective layer moduli, one being ‘Radius of Curvature’ and the other being ‘Deflection Basin Fit’. Both approaches are based on the Odemark-Boussinesq approximate method, the main difference being that the ‘Deflection Basin Fit’ approach carries out additional iterations until the calculated deflections matches the measured deflections to within specified tolerance. The ELMOD Help File indicates that the radius of curvature method is faster, often gives more believable moduli values, and comes closer to measured stresses and strains in-situ. It is therefore recommended that analysis should be carried out using the ‘Radius of Curvature’ method under ‘Backcalculation Mode’.

In backcalculating the effective moduli, ELMOD has a number of options to control the program. The drops to be analysed can be selected together or individually be checking the boxes against each drop number under ‘Select Drops’. Drop 1 is a seating drop and should not be analysed. If 4 drops are recorded in accordance with the standard procedures stipulated in RD/GN/026, then backcalculation for drops 2, 3 and 4 should be carried out. However, normally only Drop 4 needs to be further analysed. If the test run is divided into more than one section, then backcalculation should be carried out for all sections by checking the boxes against each section under ‘Select Sections’.

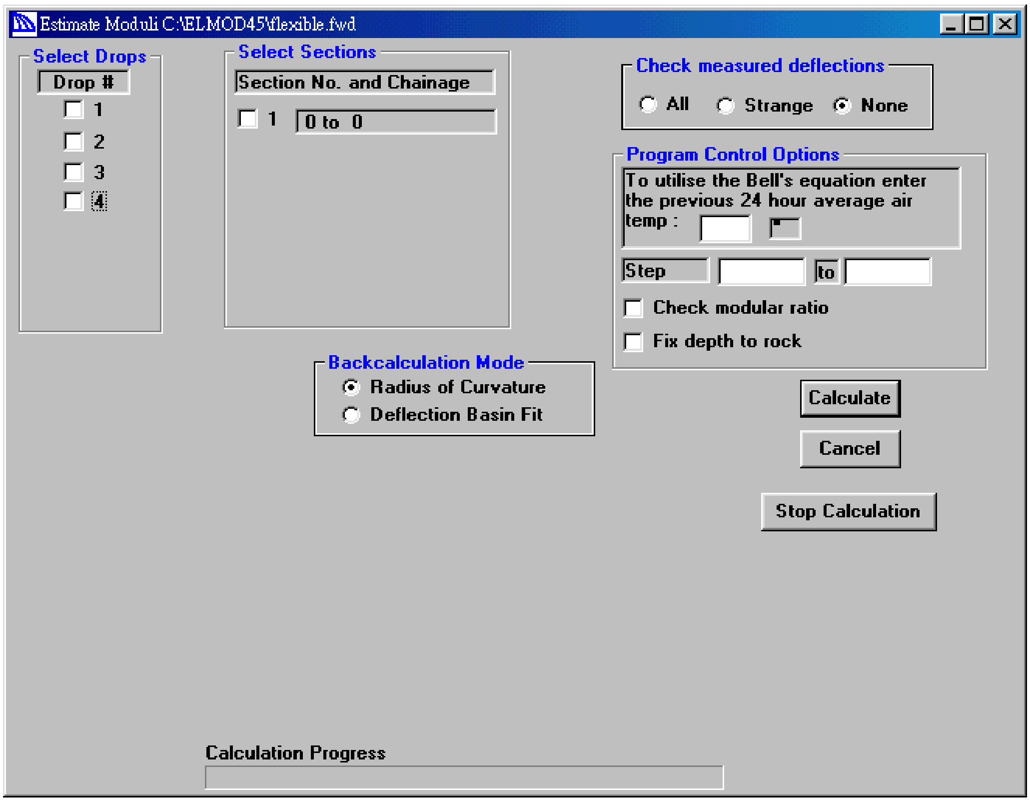

Figure 4.3 – Estimate Moduli Window

In the check measured deflection box, normally select the 'None' radio button. If 'All' is selected, ELMOD will plot out the deflection against geophone distance for each test drop, together with a row of geophone buttons. By examining the plot, the deflection data collected by each geophone can be dropped from the analysis by clicking on the corresponding geophone button. If 'Strange' is selected, the program will highlight test drops in which the calculated deflections are not uniformly decreasing with increased geophone distance from load centre.

It is recommended that the options in the 'Program Control Options' box should be left blank. The ELMOD Help File indicates that the radius of curvature method is faster, often gives more believable moduli values, and comes closer to measured stresses and strains in-situ. It is therefore recommended that analysis should be carried out using the 'Radius of Curvature' method under 'Backcalculation Mode'.

4.4 ESTIMATE RESIDUAL LIFE

ELMOD performs an overlay design by estimating the residual life of the pavement. It automatically calculates the required overlay thickness for locations where the estimated residual lives fall below the design life.

ELMOD requires the material used for each pavement layer to be entered. The overlay material used should be ‘Asphalt New Mix’. ELMOD adjusts the backcalculated moduli for each season according to the corresponding environmental conditions specified in the selected parameter file ‘HK042009.WPR’. The critical stresses and strains caused by the design loads on the pavement structure are determined. ELMOD then makes use of the critical strains in each layer and the fatigue curves defined in the selected parameter file for each material to calculate the allowable number of standard axle loads. The number of loads is divided by the annual traffic to obtain the remaining life in years. ELMOD then calculates the required overlay thickness at locations where the residual life is smaller than the design life of the pavement. It should be noted that ELMOD does not take into account past traffic loads when calculating the residual life since the pavement structural condition over a road section, i.e. its effective layer moduli as determined by FWD test, has already included the influence of past traffic.

Overlay is often not appropriate in the Hong Kong environment, and overlay for concrete pavement is not recommended. Users should refer to the HyD Pavement Design Manual when it is published and determine the required maintenance treatment independent of this overlay design from ELMOD.

4.5 CHECK RESULTS

After the initial run of the program, use the ‘Plot’ menu to plot the graphs of deflection, moduli, and structural life. Analyse the results to check if there are anomalies. Delete suspicious data and re-run the program to get new results.

The deflection data should be reviewed to see if there are large fluctuations or inconsistencies. The cumulative sums of the centre deflection can be used to assist in deciding whether the length of the test run should be divided into different sections for design purposes. The effective moduli can be recalculated where necessary, and then checked to see if they have reasonable values. The residual life needs to be re-estimated if the moduli are recalculated.

The more detailed steps after the initial run are described in the following sections.

4.6 REVIEW DEFLECTION DATA

According to RD/GN/026, 4 drops should be made at each test station. Drop 1 is used as a seating drop and the results are not used for analysis. ELMOD has plot functions that can plot out individual deflection patterns for each drop along the test run, but not more than 1 drop at the same time. The deflection pattern should be plotted for each of the test drops 2, 3 and 4. Observe if there are significant differences in deflection pattern between drops. Note down the chainage of any test station where the deflection varies significantly between drops. The tests data at these stations may have to be discarded or the test repeated to get more reliable results.

If the deflection patterns between drops are similar, it is recommended that the drop 4 data be used for analysis since the contact between the loading plate and the pavement surface is closest for the last drop.

For the drop selected for analysis, check if there are any test stations at which high fluctuation in deflection magnitudes occur. Abnormally high deflections at a test station may be due to a local weak spot and abnormally low deflections may be due to local hard ground or buried utilities. It is common for FWD test data to exhibit variations from station to station along the length of the test run. Experience and judgement is required to determine which points are suspicious. Record the chainage at which the abnormal deflections occur. These points should be removed before further analysis is carried out. Further tests and investigations on site may be required to determine the cause of the abnormality.

To delete the suspicious data, exit the ELMOD application and open the data file with the Windows Notepad or a text editor. Find the relevant data lines using the recorded chainage, delete those lines and save the amended data file.

Exit Notepad or the editor and re-open the amended data file in ELMOD. Plot the deflection pattern again to check that the suspicious data has been removed.

4.7 REVIEW CUMULATIVE SUM OF DEFLECTIONS

Sometimes the pavement conditions may vary along the test run, e.g., the pavement structure may change. For rehabilitation design purposes, it may be desirable to divide the test run into different sections. In order to help observe if there are significant changes in trend along the test run, ELMOD uses the method of cumulative sum described in Section 2.1.2.

From the cumulative sum, check if there are significant changes in trend (from upward to downward or vice versa). A homogeneous section is one in which the cumulative sums continue in the same upward or downward trend. A significant change in the upward or downward trend indicates a change in section. Divide the test run into homogeneous sections such that the trend is reasonably consistent within each section. This step is illustrated in Section 5.7. The homogeneous sections shall be re-backcalculated and analysed again. These steps are illustrated in Sections 5.8 and 5.9.

For design purposes, a set of characteristic values representative of the section has to be selected. This is done statistically by choosing the set of values at the test station where the centre deflection is at the 85 percentile of all the centre deflections in the section. While ELMOD does not provide such a function, this can be relatively easily done using a spreadsheet to import an ELMOD created file with the same filename as the raw data file but with a '.DMS' extension. The worksheet columns show the number of sensors, the section number, the drop number, the test station number, the chainage, the measured deflection for each sensor, the calculated deflection for each sensor, and the root mean square error if the curve fitting option is used.

When the data is imported into the spreadsheet, simply use the PERCENTILE function to calculate the 85 percentile value of the deflection measured by sensor 1 (the centre deflection). Choose the test station with a centre deflection having the same value or the next highest value as the 85 percentile. This step is illustrated in Section 5.12.

The effective moduli and residual life calculated for this test station can be used in the subsequent rehabilitation design. Follow the procedures stipulated in RD/GN/017, or the Pavement Design Manual when it is published, for the design. Do not simply rely on the overlay thickness automatically calculated by ELMOD.

4.8 REVIEW EFFECTIVE MODULI

The backcalculated results may contain anomalies, e.g., sometimes E_2 may be smaller than E_3 or the modulus of a particular layer may have an unreasonably large value. Apart from using the steps described in Section 5.5 and 5.6 to remove suspicious test data and divide the test run into sections, the interpretation of the backcalculated results still requires experience and expertise from the user. It is expected that a database of effective modulus values will be built up in the Highway Maintenance Management System as more and more tests and analyses are carried out in future.

For the time being, the statistical results from the 1991 Road Testing Program shown below may be used as a reference in assessing whether the backcalculated effective moduli of different pavement layers fall within a reasonable range. If the test results fall within the top or bottom 10% of the typical ranges indicated, then the FWD data and backcalculated moduli may have to be examined more carefully. For a detailed assessment, it is necessary to correlate the FWD results with other test data such as in-situ tests or laboratory tests on cored samples from site. In case the backcalculated modulus of a particular layer is deemed not reasonable, a modulus range for that layer should be adopted based on other test results or experience. Click on ‘Options’ in the top menu and select the ‘Fix Layer Moduli’. A window will pop up for the ‘E-min’ and ‘E-max’.

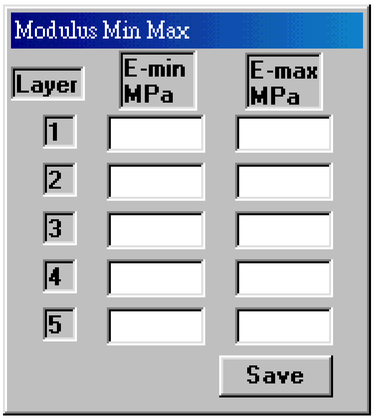

Figure 4.4 – Fix Layer Moduli

The E-min and E-max values can be selected with reference to the following table. Save the range values and run the backcalculation step again.

Concrete Modulus (MPa)	**%**	Concrete Modulus (MPa)	**Cumulative %**
< 15,000	13.0	>= 0	100.0
15,000 – 20,000	26.8	>= 15,000	87.0
20,000 – 25,000	14.6	>= 20,000	60.2
25,000 – 30,000	16.3	>= 25,000	45.6
30,000 – 35,000	13.8	>= 30,000	29.3
35,000 – 40,000	13.8	>= 35,000	15.5
> 40,000	1.7	> 40,000	1.7

Asphalt Modulus (MPa)	**%**	Asphalt Modulus (MPa)	**Cumulative %**
< 1,000	14.4	>= 0	100.0
1,000 – 1,500	19.2	>= 1,000	85.6
1,500 – 2,000	20.6	>= 1,500	66.4
2,000 – 2,500	13.4	>= 2,000	45.8
2,500 – 3,000	11.1	>= 2,500	32.4
3,000 – 4,000	10.2	>= 3,000	21.3
> 4,000	11.1	> 4,000	11.1

Sub-base Modulus (MPa)	**%**	Sub-base Modulus (MPa)	**Cumulative %**
< 100	15.5	>= 0	100.0
100 – 200	39.0	>= 100	84.5
200 – 500	21.8	>= 200	45.5
500 – 1,000	6.0	>= 500	23.7
1,000 – 5,000	11.4	>= 1,000	17.7
> 5,000	6.3	> 5,000	6.3

Subgrade Modulus (MPa)	**%**	Subgrade Modulus (MPa)	**Cumulative %**
< 50	11.6	>= 0	100.0
50 – 100	41.5	>= 50	88.4
100 – 150	24.5	>= 100	46.9
150 – 200	14.1	>= 150	22.4
200 – 300	6.9	>= 200	8.3
> 300	1.4	> 300	1.4

In general, a sub-base modulus of less than 500 MPa represents granular material and a modulus above 1,000 MPa represents lean concrete. For most tests, the ratios of granular sub-base modulus to subgrade modulus range between 1 to 4, and generally can be considered to be around 2. The values can be updated as more testing and analysis is carried out.

For the load transfer across joints in rigid pavements, the Road Testing Programme consultants recommended that the joint condition and load transfer efficiency are classified as follows:

Joint Condition	**Load Transfer Efficiency (%)**
Good	70 – 100
Fair	50 – 70
Poor	Below 50

The non-linear coefficients ‘C’ and ‘n’ of the subgrade can be displayed. The non-linearity properties of the pavement structure can be visualised by plotting the ‘surface modulus’ against equivalent depth.

4.9 REVIEW RESIDUAL LIFE

The residual life estimated by ELMOD may be used as one of the performance indices to assess the relative maintenance priority of different sections of roads. ELMOD saves the calculated remaining life for each layer at each test station in a file with the same filename as the raw data file but with a '.LNN' extension where NN is a serial number from 2 to 99. The value of 'NN' is incremented by one for each successive design run.

To better appreciate the conditions of the pavement layers, print out the residual life analysis results using the print functions in ELMOD. Click on 'Output' at the top menu to enter the output window. Click on 'Print' and then select 'Overlay design results' from the pull-down menu to print the residual life results.

Alternatively, use a spreadsheet software such as Excel to import the '.LNN' file. The worksheet shows the chainage of each test station, the remaining lives of the top layer and the subgrade layers, and their minimum is used as the residual life of the pavement structure. This analysis result provides an indication on the layer to which maintenance works may be required.

4.10 REVIEW AND ARCHIVE RESULTS

In case there are dubious results in the above analysis steps, make the necessary adjustments to the data and re-analyse the amended data. The maximum number of analysis runs that can be performed on a data set is 98 before the old 'LNN' files have to be deleted. The results of each run are saved in files that can be imported into a spreadsheet for further analysis independent of ELMOD. The final analysis results should be archived both electronically in the native digital format and in printed hardcopy together with a map showing the alignment of the test run. The data may then be entered into the Highway Maintenance Management System when it is implemented to build up a geographic database for future reference.

5 ANALYSING A FLEXIBLE PAVEMENT STRUCTURE

This Section illustrates the use of ELMOD to analyse a flexible pavement structure.

5.1 OPEN RAW DATA FILE

Invoke ELMOD. Click on ‘File’ in the top menu to select ‘Single File’ from the pull down menu. Double click on a sample data file called “FLEXIBLE.FWD”.

5.2 INPUT PAVEMENT STRUCTURE

Click on ‘Structure’ in the top menu to enter the pavement structure. A ‘Structural data’ window will pop up. In ‘Section’, default values of ‘1’, from ‘0’ to ‘0.5’ are entered.

A 3-layer model is adopted for this example. The bituminous materials are combined into a single top layer with thickness H_1 = 160 mm. The granular sub-base has a thickness H_2 = 250 mm. The subgrade is not subdivided into two layers and its thickness is considered to be semi-infinite, there is no need to input its thickness. The other fields are left blank.

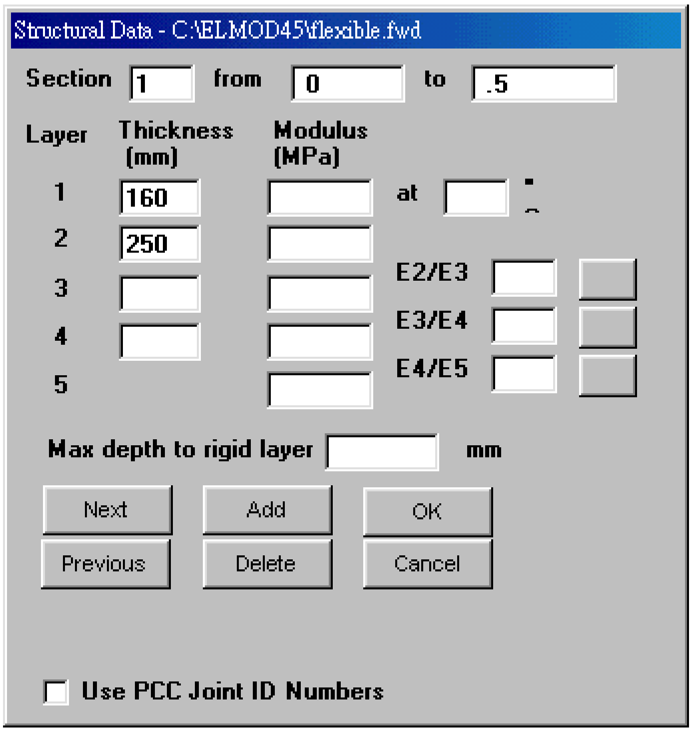

Figure 5.1 – Input Structural Data

5.3 BACKCALCULATE EFFECTIVE LAYER MODULI

Click on 'Moduli' in the top menu to backcalculate the layer moduli. In the 'Select Drops' box, check the '2', '3', and '4' boxes so that deflection data collected during Drops 2, 3, and 4 are used for analysis. In the 'Select Sections' box, check the '1' box. In the 'Check measured deflection' box, select 'None'. Leave the 'Program Control Options' box blank. In the 'Backcalculation Mode' box, select 'Radius of curvature'. Click on the 'Calculate' button to perform the analysis.

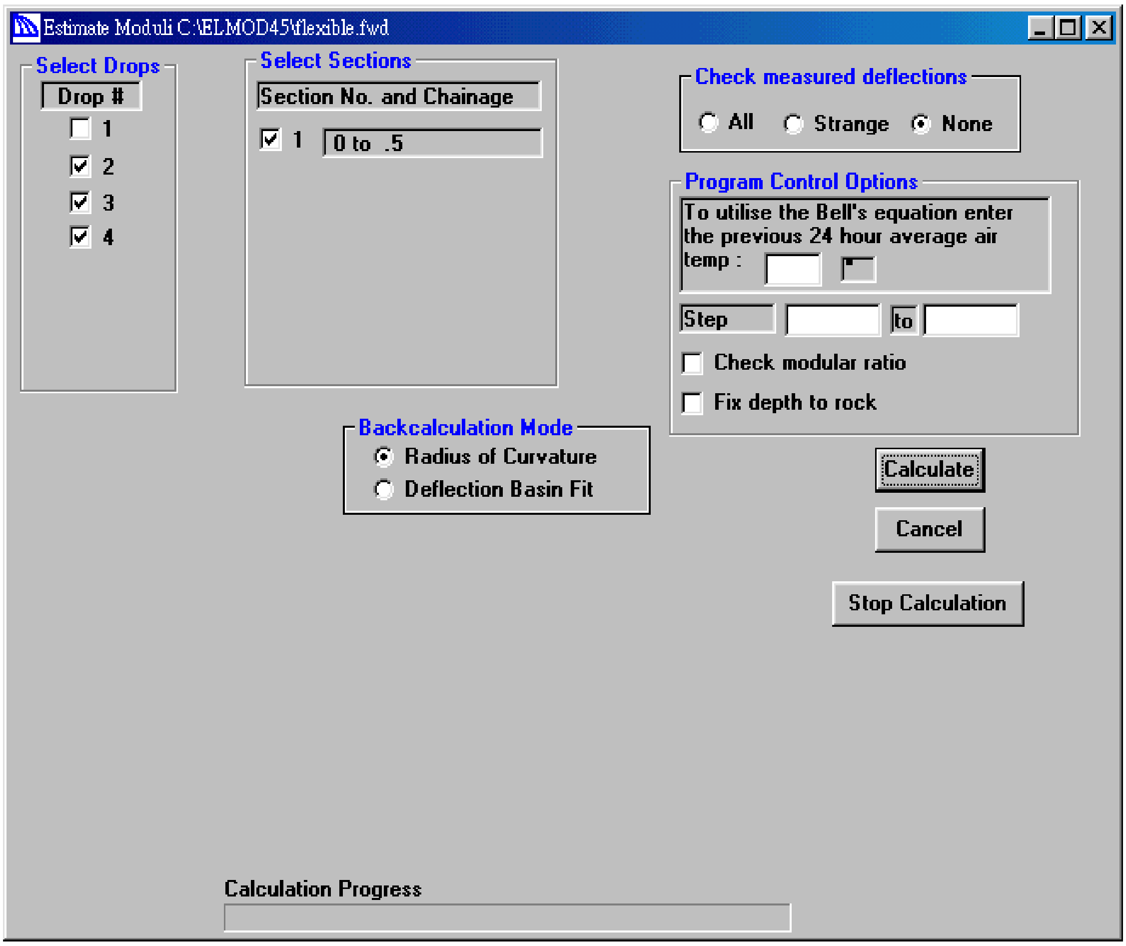

Figure 5.2 – Backcalculate Effective Layer Moduli

When the backcalculation is completed, a window will pop up asking 'Do you want to save your results for viewing and printing?' Click on the 'Yes' button. If a previous backcalculation has already been carried out, a second window will pop up asking 'Overwrite existing file? Select no to append.' Click on the 'Yes' button to overwrite the existing file. A window with the message 'Data has been saved' will pop up. Click on the 'OK' button to leave the window.

5.4 ESTIMATE RESIDUAL LIFE

Click on ‘Design’ in the top menu to estimate the residual life. A ‘Select parameter file’ window will pop up. Select the parameter file ‘HK042009.WPR’ and click the ‘Open’ button. A ‘Select Section’ window will pop up. Select Section ‘1’, and then select Drop ‘4’ to be analysed. Click on the ‘OK’ button.

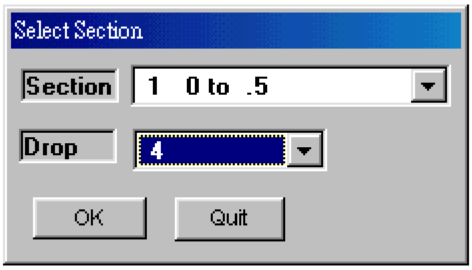

FIGURE 5.3 – SELECT SECTION AND DROP FOR ANALYSIS

A ‘Materials and Loading’ window will pop up. Select the overlay material by highlighting ‘Asphalt New Mix’ on the right hand box, then click on ‘Overlay’ in the left hand box. Since the pavement was built using the old mix design, select ‘Asphalt Old Mix’ on the right hand box and click on Layer 1. Select ‘Granular Sub-base’ on the right hand box and click on Layer 2. Select ‘Subgrade’ on the right hand box and click on Layer 3. In the ‘Number of loads per year’ box, enter the predicted average annual equivalent standard axle loads, 1285000 in this example. Click on the ‘OK’ button.

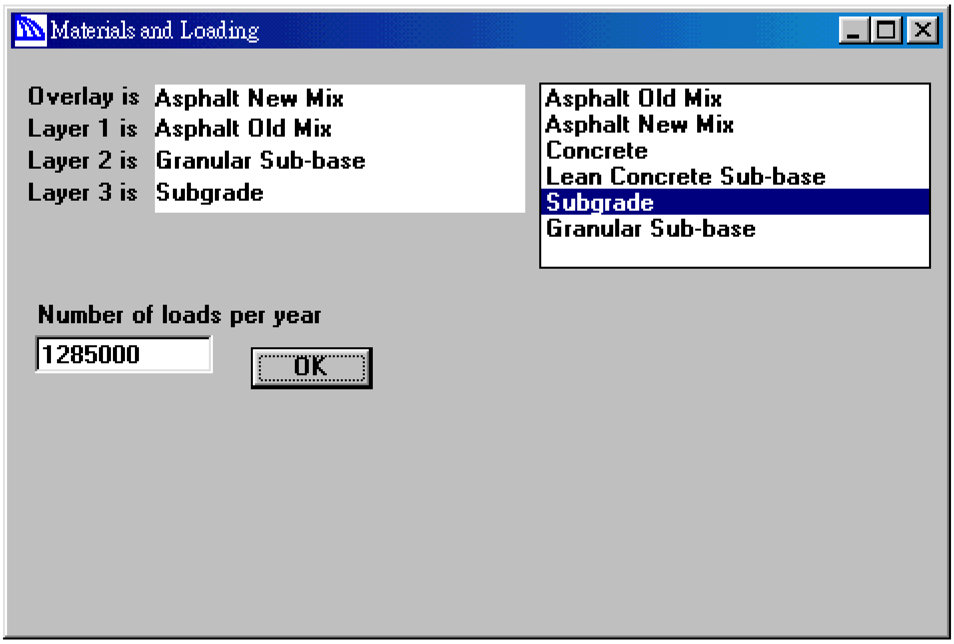

Figure 5.4 – Input Materials and Loading

A window with the message ‘Overlay design complete’ will pop up after ELMOD has completed estimating the residual life and designing the overlay requirement. Click on the ‘OK’ button.

5.5 CHECK RESULTS

Click on the ‘Plot’ menu and a graphics window will be displayed. In the lower half of the window, check the ‘Deflections (microns)’ radio button. Check all the sensor distance check boxes below. In the ‘Drop No.’ box to the right, click the ‘4’ radio button. Click on the ‘Graph’ button near the centre to show the deflection pattern along the length of the test run. The solid colour lines in the graph show the measured deflections and the broken lines show the backcalculated deflections. The first 2 sets of data on the right hand column shows the measured figures on top and the backcalculated figures underneath in terms of number of test stations, the mean deflections and the standard deviations for the deflections measured at each geophone. It is observed that the deflections of all geophones were extremely low at chainage 0.123. The next 2 sets of data on the right hand column shows the deflections at chainage 0.123.

To check the values at any point, simply click at the point in the graph and the chainage of the nearest test station will be displayed at the bottom, together with the data on the right side of the window. To see the mean values of a range of data, click and drag along the x-axis over the range of interest. To clear the graphic, click on the ‘OK’ button to the right of the graph. To clear the data display, click on the ‘CLS’ button at the bottom right of the window.

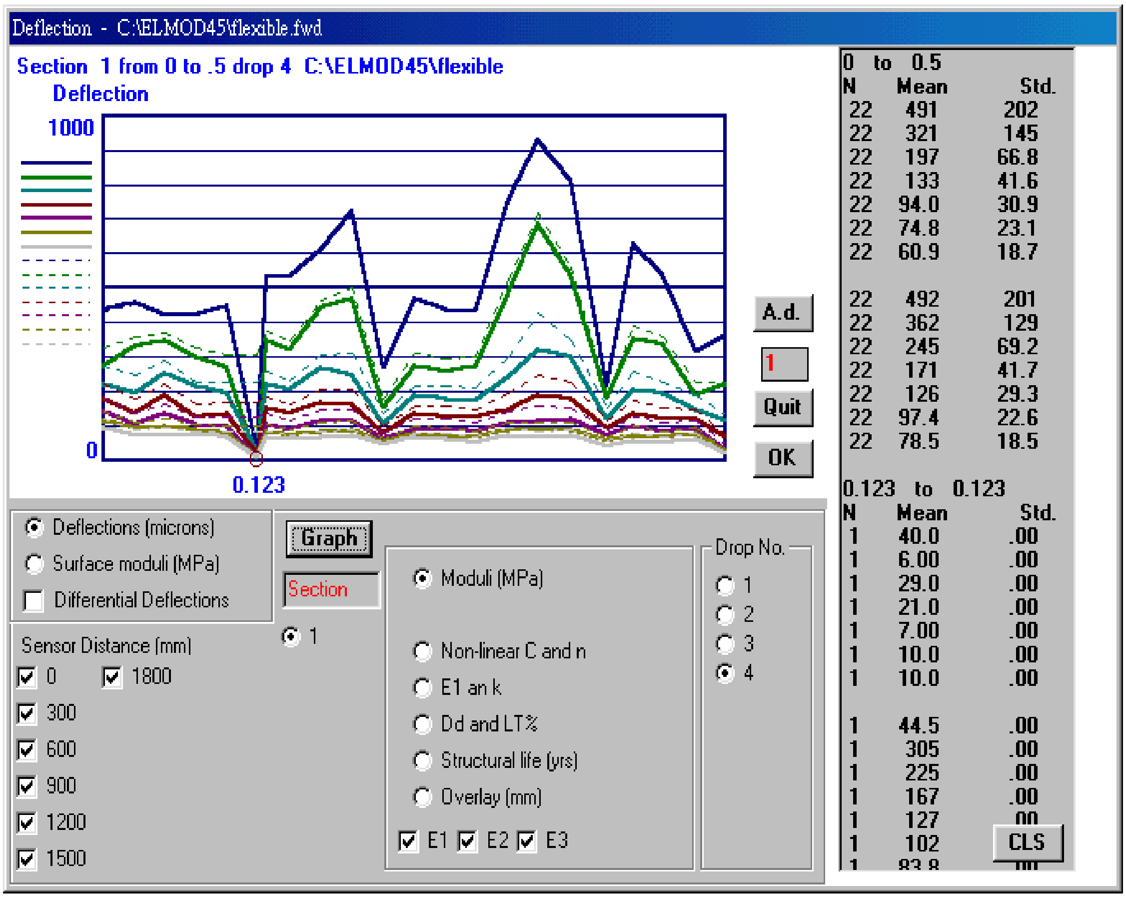

Figure 5.5 – Deflection along Test Run after Initial Analysis

In view of the abnormal deflection at chainage 0.123, the deflections should be checked against those recorded by Drop 2 and Drop 3. Click on the radio button next to ‘2’ under the ‘Drop No.’ box on the right. Then click on the ‘Graph’ button to see the deflection pattern of Drop 2. The process can be repeated for checking against Drop 3. In this example, the abnormally low deflections are present in all drops.

Click on the ‘Moduli (MPa)’ button and the graph of the 3 backcalculated layer moduli is shown. It can be observed that the moduli of the sub-base and subgrade at chainage 0.123 were unreasonably high.

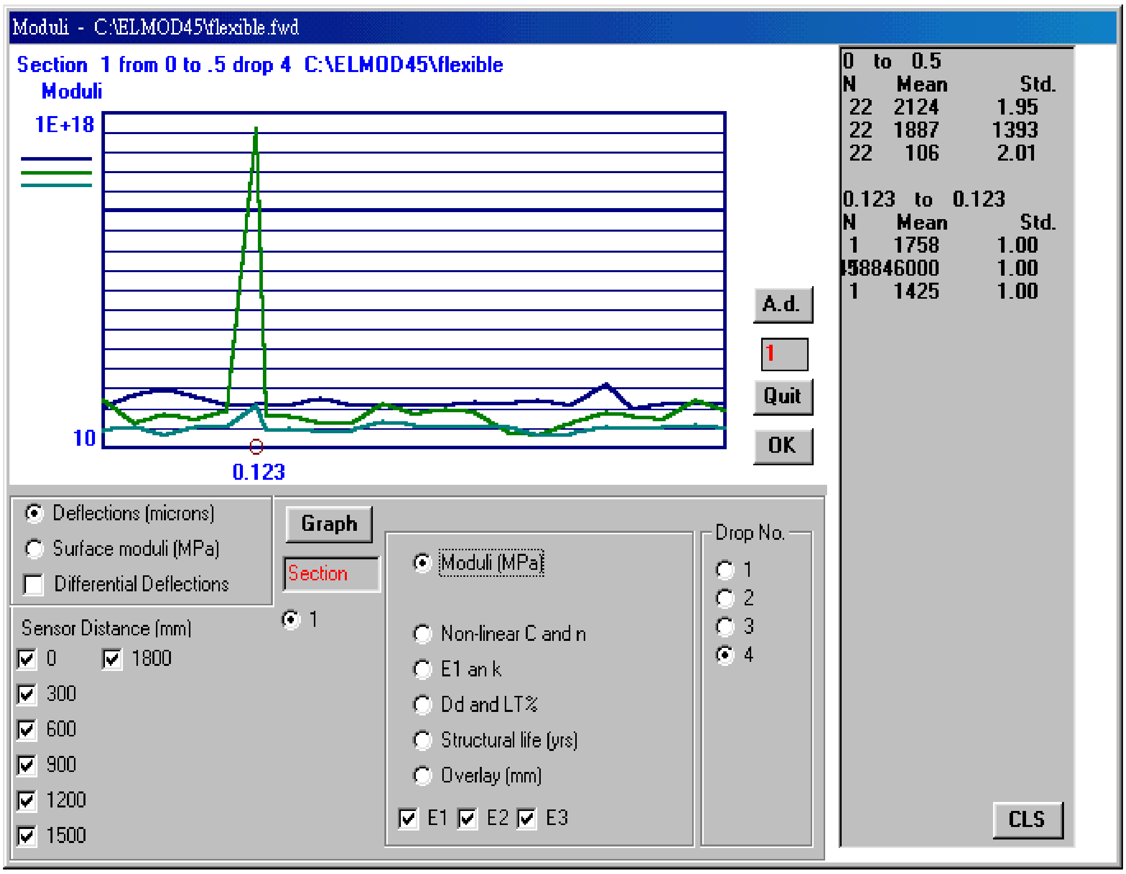

Figure 5.6 – Layer Moduli after Initial Analysis

Click on the 'Structural life (yrs)' radio button and the estimated residual life graph is shown. It can be observed that the estimated residual life varies greatly along the test run. While the mean life is 159 years, the maximum can be up to 10000 years and the minimum of 1.51 years occurs at chainage 0.326.

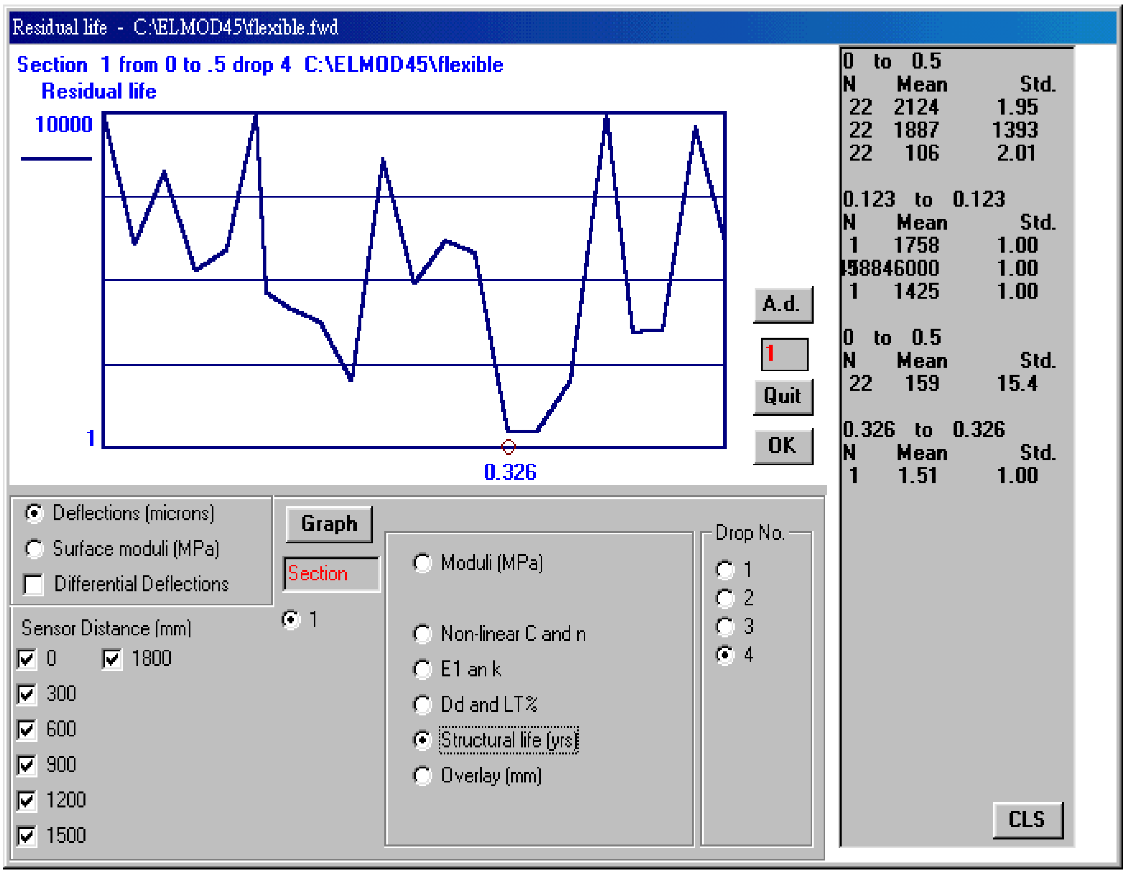

Figure 5.7 – Residual Life after Initial Analysis

In view of the very low deflection at chainage 0.123 and the corresponding unreasonably high moduli of the sub-base and subgrade at that location, it is desirable to remove the dubious data at chainage 0.123 and perform the analysis again.

It should be noted that while the dubious data affects the mean value of backcalculated results, the results at individual test stations are not affected.

5.6 REVIEW DEFLECTION DATA

The deflection data at chainage 0.123 should be removed as described in Section 3.6. Plot the deflection again to check that the dubious data has been removed.

To close the graphic window, click on the 'Quit' button to the right of the graph.

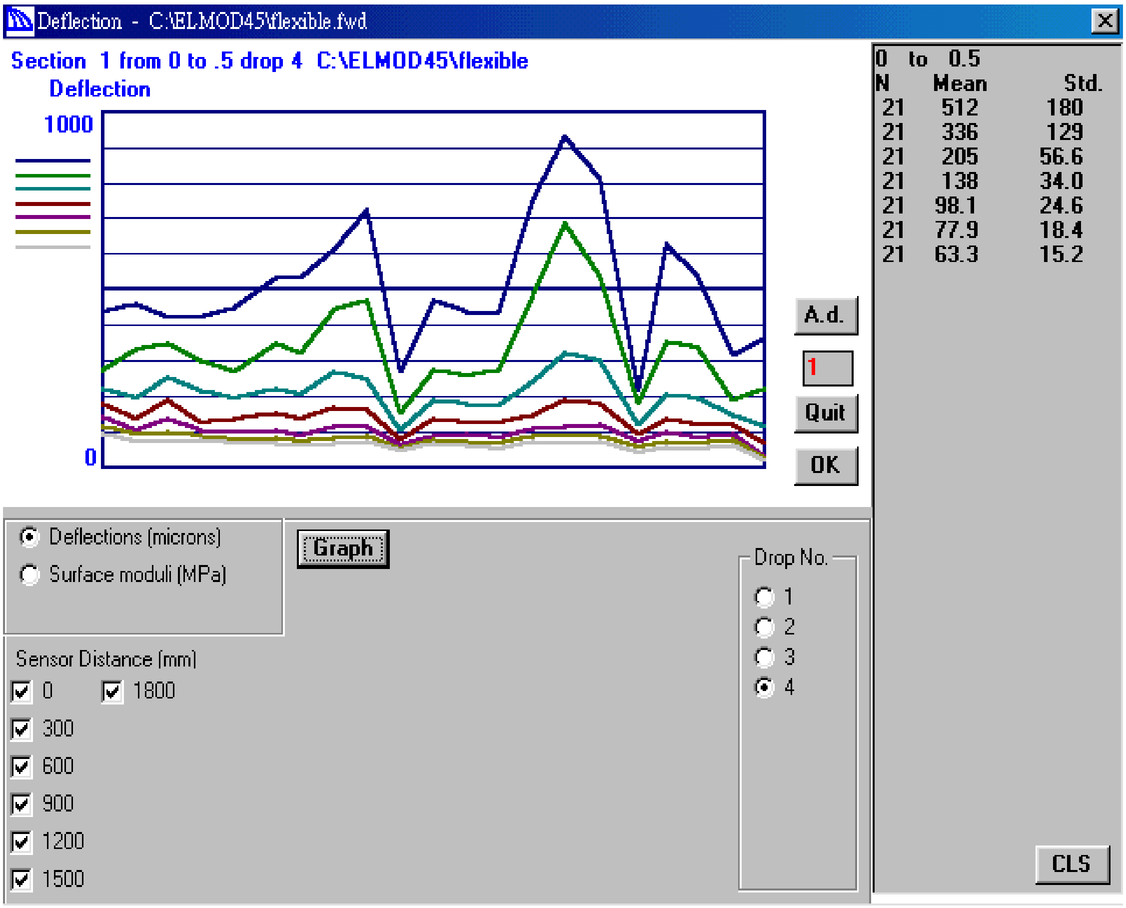

Figure 5.8 – Deflection along Test Run with Suspicious Data Removed

5.7 REVIEW CUMULATIVE DEFLECTIONS

Click on 'Plot' in the top menu and uncheck all sensors except the 0mm sensor. In the 'Drop No.' box, click on the radio button next to '4' and then click on the 'Graph' button to plot the centre deflection. Click on the 'A.d.' button to the right of the graphic to plot the deflection cumulative sum.

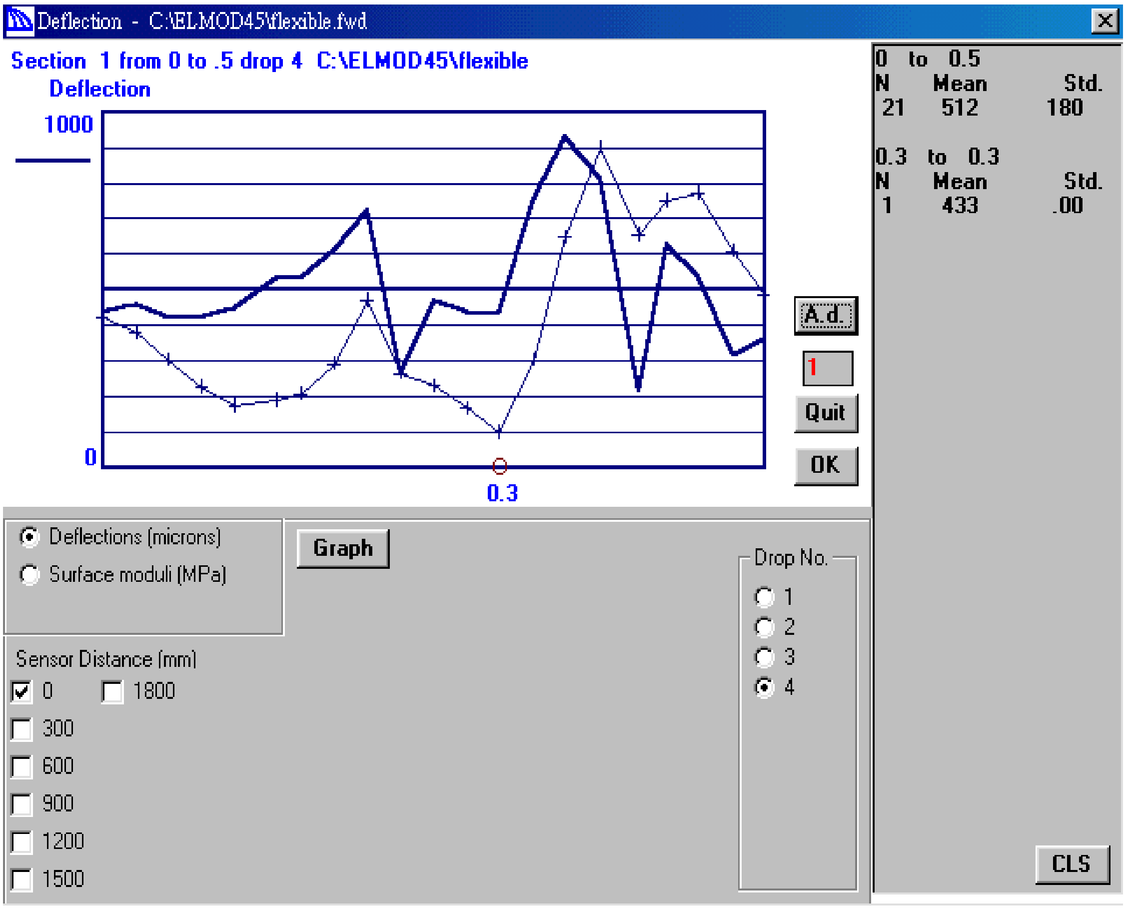

Figure 5.9 – Centre Deflection and Cumulative Sum

In the example, it appears that there is a significant change in trend at chainage 0.3. Therefore the test run is divided into 2 sections, Section 1 from chainage 0 to 0.3 and Section 2 from chainage 0.3 to 0.5. A change in section is also necessary when there is a change in construction details. Please note that whether the test run should be divided into different sections and how many sections should be used is largely a matter of engineering judgement.

Click on the 'Quit' button to leave the graphic window.

5.8 EDIT PAVEMENT STRUCTURE

Click on 'Structure' in the top menu to enter the pavement structure. A 'Structural data' window will pop up. In the 'Section' box, enter '1', from '0' to '0.3'.

A 3-layer model is adopted for this example. The bituminous materials are combined into a single top layer with thickness H_1 = 160 mm. The granular sub-base has a thickness H_2 = 250 mm. The subgrade is not subdivided into two layers and its thickness is considered to be semi-infinite, there is no need to input its thickness. The other fields are left blank.

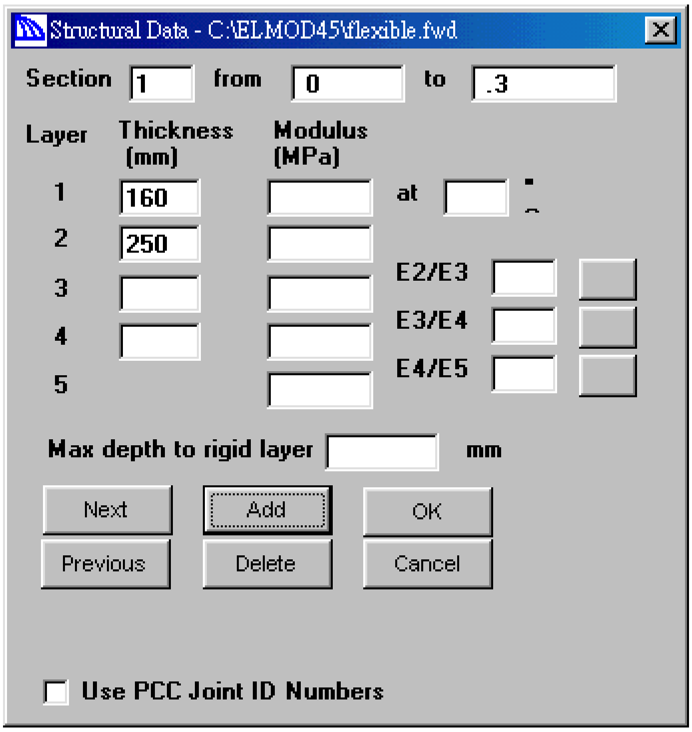

Figure 5.10 – Input Section 1 Structural Data

To input the structure for another section, click on the ‘Add’ button near the bottom. Go back to the ‘Section’ box, enter ‘2’, from ‘0.3’ to ‘0.5’. There is no change in layer thicknesses throughout the test run and therefore the same data is entered. Click on the ‘Previous’ or ‘Next’ buttons to move from one section to another. Click on the ‘Add’ or ‘Delete’ buttons to add more sections or delete existing as necessary. Click on the ‘OK’ button’ to exit the window.

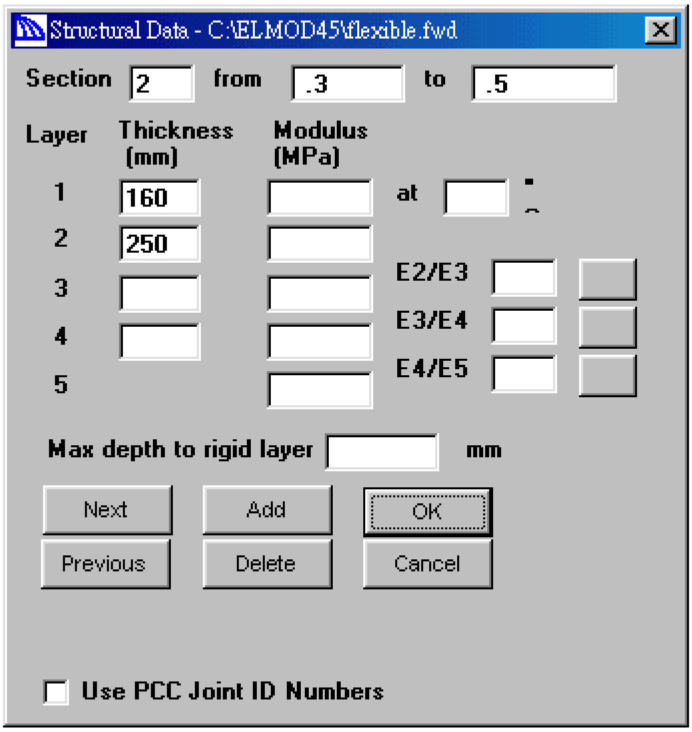

Figure 5.11 – Input Section 2 Structural Data

5.9 RE-BACKCALCULATE EFFECTIVE LAYER MODULI

Click on ‘Moduli’ in the top menu to backcalculate the layer moduli. In the ‘Select Drops’ box, check the ‘2’, ‘3’, and ‘4’ boxes so that only the deflection data collected during Drops 2, 3, and 4 are used for analysis. In the ‘Select Sections’ box, check both the ‘1’ and ‘2’ boxes so that both sections are analysed. In the ‘Check measured deflection’ box, select ‘None’. Leave the ‘Program control options’ box blank. In the ‘Backcalculation Mode’ box, select ‘Radius of curvature’. Click on the ‘Calculate’ button to perform the analysis.

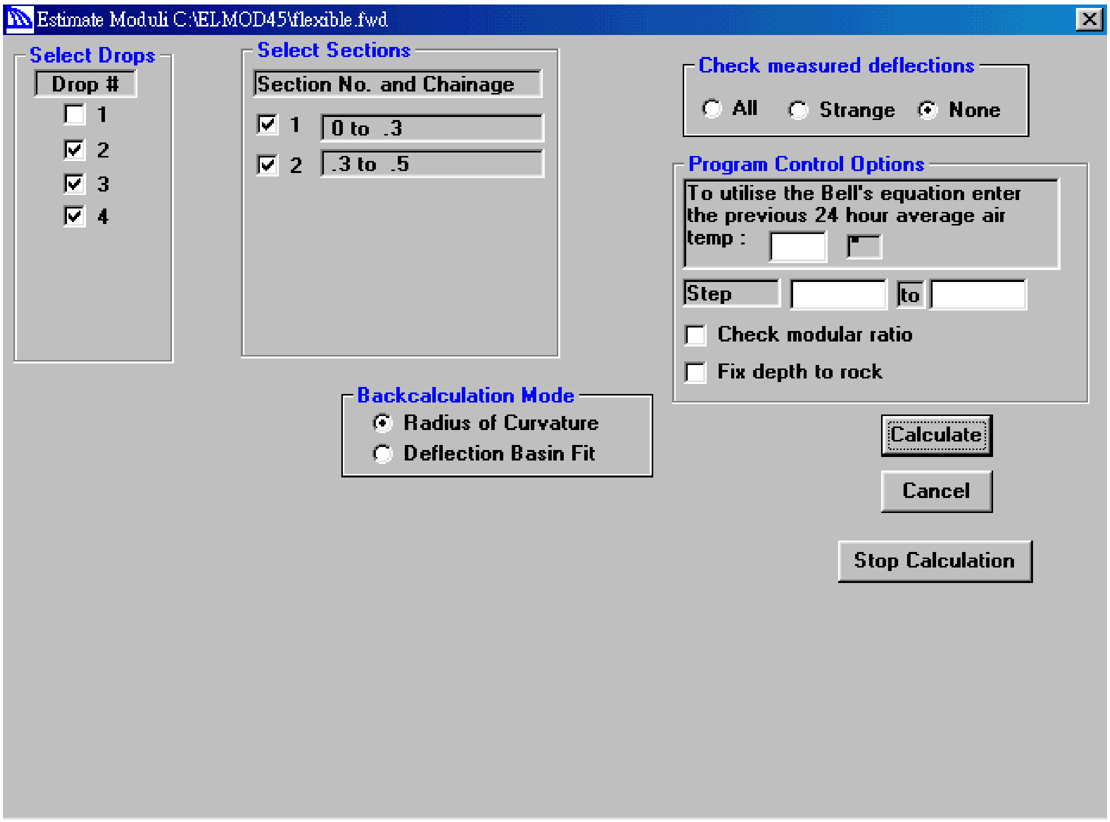

Figure 5.12 – Backcalculate Effective Layer Moduli

When the backcalculation is completed, a window will pop up asking ‘Do you want to save your results for viewing and printing?’ Click on the ‘Yes’ button. If a previous backcalculation has already been carried out, a second window will pop up asking ‘Overwrite existing file? Select no to append.’ Click on the ‘Yes’ button to overwrite the existing file. Click on the ‘No’ button to append the new results to the existing one. In this example, click ‘Yes’. Finally, a window with the message ‘Data has been saved’ will pop up. Click on the ‘OK’ button to leave the window.

5.10 REVIEW EFFECTIVE LAYER MODULI

Click on 'Plot' in the top menu and under the 'Section' box at the lower middle of the screen, click on the '1' radio button. In the 'Drop No.' box at the lower right, click on the '4' radio button. Click on the 'Moduli (MPa)' radio button to display the Section 1 layer moduli backcalculated from Drop 4 data. See if the backcalculated modulus for the same layer vary significantly along the test run. Observe the mean value and distribution of the layer moduli.

It can be seen that seemingly unreasonable results occur at chainage 0, where the backcalculated modulus of the sub-base exceeds that of the asphalt layer.

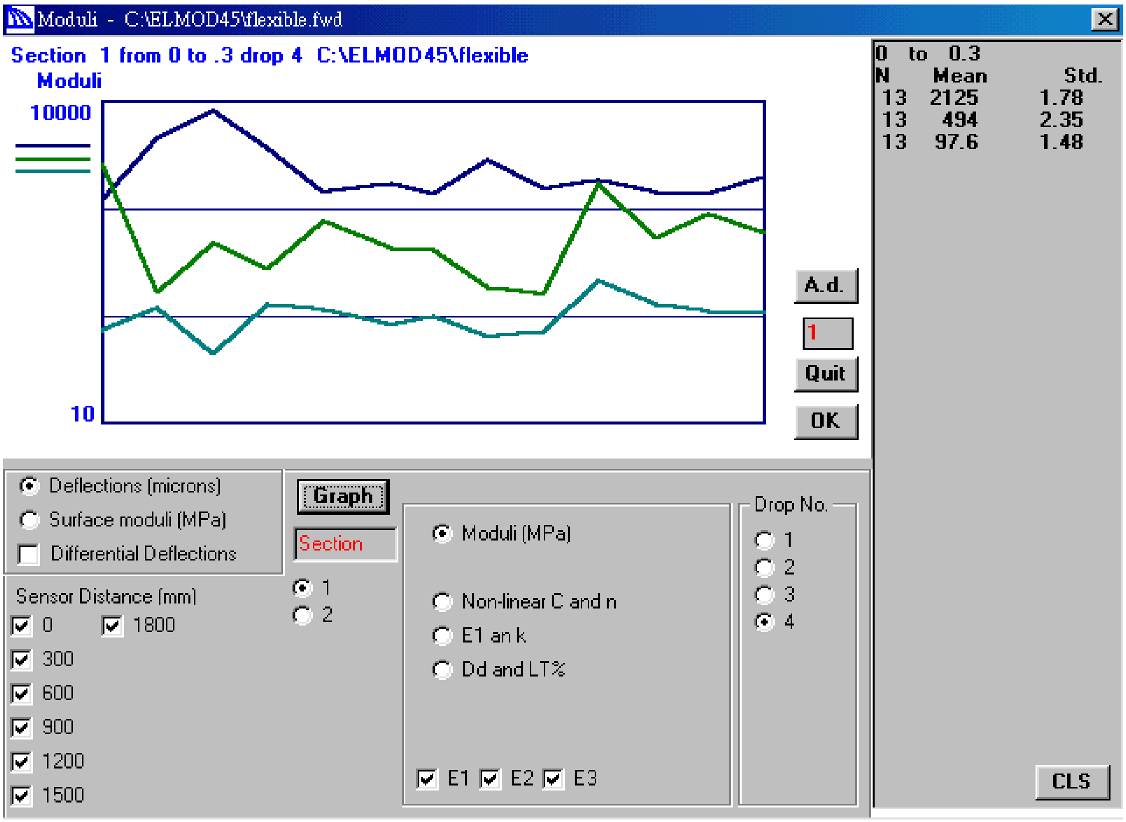

Figure 5.13 – Section 1 Layer Moduli

Under the 'Section' box, click on the '2' radio button to see the graph for Section 2. Again it can be observed that the backcalculated moduli of the sub-base appear unreasonable at a couple of locations, where it is either lower than the subgrade or higher than the asphalt layer.

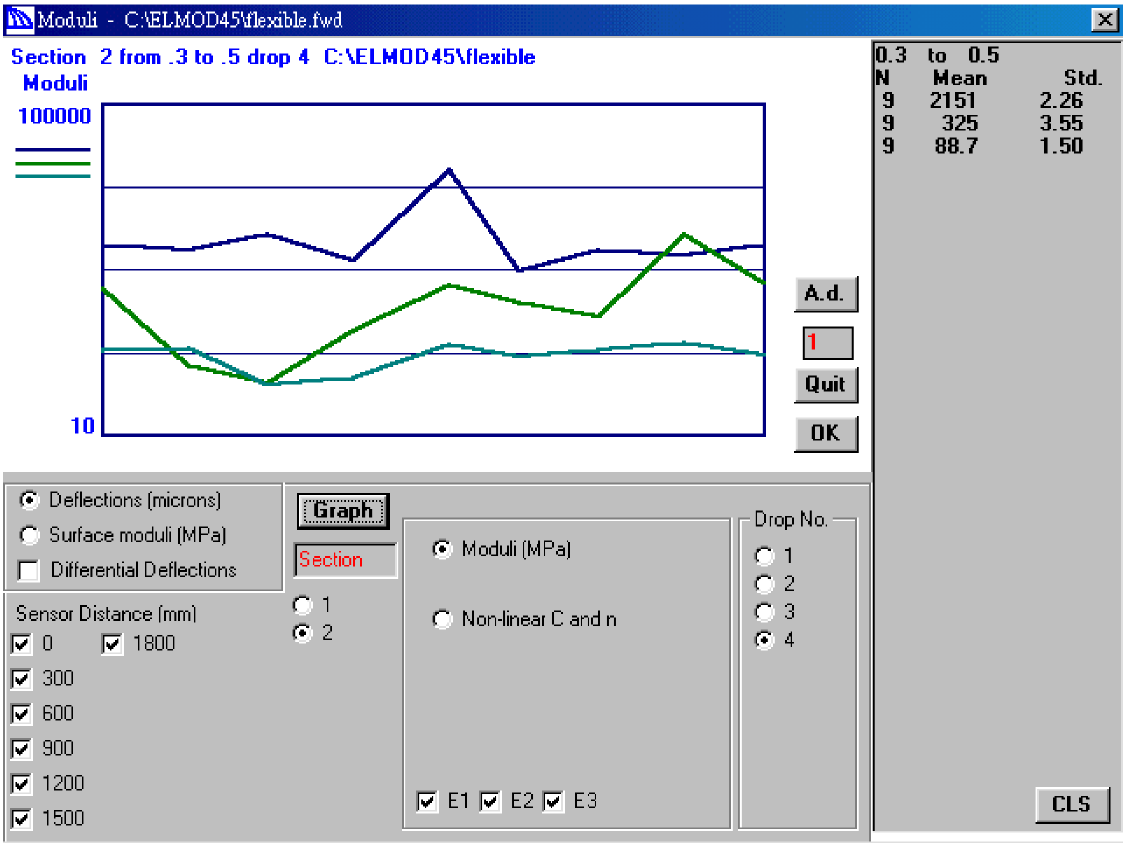

Figure 5.14 – Section 2 Layer Moduli

The anomalies can sometimes be removed by modeling an additional layer of subgrade of 500 mm to 1000 mm just below formation level. At other times the anomalies remain even after much remodeling. It may be useful to compare the dubious data against other test data, such as laboratory test results on cored samples and DCP tests. Again engineering judgement is required to determine whether additional tests are required or if the anomalies are acceptable.

In this example, the mean moduli values appear reasonable and the standard deviations are small. The anomalies are accepted for further analysis.

5.11 REVIEW RESIDUAL LIFE

Click on 'Plot' in the top menu and under the 'Section' box at the lower middle of the screen, click on the '1' radio button. In the 'Drop No.' box at the lower right, click on the '4' radio button. Click on the 'Structural life (yrs)' radio button to display the residual life values for Section 1 estimated from Drop 4 data. Observe that while the mean residual life is 142 years, the lowest residual life of 6.21 years occurs at chainage 0.2.

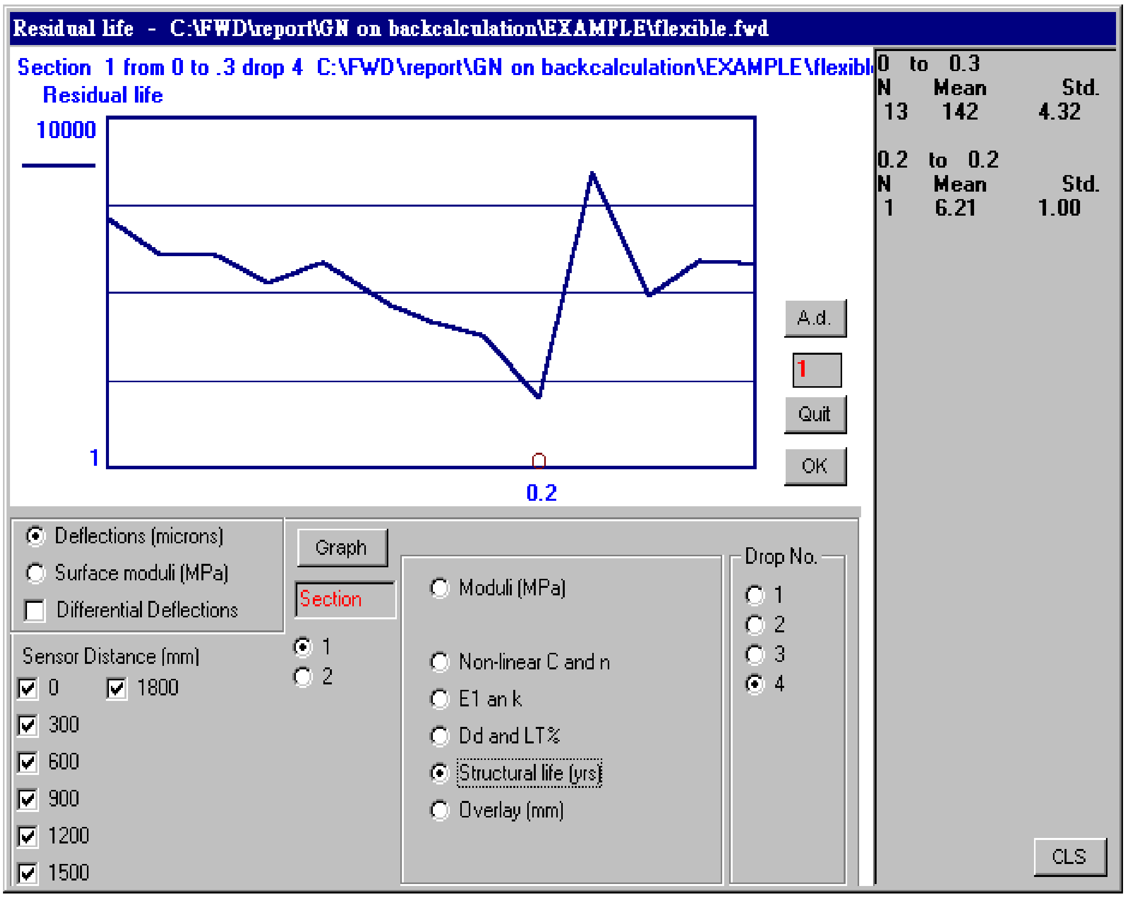

Figure 5.15 – Section 1 Residual Life

Under the ‘Section’ box, click on the ‘2’ radio button to see the residual life of Section 2. Observe that while the mean residual life is 52.1 years, the lowest residual life of 1.51 occurs at chainage 0.326.

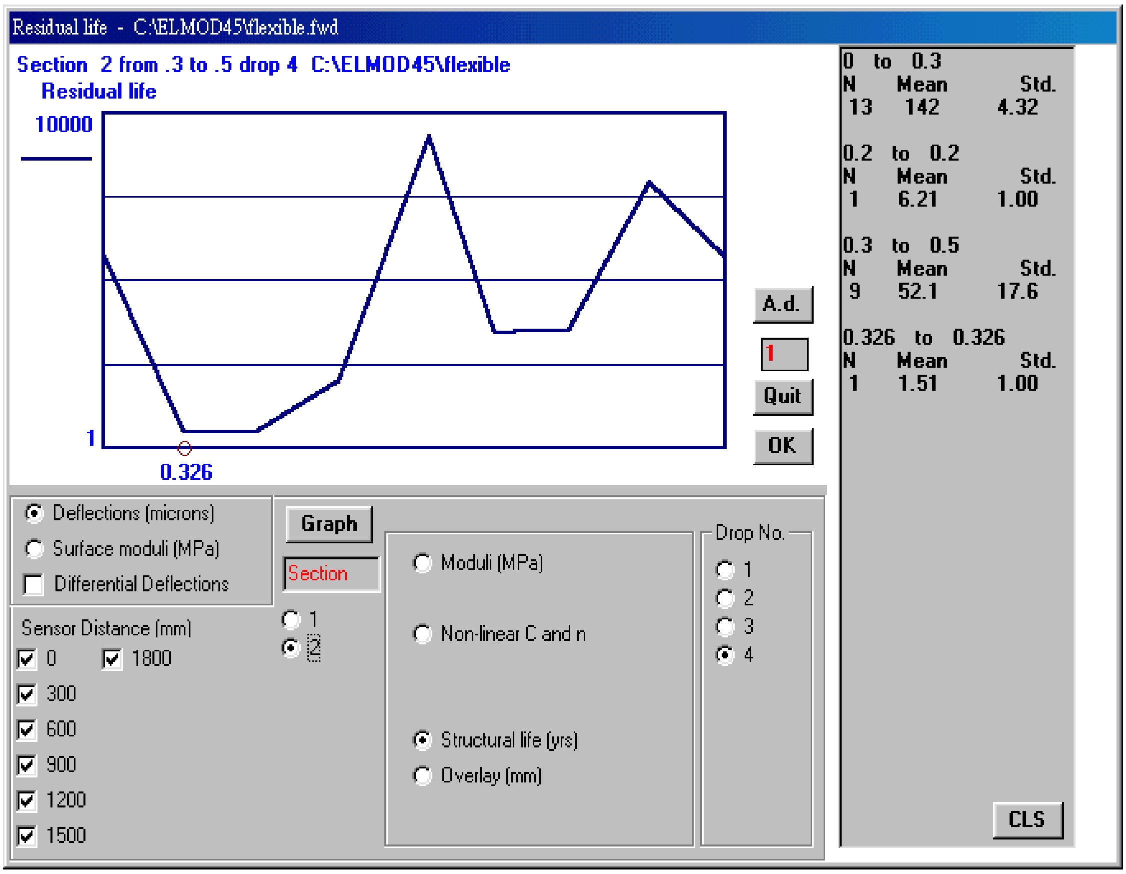

Figure 5.16 – Section 2 Residual Life

5.12 REVIEW AND ARCHIVE RESULTS

From this example, it is observed that Section 1 has a higher mean residual life than Section 2. The lower residual life of Section 2 corresponds to the larger deflections from chainage 0.326 to 0.376 and 0.426 to 0.45.

For design purposes, the condition at the test station that records the 85 percentile centre deflection should be chosen to be representative of the section. In this case, refer to Section 3.7 to import the file ‘FLEXIBLE.DMS’ into a spreadsheet. Using MS Excel as an example, the steps are shown below:

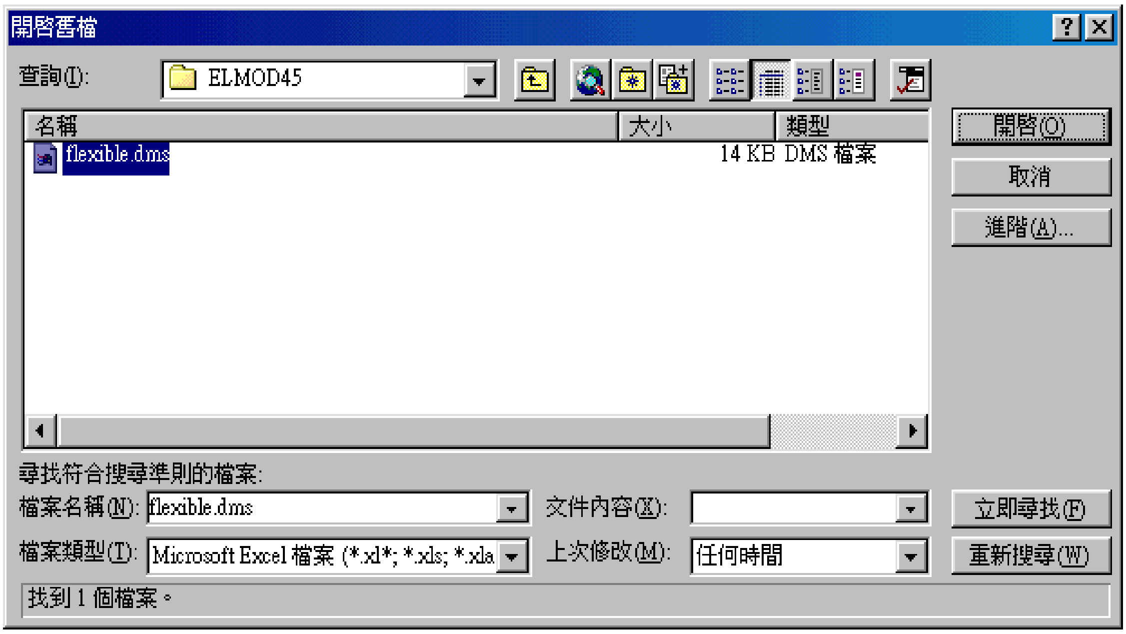

Figure 5.17 – Open ‘.DMS’ File in Excel

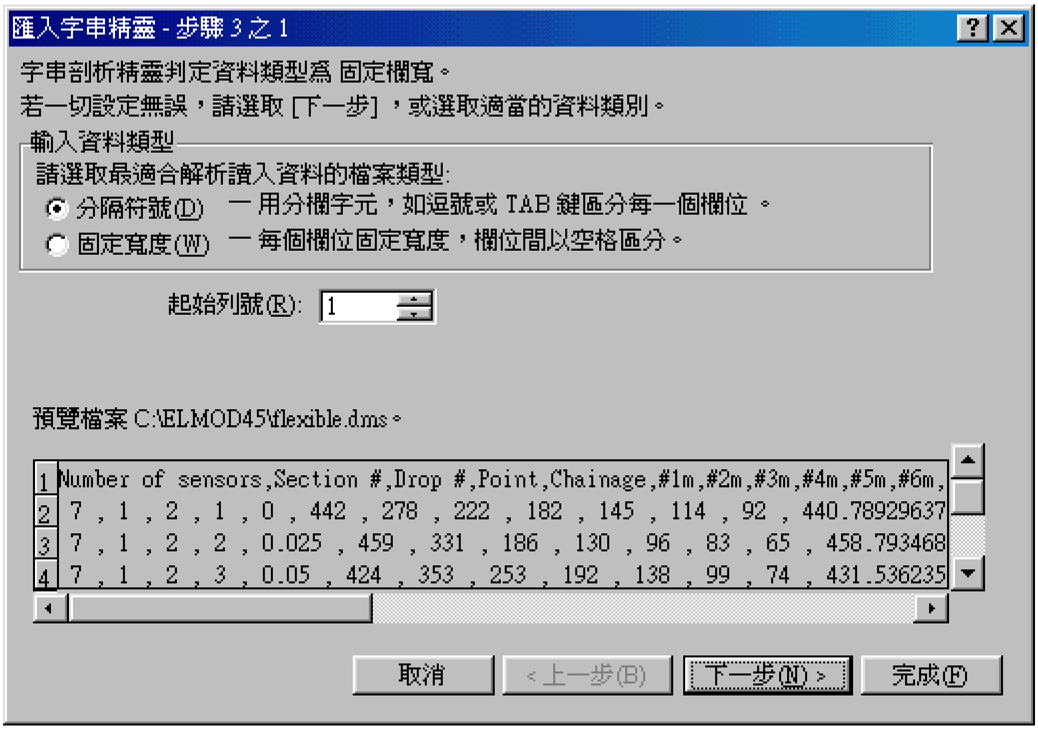

Figure 5.18 – Select the Delimit Sign

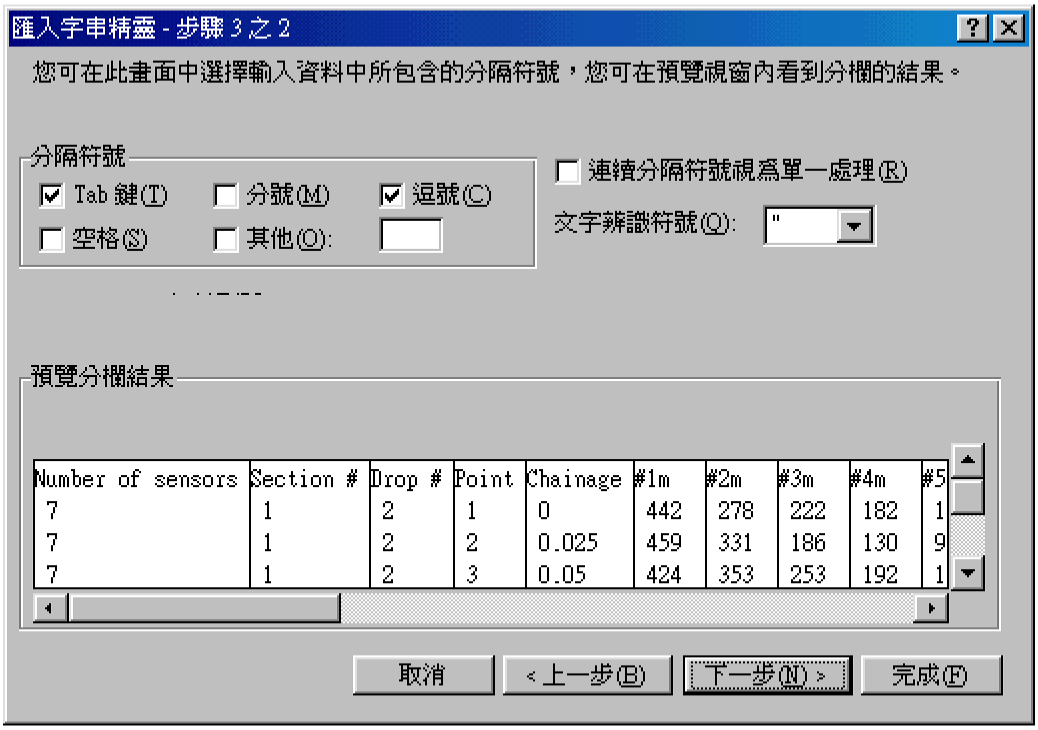

Figure 5.19 – Check Tab and Comma Boxes

Click the ‘Finish’ button to complete the import process.

A portion of the spreadsheet, up to column F containing the measured deflection at geophone number 1 (centre deflection) is shown below. The test station at the chainage 0.3 is repeated in the original file because it occurs in the boundary of both sections. The duplicate entry should be taken out when calculating the 85 percentile value for the entire test run. Note that Rows 25 to 30 are manually entered into the spreadsheet to calculate the 85 percentile centre deflection using the built-in PERCENTILE function.

	A	B	C	D	E	F
1	Number of sensors	Section #	Drop #	Point	Chainage	#1m
2	7	1	4	1	0	436
3	7	1	4	2	0.025	457
4	7	1	4	3	0.05	421
5	7	1	4	4	0.075	422
6	7	1	4	5	0.1	447
7	7	1	4	6	0.131	532
8	7	1	4	7	0.15	534
9	7	1	4	8	0.175	615
10	7	1	4	9	0.2	725
11	7	1	4	10	0.225	268
12	7	1	4	11	0.251	468
13	7	1	4	12	0.275	436
14	7	1	4	13	0.3	433
15	7	2	4	13	0.3	433
16	7	2	4	14	0.326	757
17	7	2	4	15	0.35	928
18	7	2	4	16	0.376	816
19	7	2	4	17	0.405	217
20	7	2	4	18	0.426	627
21	7	2	4	19	0.45	538
22	7	2	4	20	0.476	317
23	7	2	4	21	0.5	365
24						
25	85 percentile centre deflection for section 1 =					550.2
26	85 percentile centre deflection for section 2 =					804.2
27	85 percentile centre deflection for entire test run =					725.0
28						
29	Note: the 85 percentile for Section 1 can be calculated using the built-in					
30	function = PERCENTILE(F2:F14,0.85).					

In Section 1, the 85 percentile centre deflection value is 550μm and the test station with the nearest centre deflection is at chainage 0.15. In order to check the residual life, refer to Section 3.9 and use similar steps as shown above to import the file 'FLEXIBLE.L2' into a spreadsheet. Note that the estimated residual life at this test station is 30 years and therefore no maintenance treatment is required. However, since the estimated residual life at chainage 0.2 is only 6.2 years, some local strengthening may be desirable.

Chainage	Layer	Remaining Life (years)	Layer	Remaining Life (years)	Minimum Life (years)	Overlay Thickness (mm)
0	1	30	3	30	30	0
0.025	1	30	3	30	30	0
0.05	1	30	3	30	30	0
0.075	1	30	3	30	30	0
0.1	1	30	3	30	30	0
0.131	1	30	3	30	30	0
0.15	1	30	3	30	30	0
0.175	1	30	3	30	30	0
0.2	1	6.2	3	21.4	6.2	35.1
0.225	1	30	3	30	30	0
0.251	1	30	3	30	30	0
0.275	1	30	3	30	30	0
0.3	1	30	3	30	30	0

In Section 2, the 85 percentile centre deflection value is 804μm and the test station with the nearest centre deflection is at chainage 0.376. In order to determine the maintenance options, follow the steps described in Section 3.9 to import the file 'FLEXIBLE.L3' into a spreadsheet. Note that while the estimated residual life at chainage 0.376 is 6.4 years, failure is more likely to occur at chainages 0.326 and 0.35 that have residual lives of 1.5 and 1.6 years respectively. The residual life of the subgrade at chainage 0.35 is only 6.9 years. Therefore, local full-depth reconstruction may have to be carried out around chainages 0.326 to 0.376.

Chainage	Layer	Remaining Life (years)	Layer	Remaining Life (years)	Minimum Life (years)	Overlay Thickness (mm)
0.3	1	30	3	30	30	0
0.326	1	1.5	3	30	1.5	78.9
0.35	1	1.6	3	6.9	1.6	80.7
0.376	1	6.4	3	9.7	6.4	32.2
0.405	1	30	3	30	30	0
0.426	1	23.1	3	30	23.1	0
0.45	1	25.6	3	30	25.6	0
0.476	1	30	3	30	30	0
0.5	1	30	3	30	30	0

It should be noted that if the test run is not divided into 2 sections, then the 85 percentile centre deflection value is 725μm and the test station with the nearest centre deflection is at chainage 0.2. Since the estimated residual life at this test station is 6.2 years, in-lay strengthening may be considered. However, local reconstruction may still be required at chainages 0.326 and 0.35.

Note also that in deciding on the maintenance treatment, structural pavement evaluation should be considered together with other factors such as visual inspection results, surface roughness, traffic condition, and engineering judgement.

6 ANALYSING A RIGID PAVEMENT STRUCTURE

This Section illustrates the use of ELMOD to analyse a rigid pavement structure.

6.1 OPEN RAW DATA FILE

Invoke ELMOD. Click on ‘File’ in the top menu to select ‘Single File’ from the pull down menu. Select the raw data file to be analysed and click the ‘Open’ button. For illustration, this time a sample data file called “ RIGID.F25“ is used. It should be noted that at the time of testing, the field program was set to record only the last 2 drops. Hence only test data for 2 drops can be processed and both Drop 1 and Drop 2 are used. It is expected that newly acquired FWD data will record all 4 drops in accordance with the practice stipulated in RD/GN/026.

6.2 INPUT PAVEMENT STRUCTURE

Click on ‘Structure’ in the top menu to enter the pavement structure. A ‘Structural data’ window will pop up. In the ‘Section’ box, enter 1, from 1.1 to 21.22. A 2-layer model is adopted for this example. The concrete slab forms a single top layer with thickness H_1 = 225 mm. The granular sub-base and the subgrade is not subdivided into two layers and its thickness is considered to be semi-infinite, there is no need to input its thickness. Note that since the test is carried out on rigid pavement and the load transfer across joints is tested, check the box next to ‘Use PCC Joint ID Numbers’ at the bottom of the window. The other fields are left blank.

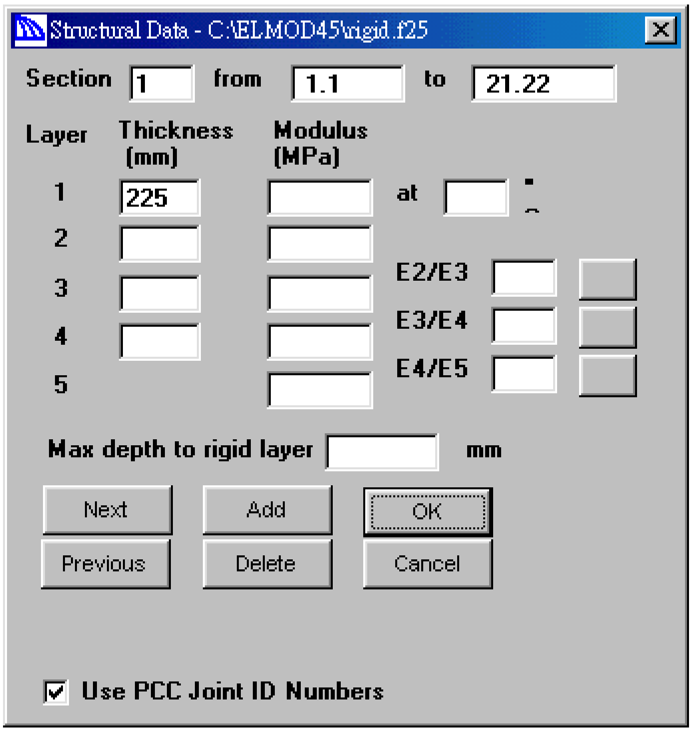

Figure 6.1 – Input Section Structural Data for Rigid Pavement

6.3 BACKCALCULATE EFFECTIVE LAYER MODULI

Click on ‘Moduli’ in the top menu to backcalculate the layer moduli. The data file does not record the test results of the first two drops, therefore the test results of Drop 3 and Drop 4 are recorded as Drop 1 and Drop 2 in the data file. In the ‘Select Drops’ box, check both the ‘1’ and ‘2’ boxes so that both sets of deflection data are used for analysis. In the ‘Select Sections’ box, check the ‘1’ box. In the ‘Check measured deflection’ box, select ‘None’. Leave the ‘Program control options’ box blank. In the ‘Backcalculation Mode’ box, select ‘Radius of curvature’. Click on the ‘Calculate’ button to perform the analysis.

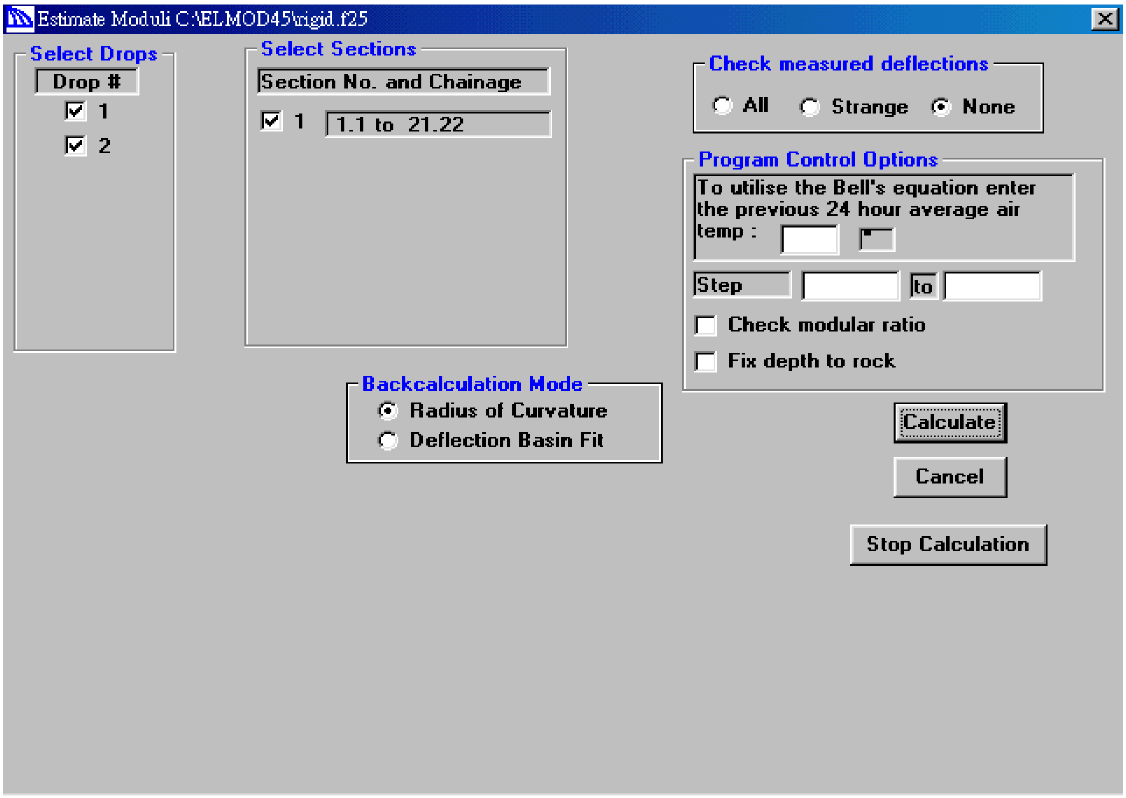

Figure 6.2 – Backcalculate Effective Layer Moduli for Rigid Pavement

When the backcalculation is completed, a window will pop up asking ‘Do you want to save your results for viewing and printing?’ Click on the ‘Yes’ button. If a previous backcalculation has already been carried out, a second window will pop up asking ‘Overwrite existing file? Select no to append.’ Click on the ‘Yes’ button to overwrite the existing file. Click on the ‘No’ button to append the new results to the existing one, useful for appending backcalculation results for different sections onto the same file. Finally, a window with the message ‘Data has been saved’ will pop up. Click on the ‘OK’ button to leave the window.

6.4 ESTIMATE RESIDUAL LIFE

Click on ‘Design’ in the top menu to estimate the residual life. A ‘Select parameter file’ window will pop up. Select the parameter file ‘HK042009.WPR’ and click the ‘Open’ button. A ‘Select Section’ window will pop up. Select Section ‘1’ and Drop ‘2’ to be analysed. Click on the ‘OK’ button.

A ‘Materials and Loading’ window will pop up. Select the overlay material by highlighting ‘Asphalt New Mix’ on the right hand box, then click on ‘Overlay’ in the left hand box. Select ‘Concrete’ on the right hand box and click on Layer 1. Select ‘Subgrade’ on the right hand box and click on Layer 2. In the ‘Number of loads per year’ box, enter the predicted average annual equivalent standard axle loads, 1200000 in this example. In the ‘Treatment before Overlay’ box, select ‘None’. Select ‘Concrete’ in the top right-hand material box, then click in the empty box below ‘Slab at joint is’.

In the ‘Treatment before overlay’ box, click ‘None’ since asphalt overlay on concrete pavement is not recommended. Click on the ‘OK’ button to start the design calculation.

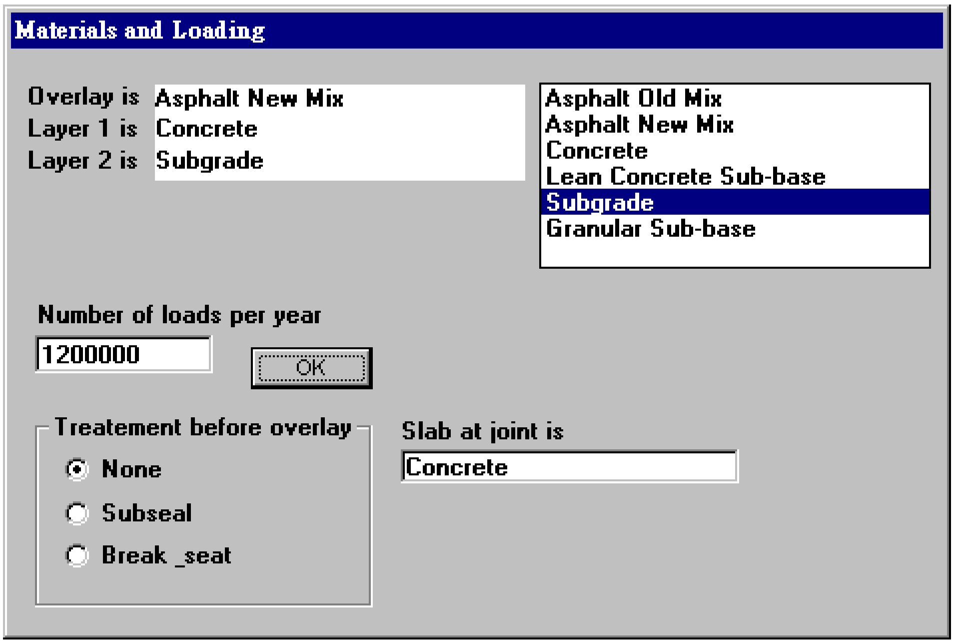

Figure 6.3 – Input Materials and Loading (Rigid)

A window with the message ‘Overlay design complete’ will pop up after ELMOD has completed estimating the residual life and designing the overlay requirement. Click on the ‘OK’ button.

6.5 CHECK RESULTS

Click on the 'Plot' menu and a graphics window will be displayed. In the lower half of the window, check the 'Deflections (microns)' radio button. Check all the sensor distance check boxes below. In the 'Drop No.' box to the right, check the '2' radio button. Click on the 'Graph' button near the centre to show the deflection pattern along the length of the test run.

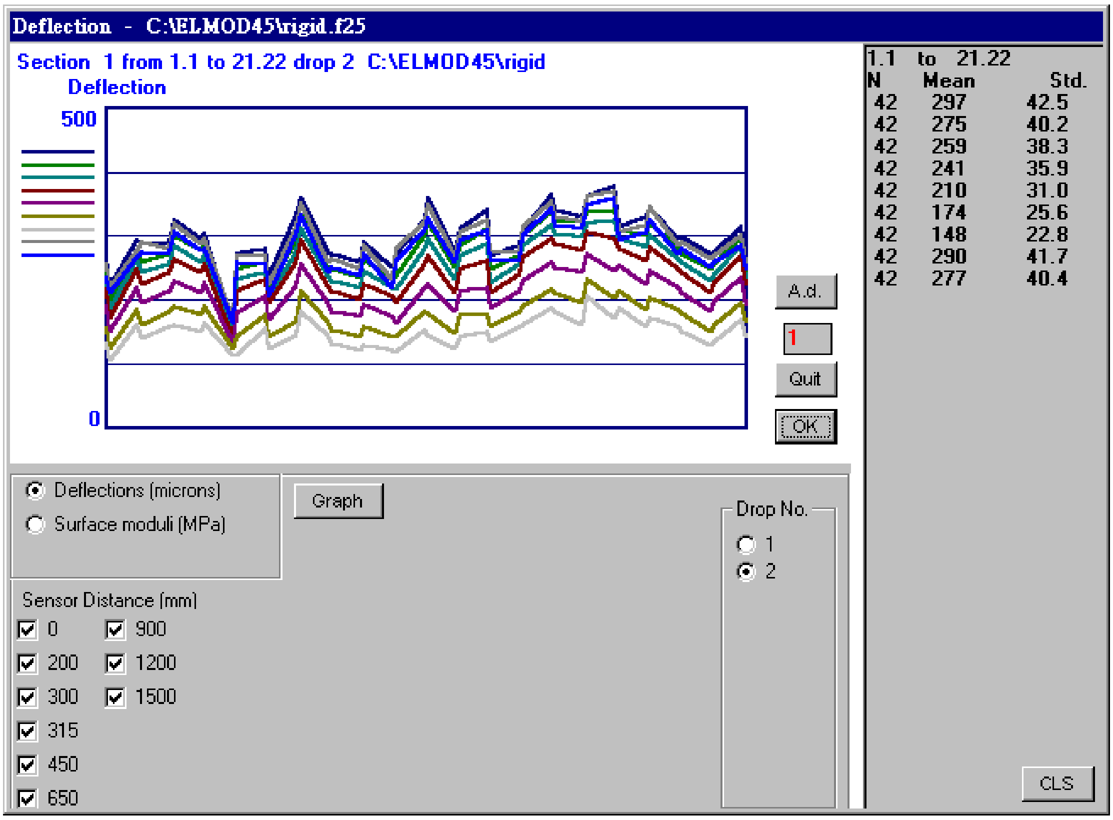

Figure 6.4 – Deflection along Test Run on Rigid Pavement

Note that the deflection pattern shows a jagged pattern due to the tests being carried out alternately at the joint position and then at the centre of the concrete slab. To check the data consistency with Drop 1, click on the radio button next to '1' under the 'Drop No.' box on the right. Then click on the 'Graph' button to see the deflection pattern of Drop 1. The graph shows that the test patterns between the 2 drops are highly consistent.

In this example, although the deflections of various geophones at chainage 5.1 appear to be compressed when compared with others, their magnitudes do not differ significantly from others. The data need not be deleted before reviewing other results. Graphs of moduli and residual life, which are same as Figures 6.7 and 6.10 respectively, shall also be checked.

Note also that 9 geophones instead of 7 geophones are used. The geophones are spaced out such that the geophones at distances 200mm (geophone no. 8) and 300mm (geophone no. 9) from the load are placed behind the load while the other 7 geophones are placed in front of the load. This arrangement allows test at transverse joints to be conveniently carried out. The geophone arrangement is as shown below:

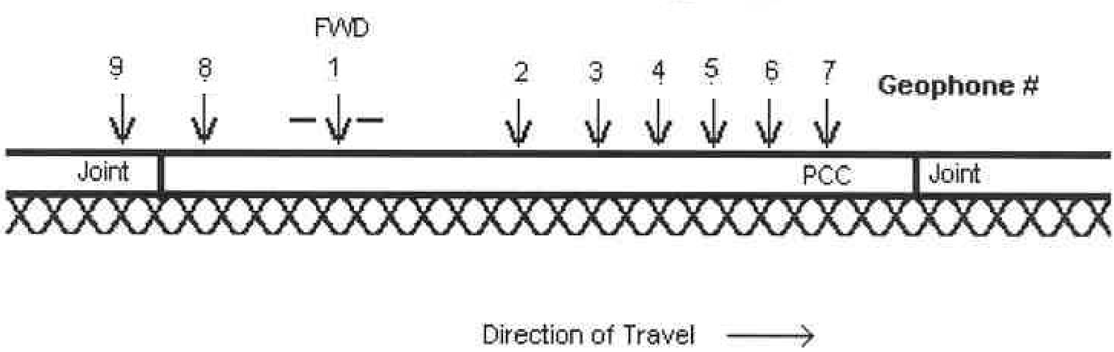

Figure 6.5 – Geophone Arrangement for Testing Joints at Rigid Pavement

To close the graphic window, click on the ‘Quit’ button to the right of the graph.

6.6 REVIEW CUMULATIVE DEFLECTIONS

Click on 'Plot' in the top menu and uncheck all sensors except the 0mm sensor. In the 'Drop No.' box, click on the radio button next to '2' and then click on the 'Graph' button to plot the centre deflection. Click on the 'A.d.' button to the right of the graphic to plot the deflection cumulative sum.

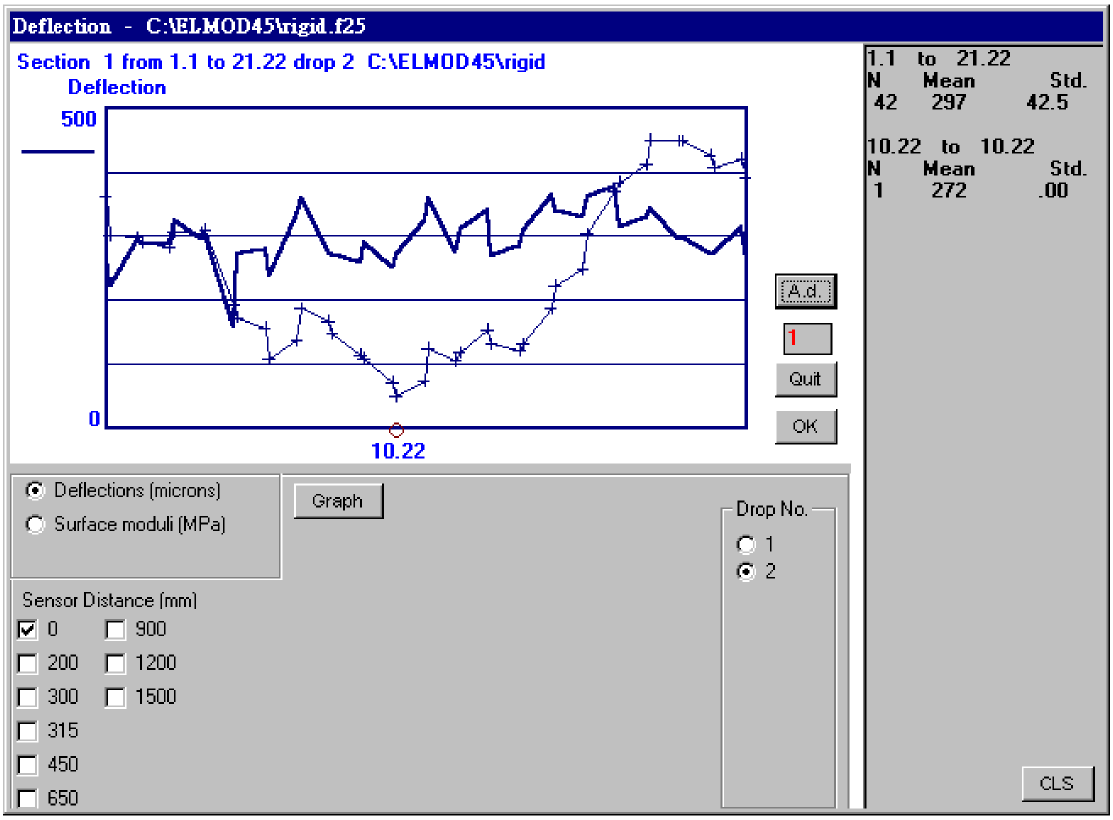

Figure 6.6 – Centre Deflection and Cumulative Sum on Rigid Pavement

In this example, the cumulative deflection curve bottomed out at chainage 10.22. Again, whether to divide up the entire test run into sections is a matter of engineering judgement. For illustration purpose, this time the test run is to be analysed as a single section. Click on the 'Quit' button to leave the graphic window.

6.7 REVIEW EFFECTIVE LAYER MODULI, MODULI OF SUBGRADE REACTIONS AND LOAD TRANSFER

Click on 'Plot' in the top menu and under the 'Section' box at the lower middle of the screen, click on the '1' radio button. In the 'Drop No.' box at the lower right, click on the '2' radio button. Click on the 'Moduli (MPa)' radio button to display the Section 1 layer moduli backcalculated from Drop 2 data. See if the backcalculated modulus for the same layer vary significantly along the test run. Observe the mean value and distribution of the layer moduli.

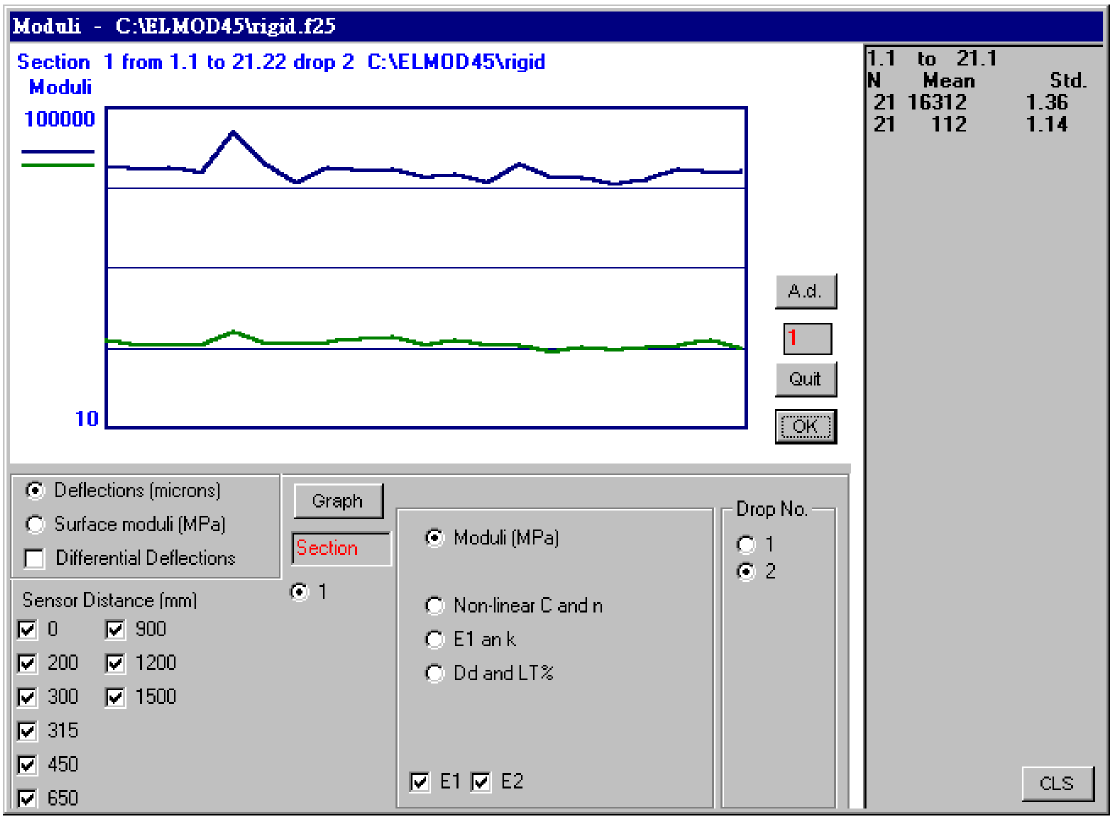

Figure 6.7 – Layer Moduli for Rigid Pavement

Note that in this example, a small bump in layer moduli occurs at the chainage where the compressed deflections are. However, the layer moduli for both the concrete slab and the combined sub-base and subgrade layer are highly consistent. As seen on the right hand column, the standard deviations are very small.

Click on the 'E1 and k' radio button to plot the concrete modulus and modulus of subgrade reaction. Note that the 'k_c' and 'k_j' represents the moduli of subgrade reaction at centre and joint of the concrete slab respectively, as if the subgrade does not transfer shear stress, like in a Winkler foundation.

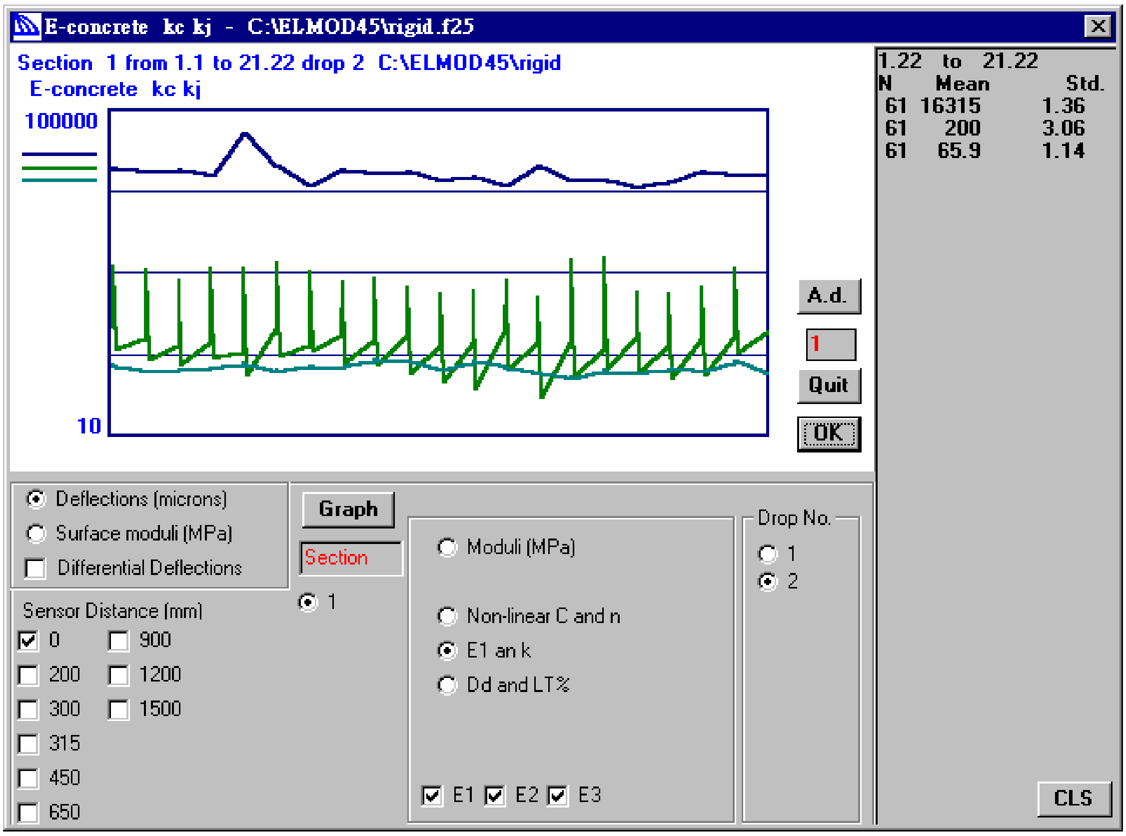

Figure 6.8 – Effective Concrete Modulus and Modulus of Subgrade Reaction (Rigid)

Click on the ‘Dd and LT%’ radio button to plot the differential deflection across joints and the load transfer ration. It can be seen that 21 tests across joints have been carried out and the mean differential deflection is 9.05mm with a standard deviation of 1.91 mm. The load transfer ratio is high at 96.8%, with a small standard deviation of 0.67 only. This indicates that the joints are in good condition.

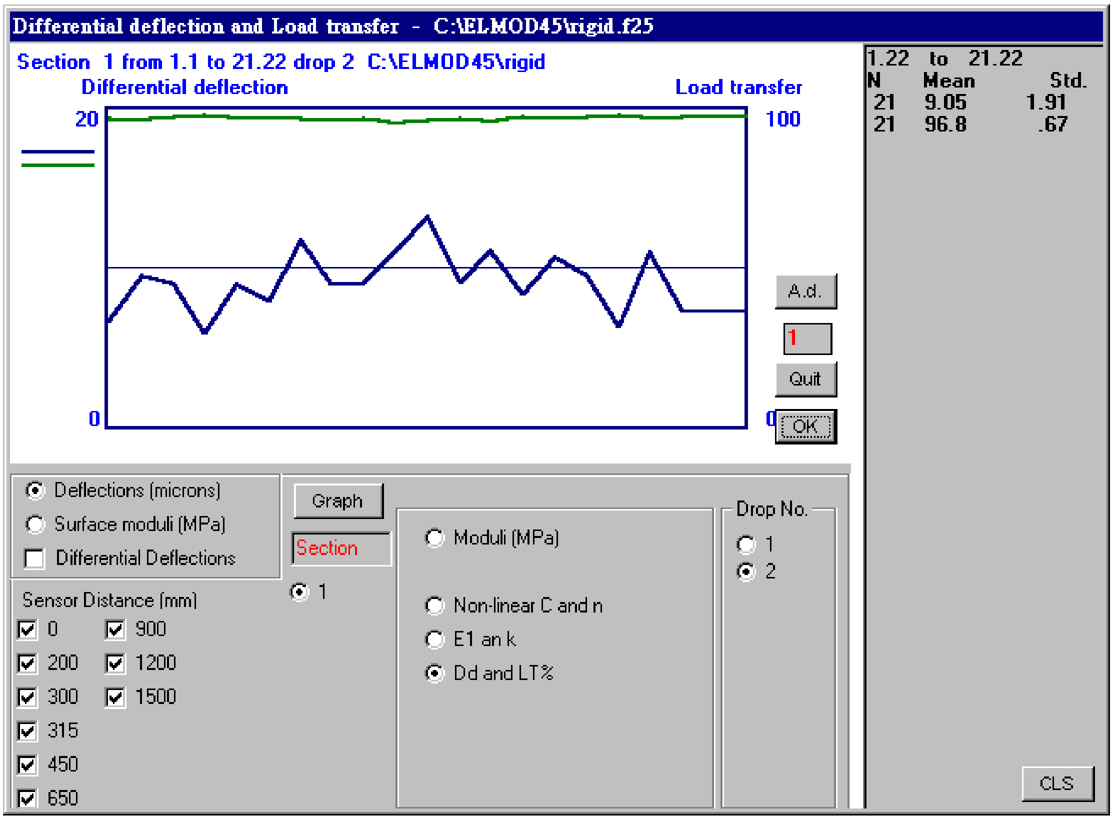

Figure 6.9 – Differential Deflection and Load Transfer Ratio

6.8 REVIEW RESIDUAL LIFE

Click on ‘Plot’ in the top menu and then click on the ‘Structural life (yrs)’ radio button to display the estimated residual life values. It can be seen that the residual life of the concrete pavement as calculated is consistently over 800 years. This indicates that the whole pavement structure is in good condition and no reconstruction work is required.

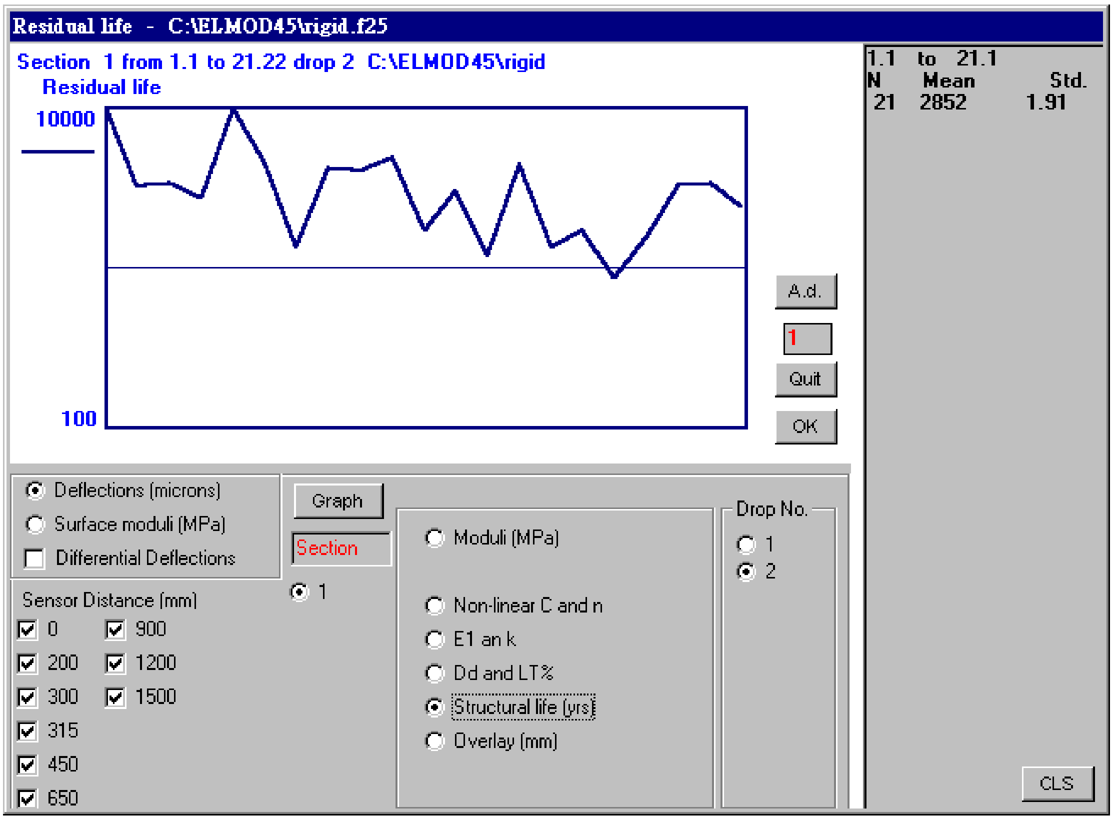

Figure 6.10 – Residual Life (Rigid)

6.9 REVIEW AND ARCHIVE RESULTS

Similar to the example for flexible pavement, the results should be reviewed. In this case, the FWD data appear fairly consistent and the results appear reasonable. Therefore, no re-analysis is required and the results are archived electronically and on paper.

APPENDIX A – REFERENCES

[1] Acer Consultants (Far East) Limited, 1995. "Highway Maintenance Management Pilot Scheme Volume A – Main Report", Highways Department.

[2] Acer Consultants (Far East) Limited, 1995. "Highway Maintenance Management Pilot Scheme Final Report Volume B4 – FWD Test Sections", Highways Department.

[3] Dynatest International, 1997. "ELMOD Help File (electronic copy installed together with ELMOD)".

[4] Dynatest International, 1998. "ELMOD Quick Start Manual".

[5] Harrison, 1989. "DCP Calibration (Indonesia)". Australian Road Research, Vol. 19, No. 4.

[6] Stubstad, Baltzer, Lukanen, and Ertman-Larsen, 1994. "Prediction of AC Material Temperatures for Routine Load/Deflection Measurements". Proceedings of the 4th International Conference on the Bearing Capacity of Roads and Airfields, Minneapolis, USA.

[7] Ullidtz, Per, 1987. "Pavement Analysis", Elsevier.

[8] Shell International Petroleum Company Limited, London, 1978, "Shell Pavement Design Manual – asphalt pavements and overlays for road traffic".

[9] J. Boussinesq,1885, Applicaation des potentiels á l 'etude de l 'equilibre et du mouvement des solides élastique.

[10] E. Winkler, 1867, Die Lehre von der Elasticität und Festigkeit, Prage Dominicus.

[11] A.M. Ioannides, M.R.. Thompson & E.J. Barenberg, 1985, Westergaard Solutions Reconsidered, Transportation Research Record 1043.