LOADMAN PORTABLE FALLING WEIGHT DEFLECTOMETER: DEVELOPMENT OF TESTING PROCEDURES

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EXECUTIVE SUMMARY

The AUSTROADS pavement design procedures were adopted by New Zealand road controlling authorities in 1995. As these procedures incorporate elastic modulus parameters of the different layers of a road pavement, this requirement has created a demand for cost-effective methods of establishing the elastic parameters for pavement materials. The Loadman Portable Falling Weight Deflectometer (FWD) which has been introduced to the New Zealand market in relatively recent times (1996), shows significant potential as a very useful tool for the pavement engineering practitioner to obtain these parameters. Also when compared with other test procedures, the Loadman is relatively inexpensive and is quick and simple to operate.

The Loadman Portable FWD basically comprises an 800-mm long by 132-mm diameter aluminium tube with a 10 kg weight inside it. The tube is closed at both ends with an electromagnet at the top and a circular steel plate at the bottom. When the Loadman is placed on a pavement material and activated, the weight falls onto the base plate and imparts a dynamic load to the material beneath the device. The acceleration of the whole device which reflects the response of the test material is monitored using an accelerometer. This acceleration is integrated to a deflection which is then analysed to determine the material's elastic modulus parameters.

One of the drawbacks of the Loadman is that it is programmed to calculate elastic modulus values using the Boussinesq theoretical model. The Boussinesq model assumes a single layer of isotropic material which is somewhat contrary to most pavement conditions. This project has included establishment of revised constants to be programmed into the Loadman to produce elastic modulus data taking into account a more realistic loading characterisation and an anisotropic material response.

The research, carried out in 1997-98, has also involved the development of both field and laboratory testing procedures to maximise the utilisation of the Loadman. The field procedures have been developed to include both single and two-layered pavement structures using a back-calculation technique to determine the anisotropic elastic moduli of the layers. Similarly, the laboratory version of the Loadman test uses a back-calculation technique to establish the elastic properties of the test material. The laboratory Loadman test involves preparation of test specimens in a 0.5 m x 0.5 m x 0.5 m steel box. The Loadman is then used both to impose the dynamic load and to measure the elastic response of the specimen. A multi-layer elastic computer program is used to back-calculate the anisotropic (or isotropic) elastic modulus. This procedure has been verified using finite element modelling.

A series of laboratory Loadman tests has been performed in this investigation and the results have been compared with data obtained using RLT tests. Analysis of the results shows that the Loadman provides data that are comparable to the RLT test.

The advantage of the proposed laboratory Loadman test over tests such as the RLT is that it is quick and simple to perform, it requires very little equipment, and representative specimens can be tested. This means, for example, that aggregates with particle top sizes of 65 mm or even 100 mm can be tested, with no need to "scalp" the larger particles (i.e. removing particles retained on a 19 mm sieve) as is required for most repeated load triaxial (RLT) tests. However the level of stress that is imposed by the Loadman may be greater than that occurring in-service, especially for subgrade soils.

The Loadman could be developed so that it incorporates an internal load cell to measure the applied dynamic load, and then the results would be even more favourable. This would result in a new method of determining anisotropic elastic modulus data that is simple, quick and cost-effective.

ABSTRACT

The Loadman Portable Falling Weight Deflectometer (FWD) which has been introduced to the New Zealand market in relatively recent times (1996), is described. It shows significant potential as a very useful tool for the pavement engineering practitioner, particularly since the AUSTROADS pavement design procedures were adopted by Transit New Zealand in 1995.

The research was carried out in 1997-98. This report of the research describes methods of improving the utilisation of the Loadman by developing revised constants that better reflect factors such as the loading configuration and material response. These constants can be programmed into the device.

The report also describes the development of Loadman test procedures for both field and laboratory-based tests. The laboratory version of the test allows anisotropic elastic modulus data to be obtained using simple and cost-effective procedures. Verification of the laboratory Loadman testing and analysis procedure has been carried out using finite element modelling.

In addition, the results of laboratory Loadman tests have been compared with data obtained using repeated load triaxial (RLT) tests. The analysis shows that the two test procedures correlate reasonably well although the level of stress imposed by the Loadman may be greater than that occurring in-service, especially for subgrade soils.

1. INTRODUCTION

1.1 General

In July 1995 Transit New Zealand adopted the AUSTROADS[1] (1992) pavement design procedures (Transit New Zealand 1997). A significant component of the AUSTROADS pavement design procedure is the modelling of trial pavements using a multiple layer elastic solutions computer program called *CIRCLY* (Wardle 1996). *CIRCLY* calculates the strains occurring at critical locations in the pavement structure under a standard loading configuration. The critical strains are then used in material performance criteria to determine the service life of the various pavement components. In *CIRCLY*, each pavement layer is characterised in terms of its thickness and elastic parameters, of elastic modulus (E) and Poisson's ratio (ν).

The requirement to use the elastic modulus of the various pavement layers in the design procedure has posed a difficulty for the New Zealand pavement designer. In the past, E values have been somewhat inconspicuous in the design procedure and so they have not received much attention from roading practitioners. Where E values were required, the general practice has been to obtain the data indirectly using empirical relationships with other material parameters. This has usually been done using relatively quick and inexpensive test methods, e.g. California Bearing Ratio (CBR), Scala penetrometer, shear vane, etc. The appropriateness of this approach is questionable and is frequently criticised in the technical literature.

The best way to determine the elastic modulus of a pavement material is to measure it directly, i.e. impose an appropriate stress on the material and measure its elastic response. This can be achieved using the Benkelman Beam, Falling Weight Deflectometer (FWD) or the repeated load triaxial (RLT) apparatus, but these tests require the use of comparatively large, expensive equipment, and a reasonably high level of skill and experience is needed to extract the appropriate answers. In addition, the results can be significantly influenced by the methodology used for the data analysis. A simpler, less cumbersome device to measure the elastic modulus is the Loadman portable falling weight deflectometer that has been available since 1996 in New Zealand.

The Loadman is a portable FWD apparatus that is used to determine the elastic modulus of pavement materials. The Loadman imparts a dynamic load on a test material and measures the resulting deflection. The load and deflection data are subsequently used to calculate the elastic modulus parameter. Testing is carried out by one person and each test drop takes about 10 to 30 seconds to complete. The Loadman is reported to be appropriate for materials ranging from soft subgrade soils to compacted high quality crushed rock basecourse, and even asphaltic concrete. The Loadman apparatus has significant potential for use in New Zealand, especially now

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1 AUSTROADS is the association of State, Territory and Federal road and traffic authorities in Australia and New Zealand.

that the AUSTROADS pavement design procedures have been adopted by road controlling authorities.

In preceding Transfund New Zealand research, Bartley Consultants Limited (BCL) investigated the accuracy, repeatability and limitations of the Loadman. The report of that research project (BCL 1998) concluded that the Loadman shows considerable potential for use in the road construction industry, particularly as a quality control tool and as a means of substantiating elastic modulus data that may have been assumed during design. The test results were found to be very repeatable and there was a reasonable correlation between the Loadman test results and laboratory resilient modulus test results. However, the latter observation was based on a relatively small number of test specimens.

A shortcoming of the Loadman device is that it calculates the elastic modulus of the test material using the Boussinesq elastic theory. This theory is valid for a single layer of isotropic material. However, in a pavement, generally more than one layer of material exists, and the AUSTROADS pavement design procedures require that unbound aggregate and subgrade materials are to be analysed using anisotropic material parameters.

1.2 Objectives

This project, carried out in 1997-98, investigates the development of the Loadman testing procedure to produce data that is realistic and consistent with the requirements of the AUSTROADS pavement design procedures. This will be done using both a theoretical and a practical approach. On the theoretical side, the procedure that is used by the Loadman to automatically calculate the elastic modulus will be revised to allow for material anisotropy. On the practical side, an appropriate Loadman test procedure will be established for both field and laboratory tests. Development of the field Loadman test will include procedures for both single and two-layered pavement structures.

The objectives of the project are as follows:

- To develop a set of constants for programming the Loadman to produce elastic modulus data that more realistically reflect the material properties;
- To develop both field and laboratory-based Loadman testing procedures that facilitate the establishment of anisotropic elastic modulus data; and
- To compare the results of laboratory-based Loadman tests with corresponding tests performed using the repeated load triaxial apparatus.

2. FUNDAMENTAL ASPECTS OF PAVEMENT MATERIALS TESTING

2.1 General

One of the objectives of this investigation has been to develop the Loadman test procedure in both the field and laboratory environments. Therefore it is useful to discuss some of the fundamental aspects of testing pavement materials. These include:

- specimen configuration;
- material non-linearity;
- loading configuration.

Each of these issues could be the subject of an entire report, but for the purposes of this investigation only a brief description of the fundamental points will be presented.

2.2 Specimen Configuration

For any material that is being tested to establish its mechanical properties, the test specimen must be representative of the material that will be used in-service. In the fields of pavement and geotechnical engineering the specimen configuration can be influenced by a number of factors. Specimen configuration issues are generally confined to laboratory testing where the disturbance of materials during sampling, and limitations of scale associated with testing equipment, can become significant.

For laboratory testing of pavement materials, specimens can be obtained directly from the field or they can be reconstituted in the laboratory to simulate the field conditions. Obtaining specimens from the field requires a high degree of skill and experience because the recovery process itself can change the properties of a material considerably. This is the case for so-called *sensitive* soils. Also, since only a small fraction of the in-service material is ever tested, it is important that the test specimens provide a reasonable representation of the material as a whole.

When preparing reconstituted test specimens of pavement materials for laboratory testing it is vital that the water content, density and particle size distribution properties all correspond with the in-service conditions. Achieving these properties can be quite onerous because of the small scale of the laboratory environment.

Limitations of scale are caused by the comparatively small size of laboratory test specimens. This can be particularly troublesome where aggregate materials incorporating relatively large particles are concerned. The large particles can unduly influence the performance of a small test specimen especially around its boundaries where loads may be applied and/or material responses are being measured. The temptation to omit the large particles from an aggregate specimen should be resisted because this changes the specimen's particle size distribution which affects the density and consequently the specimen's strength and stiffness properties.

Another aspect of limitations of scale is where macroscopic features are overlooked because of the size of the specimen. Such an example could be cracks in a cemented material. The cracks may be the dominant factor in the performance of the material, yet the test specimen may, or may not, include cracks, depending on the techniques used to sample or prepare the specimen.

To conclude, the effects of inconsistencies between test specimens and in-service materials, and limitations of scale, can be minimised by either performing tests in the field or by using sufficiently large laboratory specimens with very careful quality control.

2.3 Material Non-linearity

An important issue in either field or laboratory materials testing is to ensure that stress conditions imposed on the test specimen are representative of those occurring in-service. This is particularly true for pavement materials which generally display a non-linear stress–strain response. This means that the elastic modulus of a material is not a unique value but rather a function of the prevailing state of stress.

It is a well established fact that the elastic modulus of an unbound aggregate material increases as the level of mean stress increases. Many correlations between resilient modulus and the state of stress have been reported in the literature but the one that is often quoted is the so-called *k-θ relationship* (Hicks & Monismith 1971), i.e.

$$M_R = k_1 \theta^{k_2}$$

where M_R = resilient modulus of granular material;
θ = sum of the principal stresses; and
k_1, k_2 = material constants.

It is also well established that the elastic modulus of a fine-grained subgrade soil decreases as the deviator stress increases. The generally accepted relationship between resilient modulus and deviator stress for fine grained soils is as follows:

$$M_R = a\sigma^b$$

where M_R = resilient modulus of fine grained soil;
σ = deviator stress; and
a, b = material constants.

Therefore, if the pavement designer is investigating the elastic parameters of a pavement material and the testing procedure imposes a higher state of stress on the test specimen than the in-service loading, then the elastic modulus deduced for an unbound aggregate material is likely to be overstated. Conversely, the elastic modulus deduced for a fine-grained soil is likely to be understated. If the testing procedure imposes a lower state of stress than the in-service loading, then the opposite errors will be introduced.

There are two ways of evaluating the response of materials operating at different states of stress.

First, a test specimen can be subjected to a range of stress conditions and its response can be measured directly. A relationship between elastic modulus and deviator or mean stress can then be established. This is the preferred method as it is not reliant on empirical relationships or approximations.

Second, procedures are available whereby the elastic parameters of a material can be adjusted so that they are appropriate for stress levels other than those prevailing during testing. An example is the procedure described in the APRG 94/10 (DA) (1994) document. This procedure is summarised as follows:

Unbound aggregate layers:

$$E_{\text{In Service}} = E_{\text{Test}} \left[\frac{\sigma_{m\ (\text{In Service})}}{\sigma_{m(\text{Test})}} \right]^K$$

where
$E_{\text{In-service}}$ = Elastic modulus under in-service mean stress conditions;
E_{Test} = Elastic modulus test mean stress conditions;
$\sigma_{m\ (\text{In-service})}$ = mean in-service stress;
$\sigma_{m\ (\text{Test})}$ = mean test stress; and
K = constant depending on the material;
= 0.3 (low quality sub-base) to 0.5 (high quality basecourse).

Fine grained subgrades:

$$E_{\text{In Service}} = E_{\text{Test}} \left[\frac{300 - \sigma_{d\ (\text{In Service})}}{300 - \sigma_{d(\text{Test})}} \right]^P$$

where
$\sigma_{d\ (\text{In-service})}$ = in-service deviator stress;
$\sigma_{d\ (\text{Test})}$ = test deviator stress; and
P = constant depending on subgrade CBR as described in Table 2.1.

Table 2.1 Subgrade stress dependency exponents (P).

Subgrade CBR	P
2	8
3	6
4	5
5	4
7	2
10	0.5
15	0

2.4 Loading Configuration

The configuration of the loading applied to a test specimen should be representative of the in-service loading configuration because of the material non-linearity issue described in Section 2.3 of this report. However, the magnitude of the load is not the only important consideration. The orientation, period and frequency of loading can all be significant.

During the passage of a wheel load, an element of pavement material experiences a combination of normal and shear stresses that are a function of the position of the wheel. This results in a continuous rotation of the principal stress axes as the wheel approaches, passes directly overhead, and finally moves away. This condition is not easily simulated in the laboratory, or in the field for that matter. The triaxial apparatus can produce rotations of the principal stress axes but only in 90 degree jumps. One of the only laboratory test devices that does produce a continuous rotation of principal stresses is the simple shear apparatus, but this device has a problem with applying uniform normal stresses. Field test methods that utilise a falling weight to produce a dynamic load do not produce the rotation of principal stress axes associated with a moving wheel load.

Materials that possess a viscous response to loading, such as asphalt, are the most vulnerable to loading period and frequency influences. Viscous type materials generally show a greater resistance to loading when the period of loading is short.

Loading may also be applied to a test specimen in a controlled stress or a controlled strain configuration. Loads may also be applied in the analogous forms of controlled force or controlled displacement. A controlled stress configuration is where a specimen is loaded until a specified stress condition is achieved. Generally the resulting strain is monitored during this operation. Conversely, a controlled strain configuration is where a specimen is loaded until a specified strain condition is achieved. Generally the stress required to produce the strain condition is monitored during the operation. In most pavement engineering applications a controlled stress test configuration is the most appropriate.

Finally, the stiffness and shape of the loading platen can influence the response of a test specimen. It should be recognised that very stiff loading elements generally produce non-uniform contact stress and the magnitude of the stresses around the edges of a stiff loading platen can be very high. The stresses in these areas may be sufficiently high to produce yielding of the material which can influence the analysis of test results, especially where assumptions of elastic behaviour have been inferred.

2.5 Discussion

Tests performed in the field will inevitably produce different results from those performed in the laboratory unless the effects of specimen configuration, scale and loading described in the preceding paragraphs can be successfully mitigated. Houston et al. (1992) suggest that, "a lack of agreement between lab-measured and field-measured values of elastic moduli for pavement materials should be the rule rather than the exception".

As the current project includes the development of a Loadman testing procedure for use in the laboratory, considerable effort has been made to minimise the factors that contribute to inconsistencies between laboratory and field test results.

3. THE LOADMAN PORTABLE FWD

3.1 Description of the Loadman Apparatus

The Loadman is a portable FWD apparatus that is used to determine the elastic modulus of pavement materials. The Loadman imparts a dynamic load on a test material and measures the resulting deflection. The load and deflection data are subsequently used to calculate the elastic modulus parameter. It consists of an aluminium tube that accommodates a freely moving 10 kg steel weight with a rubber buffer attached to its lower end. The top of the tube is fitted with a powerful electromagnet and the electronic components that control the test and display the test results. An accelerometer is also housed within the electronics compartment. The bottom of the tube is closed with a steel plate. A cross-section of the Loadman is presented in Figure 3.1.

With the Loadman powered up, the operator gradually tilts the device so the weight slides to the top end of the tube. The weight is then held by the electromagnet. In preparation for a test, the Loadman is positioned vertically with the base plate in full contact with the surface of the test layer. The operator then presses the activating button so the current to the electromagnet is cut and the weight is released. The weight falls a distance of 800 mm and impacts with the bottom plate. The rubber buffer on the bottom of the weight cushions the impact so that the duration of loading is similar to that caused by the passage of a wheel load.

The dynamic force created by the falling weight causes the test layer to deform. The magnitude of the deformation is established by performing a double integral on the time history of the Loadman's accelerometer. Depending on the nature of the test layer, part of the total deflection resulting from the dynamic load will be elastic and some will be plastic, i.e. some of the energy will produce a deformation that is recovered at the end of the dynamic loading while the remainder effects a permanent consolidation of the test material. The latter deformation is not recovered and it shows as a small depression left in the surface of the test layer.

By monitoring the complete acceleration time history the Loadman is able to determine what proportion of the total deflection is recovered. The Loadman's electronics are programmed to calculate an effective single layer elastic modulus of the test material using the measured peak deflection. The calculation is based on Gros' Formula, which is described in detail in Section 3.3 of this report.

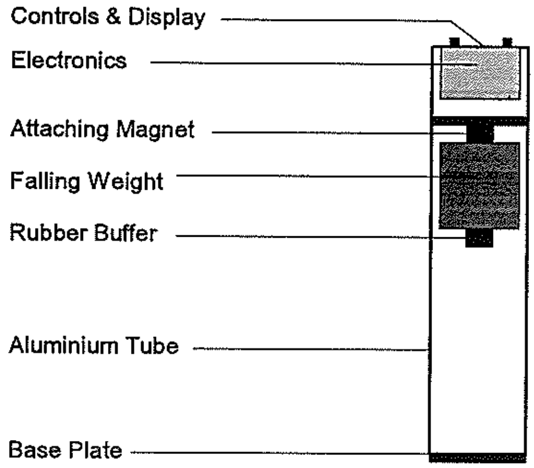


Figure 3.1 Cross section of Loadman FWD and its components.

The Loadman is supplied with two base plates. The smaller base plate is the same diameter as the Loadman tube, i.e. 132 mm, while the larger plate has a diameter of 200 mm. The Loadman manufacturer states that the dynamic load imposed by the device is approximately 22 kN (AL-Engineering Oy 1996). This correlates to average applied pressures of 1.6 MPa and 0.7 MPa for the 132 mm- and 200 mm-diameter base plates respectively. However, the magnitude of the dynamic load that is imposed on the test layer is a function of the elastic deflection generated by that load.

Livneh et al. (1996) studied the performance of an early model Loadman device. They established a relationship between dynamic load and pavement layer deflection, but the results cannot be used in the current study as the Loadman used in their study had a different geometrical configuration to the current 132 mm-diameter model. Research is currently being undertaken to investigate the relationship between the dynamic load imposed by the 132 mm-diameter Loadman and the response of the test material (Siekmeier, pers.comm. 1998; Lampenen, pers.comm. 1998).

3.2 Operation of the Loadman FWD

At the top of the Loadman is a panel with an ON/OFF switch, a liquid crystal display and three buttons. With the Loadman switched on and positioned ready for a test, the operator initiates the dropping of the weight by pressing the red button. At the completion of the drop a series of four numbers are shown on the display screen. These are described as follows:

- E162 Pre-selected constant for the testing configuration;
- d(mm) Total measured deflection;
- T(ms) Elapsed time to peak deflection;
- Q(%) Percentage recovery,
  i.e. (elastic deflection / total deflection) x 100.

Therefore, if the screen shows the following:

E350	0.46	06	65

that translates into:

- elastic modulus = 350 MPa;
- total deflection = 0.46 mm;
- time to peak deflection = 6 ms; and
- percentage of total deflection that was recovered = 65%.

On subsequent drops only three numbers are displayed, i.e. the elastic modulus (MPa), the measured total deflection, and the ratio of the elastic modulus for the current drop to that for the original drop in the sequence.

The electronics can be re-set to give the four output display by pressing the green button on the top panel. The black button is used to change the constant (E_{modify}) for the elastic modulus calculation. The use of this constant is described in Section 3.3 of this report.

3.3 Calculation of Elastic Modulus

The Loadman automatically calculates an equivalent single layer (isotropic) elastic modulus using Gros' Formula, i.e.

$$\Delta = 1.5 \frac{p a}{E}$$ Equation (1)

where Δ = deflection;
p = applied pressure;
a = radius of loaded area; and
E = elastic modulus.

Gros' Formula was developed from the general relationship describing the deflection of an elastic half-space under a circular loaded area, i.e:

$$\Delta = \frac{k(1 - v^2) P}{a E}$$ Equation (2)

where k = constant;
v = Poisson's ratio;
P = total load; and
Δ,a,E are as defined above.

For the Boussinesq model, i.e. a uniformly loaded circular area, the constant k in Equation (2) is defined as follows:

$k = 2 / \pi$ at the centre of the loaded area;

$k = 4 / \pi^2$ at the edge of the loaded area.

In the Boussinesq model the load is applied uniformly over the circular area, therefore the pressure $p = P/\pi a^2$. Assuming that the material is incompressible implies Poisson's ratio, $\nu = 0.5$. Substituting for P and ν in Equation (2) confirms Gros' Formula, as shown in Equation (1):

$$\Delta = \frac{2(1-0.5^2)p\pi a^2}{\pi a E} = 1.5\frac{pa}{E} \qquad \text{Equation (3)}$$

For Boussinesq's model the deflection at the edge of the loaded area is found by substituting:

$k = 4 / \pi^2$

$p = P\pi a^2$

$\nu = 0.5$

into Equation (2), i.e:

$$\Delta = \frac{4(1-0.5^2)p\pi a^2}{\pi^2 a E} = 0.95\frac{pa}{E} \qquad \text{Equation (4)}$$

The Loadman's electronics are programmed to perform the following calculation for E:

$$E = \frac{E_{modify}}{\Delta} \qquad \text{Equation (5)}$$

where E_{modify} = E modify factor (supplied by Loadman operator).

The Loadman operating manual recommends the use of E_{modify} factors of 162 for the 132 mm-diameter Loadman base plate, and of 107 for the 200 mm-diameter Loadman base plate.

The standard E_{modify} factors (162 and 107) can be verified by substituting into Gros' Formula:

a = 66 mm for the 132 mm-diameter Loadman base plate; (or 100 mm for the 200 mm-diameter base plate); and

p = 1.6 MPa for the 132 mm-diameter Loadman base plate; (or 0.7 MPa for the 200 mm-diameter base plate).

4. IMPROVING THE LOADMAN ELASTIC MODULUS CALCULATION

4.1 General

The Loadman uses the Boussinesq model to calculate the elastic modulus of the test layer. This is something of a simplification because it assumes that the test layer is isotropic and that the load is applied uniformly over the area of the Loadman base plate. In reality, the Loadman base plate is very stiff in relation to the test layer. This means that the Loadman acts more like a punch causing a uniform deflection of the test layer. In this situation the applied load is not applied uniformly over the contact area.

The second issue is the assumption of isotropy in the Loadman elastic modulus calculation model. The AUSTROADS pavement design procedure is based on characterising both unbound aggregate and subgrade materials as being anisotropic with a degree of anisotropy of 2.0. This means that the elastic modulus in the vertical direction is taken as being twice the elastic modulus in the horizontal direction.

The basis for AUSTROADS adopting anisotropic material parameters in the pavement design model stems from the analysis of pavement deflection profiles. The developers of the AUSTROADS design procedures found that theoretical pavement models incorporating anisotropic material parameters predicted deflected pavement shapes better than those using isotropic material parameters.

4.2 Punch Loading Problem

The solution for a cylindrical punch penetrating an isotropic elastic half-space can be found from the general equation for deflection under a circular loaded area (Equation 2). In this case the coefficient (k) is assigned a value of 0.5. If the material is assumed to be incompressible, then Poisson's ratio is taken as 0.5 and the relationship for deflection becomes:

$$\Delta = \frac{k(1-v^2)P}{aE} = (0.5)(0.75)\frac{P}{aE} = 0.375\frac{P}{aE} \qquad \text{Equation (6)}$$

where Δ = vertical deflection;
P = total applied load;
E = elastic modulus; and
a = radius of loaded area.

If the Poisson's ratios assumed in the AUSTROADS design procedures are used, i.e. $v = 0.35$ for granular material and $v = 0.45$ for cohesive soil, Equation 6 becomes:

$$\Delta = (0.5)(0.88)\frac{P}{aE} = 0.439\frac{P}{aE} \quad \text{(for granular materials)}$$ Equation (7)

$$\Delta = (0.5)(0.80)\frac{P}{aE} = 0.400\frac{P}{aE} \quad \text{(for cohesive soils)}$$ Equation (8)

If the dynamic load P applied by the Loadman is assumed to be 22 kN for all tests, then the E_{modify} factors can be simply established for entry into the Loadman memory.

4.3 Anisotropic Material Properties

The issue of anisotropic material properties has been examined for this project by Professor Ian Collins at the University of Auckland (Prof. I.Collins, pers.comm. 1998). The following is a summary of the analyses carried out by Professor Collins.

Isotropic material models are defined by only two parameters, i.e. elastic modulus and Poisson's ratio. However, anisotropic material models are defined by the following five parameters:

- E_h : elastic modulus in the horizontal direction;
- E_v : elastic modulus in the vertical direction;
- ν_h : Poisson's ratio in the horizontal direction due to horizontal stress;
- ν_v : Poisson's ratio in the vertical direction due to horizontal stress;
- G : shear modulus.

In addition, if ν is the Poisson's ratio in the horizontal direction due to vertical stress, then:

$$\nu = \nu_v \frac{E_v}{E_h}$$ Equation (9)

To satisfy physical compatibility, then $\nu_h + \nu_v \leq 1$ and $\nu \leq 0.5$, with equality for incompressible materials.

The shear modulus (G) is defined by the complex inequality (Koning 1997):

$$\frac{G}{E_h} \leq \frac{-\nu\nu_v + \left(\frac{\nu\nu_v(1-\nu\nu_v)(1-\nu_h)}{1+\nu_h}\right)^{1/2}}{\nu_v(1-\nu_h-2\nu\nu_v)}$$ Equation (10)

where equality is often assumed.

The general relationship between elastic modulus and deflection is as follows:

$$\Delta = k\frac{P}{aE_v}$$ Equation (11)

where the constant k has been established numerically (Prof. I.Collins, pers.comm. 1998) to be:

k = 0.550 (for $\nu = \nu_h = 0.35$)
= 0.518 (for $\nu = \nu_h = 0.45$)

Note that the constants presented above are only applicable to the situation where the degree of anisotropy is 2.0, i.e. $E_v / E_h = 2.0$.

To determine the E_{modify} factors for incorporating anisotropy into the Loadman elastic modulus calculation it is simply a matter of assuming P = 22 kN and a = 66 mm (or 100 mm) and substituting the appropriate parameters into Equation 11.

4.4 Discussion

The analyses described in Sections 4.2 and 4.3 provide a means of improving the Loadman output by providing appropriate E_{modify} factors for use in the Loadman memory. In each case the assumption is that the dynamic load is constant for all tests. While this is not strictly true, an approximate dynamic loading P of 22 kN can be assumed so that an estimate of elastic modulus can be obtained directly from the Loadman output.

Table 4.1 presents a summary of the E_{modify} factors determined for the Boussinesq model, the punch model with isotropic material properties, and the punch model with anisotropic material properties.

Table 4.1 Loadman E_{modify} factors for the isotropic Boussinesq model and both isotropic and anisotropic punch models.

(a) with 132 mm-diameter Loadman base plate

Material	Poisson's Ratio	Loadman E_{modify} Factor (132 mm-Diameter Base Plate)		
		Isotropic Boussinesq Model	Isotropic Punch Model	Anisotropic Punch Model (Note 1)
Granular	0.35	185	146	183
Cohesive	0.45	168	133	173
Incompressible	0.50	162	125	no result (Note 2)

(b) with 200 mm-diameter base plate

Material	Poisson's Ratio	Loadman E_{modify} Factor (200 mm-Diameter Base Plate)		
		Isotropic Boussinesq Model	Isotropic Punch Model	Anisotropic Punch Model
Granular	0.35	123	97	121
Cohesive	0.45	112	88	114
Incompressible	0.50	106	83	no result (Note 2)

Note 1: E_{modify} factors for the anisotropic model correspond to vertical elastic modulus values. The horizontal elastic modulus is taken as one half of the vertical elastic modulus.

Note 2: Numerical solution of the anisotropic punch model has not been carried out for an incompressible ($\nu = 0.50$) material.

The data presented in Table 4.1 indicate that the E_{modify} factors required by the Loadman for the isotropic Boussinesq model and the anisotropic punch model are quite similar. The factors required for the isotropic punch model are significantly less than those associated with the other two models.

5. LABORATORY-BASED LOADMAN TESTING PROCEDURE

5.1 General

Establishing the elastic modulus of pavement subgrade, sub-base and basecourse materials in the laboratory is generally achieved using the repeated load triaxial (RLT) apparatus. The triaxial apparatus encloses a specimen of test material in a cylindrical cell and repeated axial loads are applied to the specimen via a vertical load ram. A confining stress is applied to the specimen by pressurising the fluid inside the triaxial cell. This combination of axial (deviator) stress and confining stress is used to approximate the passage of multiple wheel loads.

At least three standard resilient modulus test procedures use the RLT apparatus, e.g. AS 1289:1995 (SAA 1995), APRG Report No. 8 (1993), and SHRP Protocol P46 (AASHTO 1992). In each of those standard procedures the test specimen is subjected to a series of different deviator and confining stresses, and the resilient modulus, i.e. the ratio of the applied deviator stress to the recoverable portion of the axial strain, is calculated for each. The elastic modulus results are presented as a function of the stress conditions because of the non-linear properties of most pavement materials.

While the RLT apparatus provides the ability to closely control the stress and drainage conditions experienced by a resilient modulus test specimen it does have a number of drawbacks. These include:

- The resilient modulus calculation does not allow for anisotropic material properties. Anisotropy is inherent in the characterisation of subgrade and unbound aggregates in the AUSTROADS pavement design procedure.

- The RLT apparatus is relatively complex and requires skilled personnel to operate it. This also equates to high test costs. Houston et al. (1992) state that RLT tests for measuring elastic moduli can be 60 to 100 times more costly than a non-destructive in situ test procedure.

- The test results are influenced by the location at which the loads and displacements are measured. Significant differences can be obtained if loads and displacements are measured outside the triaxial cell as opposed to being measured internally (Duske & Pender 1998).

- The maximum specimen size is generally 100 mm in diameter by 200 mm high which limits the particle size. If the specimen contains particles that are too large in relation to its overall dimensions, the test results are likely to be adversely influenced by edge effects and the response of a small number of isolated particles. Removing the large fraction of a specimen does not resolve this issue as the resulting particle size distribution will be different from that of the original sample.

Considering the drawbacks of the RLT test described above, it is proposed that the Loadman could provide resilient modulus data suitable for use in mechanistic design from laboratory prepared specimens.

5.2 Development of the Loadman Laboratory Test Procedure

5.2.1 General Procedure

It is proposed that the Loadman can be used to establish the elastic modulus of subgrade soils, and of sub-base and basecourse aggregates, using laboratory prepared specimens. The general procedure is as follows:

- A representative sample of material is compacted into a steel box at the design water content and dry density. The box must be large enough so that all reasonable particle sizes can be used and there are no edge effect problems. The box is placed on a flat, rigid floor so that any displacement attributable to movement of the box as a whole can be considered to be negligible.

- The Loadman is used to apply the dynamic load and to measure the deflection response of the specimen. Loadman tests are performed using at least two base plate sizes to establish the effect of the material's non-linear stress/strain response.

- The resilient modulus of the specimen is determined by back-calculation using the *CIRCLY* program. The test configuration is modelled in *CIRCLY* using a rigid layer beneath the test layer. The appropriate Loadman load is applied to the *CIRCLY* model and the elastic modulus of the test layer is adjusted until the theoretical deflection under the Loadman load matches the measured elastic deflection.

The procedure described above has the significant advantage that anisotropy can be included in the analysis. It is also relatively simple to perform and no complex testing equipment is required.

5.2.2 Specimen Preparation

One of the most fundamental aspects of laboratory specimen preparation is to ensure that the water content and dry density of the test specimen correspond with the conditions expected in the field. Therefore, a target water content and dry density must be specified before preparation of the specimen commences.

The box used for the laboratory Loadman test should be approximately 500 mm square in plan and 500 mm high. It should be effectively rigid and it must sit squarely on a stiff (concrete) floor. If there is any possibility that the box may rock or vibrate during testing it should be set in a thin layer of plaster or bedded into a small amount of fine sand. The box should be constructed so that the base can be removed while the walls remain in place. The walls should also be removable to expedite the demolition of the specimen at the end of a test.

The test material should be conditioned to achieve the desired water content and covered to ensure there is no change to the water content or contamination during the specimen preparation. The operator should weigh out the exact quantity of material required to fill the box at the specified water content and dry density and then divide the sample equally into five bags. The walls of the box should be marked in increments of 100 mm and the operator should ensure that each bag of material produces a compacted thickness of 100 mm. This provides a means of checking that the specified density is being achieved during specimen preparation. Care should be taken to ensure that the material does not become segregated during this procedure.

A manageable quantity (e.g. a lift of about 75 mm) of loose test material should be placed in the box and compacted using appropriate equipment and effort so that the desired density is achieved without changing the particle size distribution significantly. Compaction equipment may be a vibrating hammer for aggregate specimens or a tamping plate for cohesive soils. It is important that the density of the compacted specimen is monitored closely, especially in the early lifts. A weighing device can be used to monitor the dry density of the specimen both during, and at the completion of, the specimen preparation. This will verify that the appropriate compaction procedure is being used for each test. Other tests, such as the Clegg Hammer, may also be used to monitor the consistency of the specimen.

The top surface of the specimen should be blinded off with a small amount of suitable fine material or sand so that there is a flat, smooth surface on which to conduct the Loadman tests. If the compaction process causes the top surface of the specimen to become excessively flushed with fines then the specimen should be turned upside-down. The base of the specimen box should be removed and the Loadman tests can then be carried out on the exposed lower surface. In this situation the operator must ensure that the box is stable in its new position. If it is not stable it should be set in a small amount of sand or plaster.

5.2.3 Loadman Testing

The Loadman test should be carried out at the centre of the top surface of the specimen according to the manufacturer's instructions. Care should be taken to ensure that the Loadman base plate is properly seated on the specimen and that the device is as near as possible to vertical throughout the tests.

The Loadman is supplied with two base plates, one 132 mm in diameter and the other 200 mm in diameter. Additional plates could easily be produced to achieve alternative levels of loading. The Loadman operator should endeavour to use a range of base plate sizes for any given test. Two criteria dictate which Loadman base plates should be used, i.e:

- the levels of applied stress should be of a similar magnitude to the stresses expected for the test material in-service; and
- the test deflections should be within the resolution range of the Loadman's measuring components, i.e. approximately 0.2 mm to 10.0 mm.

In general, the smaller diameter plates will be best suited to the testing of relatively stiff materials and/or those materials located in the upper pavement layers. Conversely, the larger diameter plates will be best suited to the testing of relatively low stiffness materials and/or those materials located in lower pavement layers.

Tests should be carried out with both of the supplied base plates, and any other sizes that the operator has available. Whichever base plate sizes are used, each test should be repeated until the deflection measured by the Loadman achieves a reasonably consistent value. Once this is achieved, the operator should record the *deflection* and *percentage of deflection recovery* for at least five Loadman drops. This will require the electronics to be re-set for each drop, otherwise the percentage of deflection recovery will not be displayed. Care should be taken to ensure that the Loadman drops are performed at the same location each time. This should be easy to achieve as the device is likely to leave an impression in the surface of the specimen after the first few drops are made.

The final outcome will be a mean deflection and mean percentage of deflection recovery for the five (or more) Loadman drops. At the completion of each set of Loadman tests the base plate should be removed and replaced with the next larger sized base plate. The process is repeated until each of the chosen base plates has been used.

5.2.4 Elastic Modulus Back-calculation

The third and final phase of the testing procedure is to analyse the test results using a back-calculation technique. In this analysis the elastic modulus of the test material is varied in a multi-layer elastic solutions computer model until the theoretical deflection under the Loadman loading conditions corresponds with the mean recoverable deflection measured in the Loadman tests.

The configuration of the multi-layer elastic model should match that of the Loadman tests, i.e. a test layer thickness of 500 mm, a rigid underlying layer, and the appropriate load applied via a circular loaded area (see Figure 5.1). The operator has the option of using an isotropic or an anisotropic material model as required.

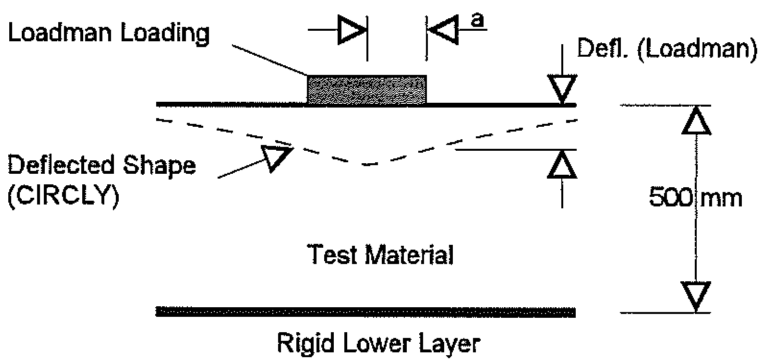
The deflection that is used in the back-calculation is the elastic or recoverable deflection. This is given by:

$$\Delta_R = \Delta_T \frac{Q(\%)}{100} \qquad \text{Equation (12)}$$

where Δ_R = mean recoverable Loadman deflection;
Δ_T = mean total Loadman deflection; and
Q(%) = mean percentage of recoverable Loadman deflection.

When performing the back-analysis it must be recognised that the deflection measured by the Loadman is the deflection at the edges of the Loadman base plate (Figure 5.1). This is because the accelerometer that monitors the movement of the Loadman is mounted on the body of the device, i.e. it is independent of any deflection occurring within the base plate itself. Therefore, the deflection that is calculated in the multi-layer elastic analysis must be examined at a distance a from the centre of the applied load where a is the radius of the Loadman base plate.

Figure 5.1 Schematic section of *CIRCLY* Loadman model.



5.3 Verification of Back-calculation Using *CIRCLY*

The widespread availability and user friendliness of the computer program *CIRCLY* means that it is desirable to use it for the back-calculation analysis of laboratory Loadman tests. An analysis has been undertaken to verify that the *CIRCLY* program can model the Loadman test conditions in a representative fashion.

One of the main concerns with using *CIRCLY* to model the Loadman, is that loads in *CIRCLY* are applied to the model uniformly over a circular area. This corresponds to a completely flexible interface between the load and the top surface of the model. This is contrary to the situation with the Loadman where the device's base plate comprises a stiff, circular steel plate. To examine the effect of this inconsistency, trial analyses were run using the *CIRCLY* program and a finite element method (FEM) program called *LUSAS*. The benefit of using the FEM was that the Loadman base plate could be modelled very accurately compared with the reasonably simple loading conditions generally used in the *CIRCLY* program.

Three pavement structures were modelled using *CIRCLY* and *LUSAS*. Each model comprised a 250 mm-thick layer of linear elastic material with an underlying rigid base. The elastic modulus values for the soil layer were 30 MPa, 50 MPa and 100 MPa for the three structures respectively. In addition, the soil layer was treated as being anisotropic with a degree of anisotropy of 2.0. A Poisson's ratio value of 0.35 was assigned to the soil layer in each model.

For each pavement model, three loading situations were considered, one using the *CIRCLY* model and two using the *LUSAS* models. In the *CIRCLY* model a vertical stress of 1.61 MPa was applied uniformly over a circular area with a diameter of 132 mm. In the *LUSAS* models two loading cases were used. One applied the 1.61 MPa stress to the model via a 132 mm-diameter circular steel plate with an elastic modulus of 210 GPa. A second analysis applied the stress to the model via a rigid plate. The actual situation with the Loadman is considered to be somewhere between the steel and the rigid plate situations. This is because the Loadman base plate is bolted to the cylindrical body of the device giving it a degree of fixity that has not otherwise been considered in the analysis. In both the *LUSAS* models the load was transferred to the base plate only over the central 80 mm of the plate. This corresponds approximately to the dimensions of the rubber buffer that cushions the impact between the falling weight and the Loadman base plate.

Figure 5.2 shows plots of vertical deflection at the top of the models versus lateral offset for models with (vertical) elastic moduli (E_v) of (a) 30 MPa, (b) 50 MPa and (c) 100 MPa respectively. Note that the zero offset corresponds to the centre of the Loadman base plate. The vertical dashed line in each plot represents the edge of the base plate.

The three deflection profiles shown in Figure 5.2 represent the deflection profiles for the models. These are designated as:

- *CIRCLY* : Loadman base plate modelled as a uniformly loaded area.
- FEM (Steel) : Loadman base plate given typical elastic properties of steel.
- FEM (Rigid) : Loadman base plate treated as being effectively rigid.

Not surprisingly, the plots show the deflection at the centre of the base plate increasing as the flexibility of the base plate increases, i.e. the rigid plate model predicts the lowest central deflection, followed by the steel plate model and finally the flexible *CIRCLY* base plate. This can represent a significant difference in the central and plate-edge deflections, particularly for the low-stiffness materials.

The result that is significant from Figure 5.2 is that the deflections for the rigid base plate and the flexible *CIRCLY* base plate coincide very well at the edge of the plate. As this is the deflection that is measured in a Loadman test, it is reasonable to conclude that *CIRCLY* is a suitable program for back-analysing Loadman deflections, as long as the base plate edge deflection is used in the *CIRCLY* model and not the central deflection.

Figure 5.3 shows plots of mean elastic Loadman deflection values versus resilient moduli for the (ȧ) 132 mm-diameter and (b) 200 mm-diameter Loadman base plates respectively. In these plots the test specimen is taken as being 500 mm deep. Also, the resilient modulus values represent the vertical moduli (E_v) and the horizontal moduli are assumed to be $0.5E_v$.

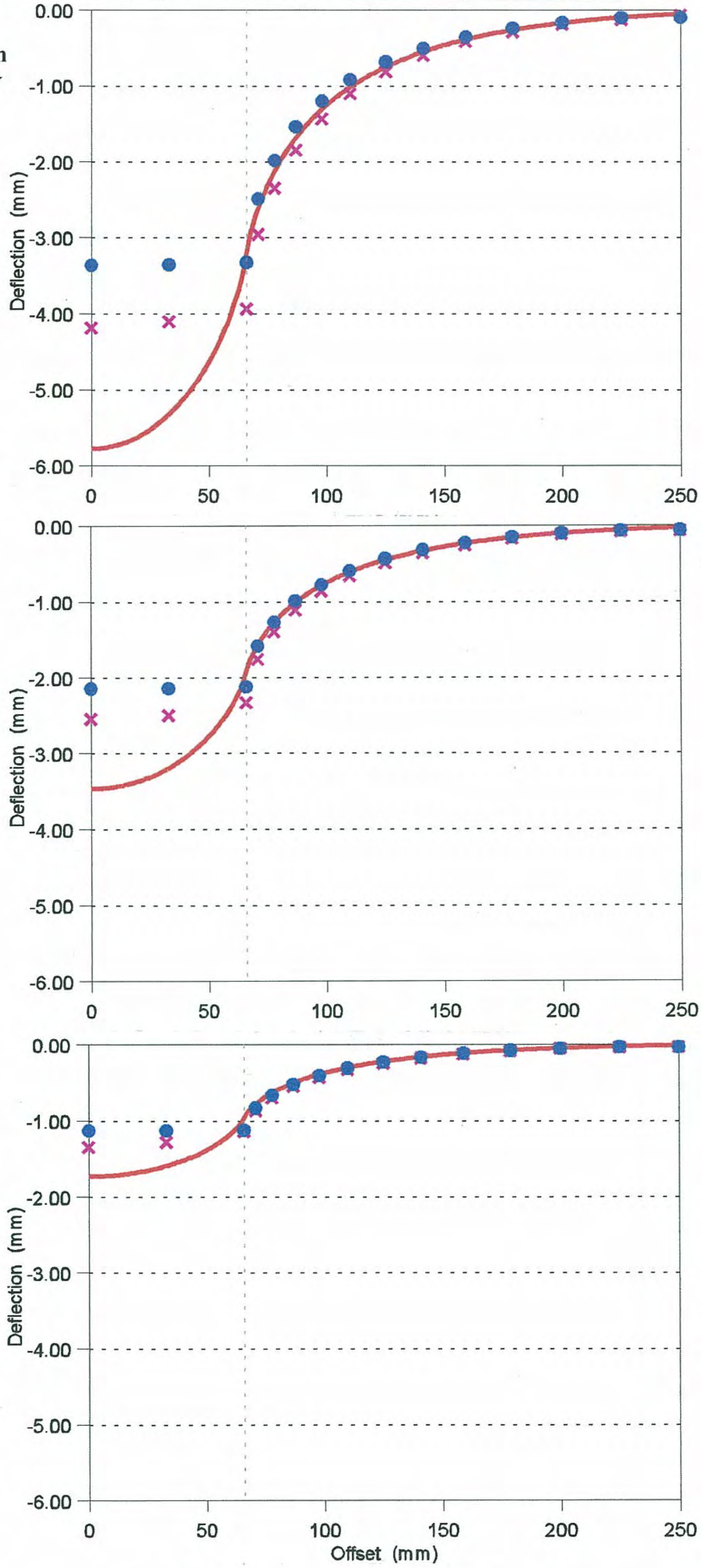


Figure 5.2
Analysis of the Loadman deflections using *CIRCLY* and FEM procedures
(a) Ev = 30 MPa

—— *CIRCLY*
× FEM Steel
● FEM Rigid

(b) Ev = 50 MPa

—— *CIRCLY*
× FEM Steel
● FEM Rigid

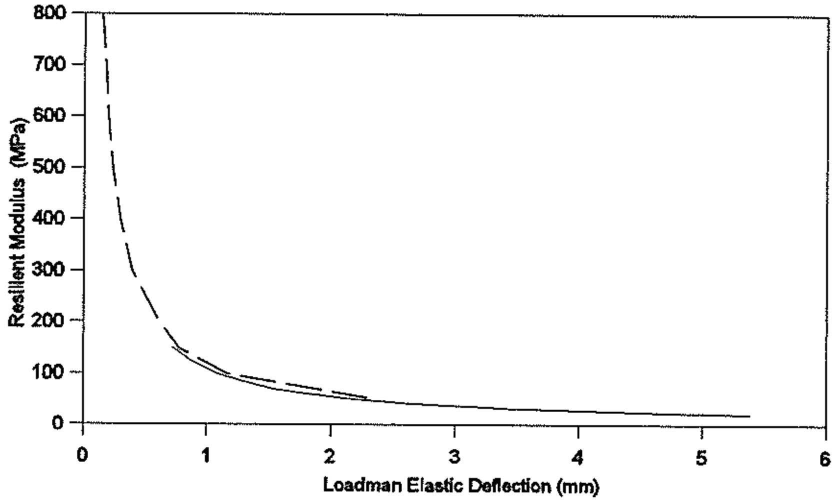
(c) Ev = 100 MPa

—— *CIRCLY*
× FEM Steel
● FEM Rigid

Figure 5.3 Resilient modulus versus mean elastic deflection for laboratory Loadman test, and base plates of (a) 132 mm diameter, and (b) 200 mm diameter.

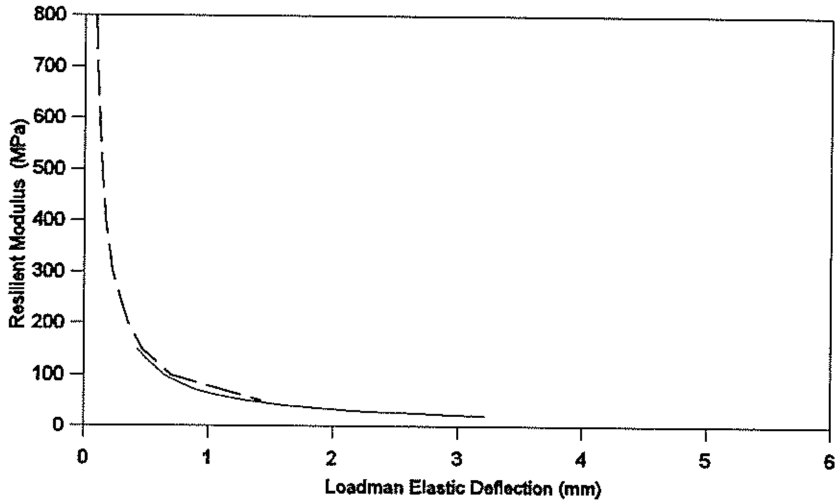
(a) = 132 mm

Poisson's ratio
——— 0.45
— — — 0.35



(b) = 200 mm

Poisson's ratio
——— 0.45
— — — 0.35



6. LOADMAN LABORATORY TEST TRIALS

6.1 General

A series of laboratory-based Loadman tests have been carried out using the procedures described in Section 5.2 of this report. Three aggregate specimens and two subgrade soil specimens were selected on the basis that RLT test results were available for these materials for comparative purposes. The materials used in the testing were as follows:

- Waitemata Group soil recovered from the Albany area of North Shore City;
- Pumice soil recovered from Kaingaroa Forest;
- AP[2]25 andesite aggregate from Winstone's Flat Top Quarry;
- AP65 greywacke aggregate from Stevenson's Drury Quarry; and
- AP65 stabilised greywacke aggregate from Stevenson's Drury Quarry.

In general terms the Waitemata Group silty clay and pumice soil represent common sedimentary and volcanic subgrade soils respectively. Both the Flat Top AP25 and the untreated Drury AP65 aggregates represent good quality sub-base. The stabilised AP65 represents a sub-base material suitable for heavily loaded pavement applications.

All specimens were tested using both the 132 mm-diameter and the 200 mm-diameter Loadman base plates.

6.2 Loadman Laboratory Test Specimens

The Loadman laboratory test specimens were prepared at optimum water content (owc) and maximum dry density. The aggregate specimens were prepared using vibrating hammer compaction and the subgrade soil specimens were prepared using standard Proctor compaction.

The three aggregate specimens were 500 mm thick, however a shortage of test material dictated that the pumice and Waitemata Group soil specimens were 200 mm and 300 mm thick respectively. Target and actual specimen water contents and dry densities are shown in Table 6.1.

6.2.1 Waitemata Group Soil

The Waitemata Group soil is a silty clay material, the weathering product of the alternating sequences of siltstone and mudstone that comprise the Waitemata Group sediments. The Waitemata Group materials are a prominent geological formation in the Auckland region.

[2] AP all passing a certain sized sieve

The properties of the Waitemata Group soils vary from location to location. The soil used in the current project had a Plasticity Index of 38% and it plotted on the boundary of the CH[3] and MH[3] classifications on the Casagrande Plasticity Chart.

Soaked CBR tests carried out on the material gave a mean result of 13% (compacted dry density = 1.48 t/m^3 and water content = 29.5%).

6.2.2 Kaingaroa Pumice Soil

Pumice soils are common in the central area of the North Island and are formed from the products of volcanic eruptions from vents such as Taupo, Mount Ruapehu, Mount Tongariro, White Island, etc. The pumice used in the current project comprised particles ranging from clay to coarse sand sizes.

The pumice soil generally forms a very good subgrade if it is compacted to a high density. It produces very high CBR results (e.g. 30% or more), but its resilient modulus is generally very low in relation to the high CBR.

6.2.3 Winstone's Flat Top AP25 Aggregate

The AP25 andesite aggregate from Winstone's Flat Top Quarry is a so-called marginal aggregate in that it has a relatively low Sand Equivalent Value (approximately 32) and a high Clay Index (about 4). Lime and/or cement is often used with the Flat Top aggregate to improve its properties. A soaked CBR test carried out on the material gave a result of 180% (compacted dry density = 2.08 t/m^3 and water content = 11.3%).

At completion of the preparation of the Loadman specimen, the top surface of the specimen was noticed to be somewhat flushed with fines. Therefore the specimen was turned over and the base of the test box was removed. Loadman tests were then carried out on the bottom surface of the specimen.

6.2.4 Stevenson's Drury AP65 Aggregate

The AP65 greywacke aggregate from the Drury Quarry of W. Stevenson and Son is a sub-base material that has been used widely on pavement projects in the South Auckland and Franklin regions. The stabilised greywacke specimen was treated with 4% KOBM[4] and 0.5% cement. The compacted specimen was allowed to cure at room temperature for 28 days before testing.

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[3] CH clay, high plasticity; MH silt, high plasticity

[4] KOBM is a by-product of the steel making process at BHP NZ Steel Limited (Glenbrook).

Table 6.1 Laboratory Loadman test specimen details.

Specimen	Specimen Dry Density (t/m³)		Specimen Water Content (%)	
	Specified	Achieved	Specified	Achieved
Subgrade Soil				
Waitemata Group	1.46	1.35	30.3	29.4
Kaingaroa Pumice	1.20	1.28	20.0	22.3
Aggregate				
Flat Top AP25	2.10	2.20	10.3	10.6
Drury AP65 (untreated)	2.19	2.39	5.2	4.8
Drury AP65 (stabilised)	2.27	2.24	5.3	5.1

6.3 Laboratory Loadman Test Results

The results of the laboratory Loadman tests are presented in Table 6.2. The elastic modulus data presented there have been back-calculated using the *CIRCLY* procedure described in Section 5 of this report. They correspond to vertical elastic moduli where the degree of anisotropy of the material is 2.0, i.e. the vertical elastic modulus is twice the horizontal elastic modulus.

Table 6.2 Laboratory Loadman test results.

Specimen	Loadman Test Results			
	132 mm-Diameter Base Plate		200 mm-Diameter Base Plate	
	Mean Elastic Deflection (mm)	Elastic Modulus (Vertical - MPa)	Mean Elastic Deflection (mm)	Elastic Modulus (Vertical - MPa)
Subgrade Soil				
Waitemata Group	1.42	65	1.12	45
Kaingaroa Pumice	2.72	30	3.04	12
Aggregate				
Flat Top AP25	0.89	130	1.01	70
Drury AP65 (untreated)	0.45	260	0.52	135
Drury AP65 (stabilised)	0.12	800	0.16	450

6.4 Comparison Between Laboratory Loadman and RLT Test Results

The repeated load triaxial (RLT) test is the recognised standard test for determining the elastic modulus of pavement materials. The following analysis provides a comparison between RLT test results and the laboratory Loadman test results.

The stress dependency of pavement materials has been discussed in Section 2.3 of this report. To provide a realistic comparison between the results of the laboratory Loadman tests and the RLT tests, the state of stress occurring in the laboratory Loadman test must be considered. This has been achieved using *CIRCLY* to calculate the prevailing deviator stress or mean normal stress as required. The location within the Loadman specimen that has been used to characterise the state of stress has been taken as the point at which the vertical stress is expected to reduce to one half of the magnitude of the stress applied at the surface. Lambe & Whitman (1979) provide "influence charts" that establish the appropriate depth to be approximately 1.3 times the radius of the loaded area. Therefore, the state of stress for the 132 mm-diameter Loadman base plate has been determined at a depth of approximately 86 mm. On the same basis, the state of stress for the 200 mm-diameter Loadman base plate has been determined at a depth of approximately 130 mm.

Comparisons of resilient modulus values from the laboratory Loadman and RLT tests are presented in Figures 6.1 to 6.5. Note that the configurations of the RLT tests are not entirely consistent as the results were obtained from a range of projects that were carried out before this current project. When viewing Figures 6.1 to 6.5 the reader should be aware that resilient modulus test results are generally plotted on a log scale. The results shown below have been plotted on arithmetic scales so that the magnitude and variation of the data are not masked by non-linear scales. The test results are also presented in tabular form in the Appendix.

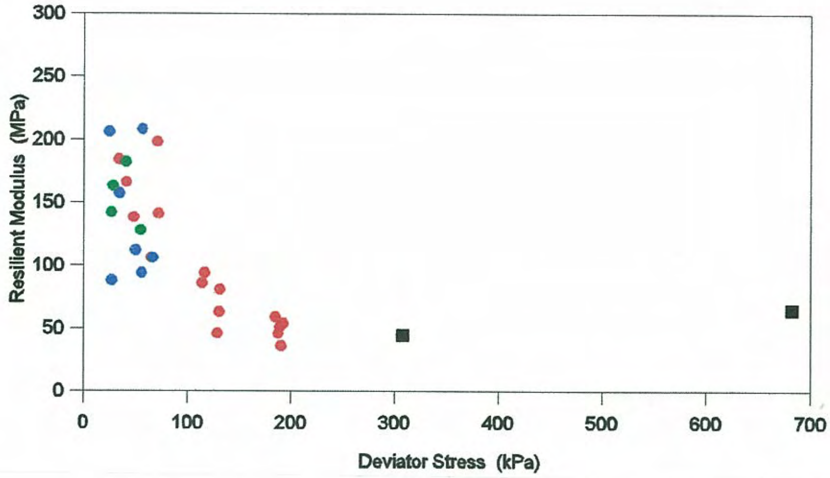
6.4.1 Subgrade Soil Specimens

Figures 6.1 and 6.2 show that the deviator stresses imposed by the Loadman are significantly greater than those used in typical RLT tests for subgrade soils.

In Figure 6.1 the RLT test results for deviator stresses less than approximately 100 kPa represent the results that would be associated with a typical testing programme for a subgrade soil. Further tests have been carried out in this project with deviator stresses in the range 100 kPa to 200 kPa and the results are shown in Figure 6.1. As expected for a cohesive soil, the resilient modulus tends to decrease with increasing deviator stress. The two laboratory Loadman test results tie in very well with the RLT tests, albeit that the deviator stresses associated with the Loadman tests are somewhat excessive.

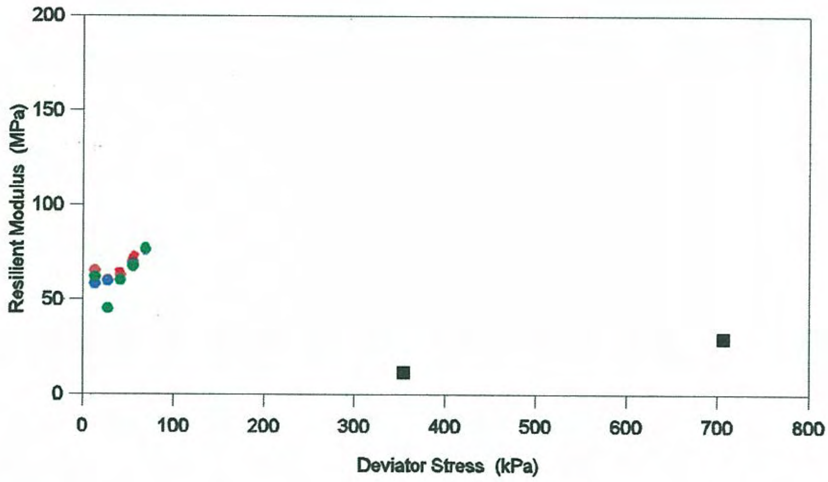
A similar result was found for the Kaingaroa pumice test results shown in Figure 6.2. While no RLT tests were carried out at higher levels of deviator stress, it is reasonable to postulate that the Loadman test results are credible.

Figure 6.1
RLT test and laboratory Loadman test results for Waitemata Group soil specimens.



Test Configuration / Confining Stress
- RLT Test / 41 kPa
- RLT Test / 21 kPa
- RLT Test / 0 kPa
- Lab Loadman

Figure 6.2
RLT and laboratory Loadman test results for Kaingaroa pumice soil specimens.



Test Configuration / Confining Stress
- RLT Test / 41 kPa
- RLT Test / 28 kPa
- RLT Test / 14 kPa
- Lab Loadman

Figure 6.3
RLT test and laboratory Loadman test results for AP25 Flat Top aggregate specimens.

Test Configuration
—— RLT Test
■ Lab Loadman

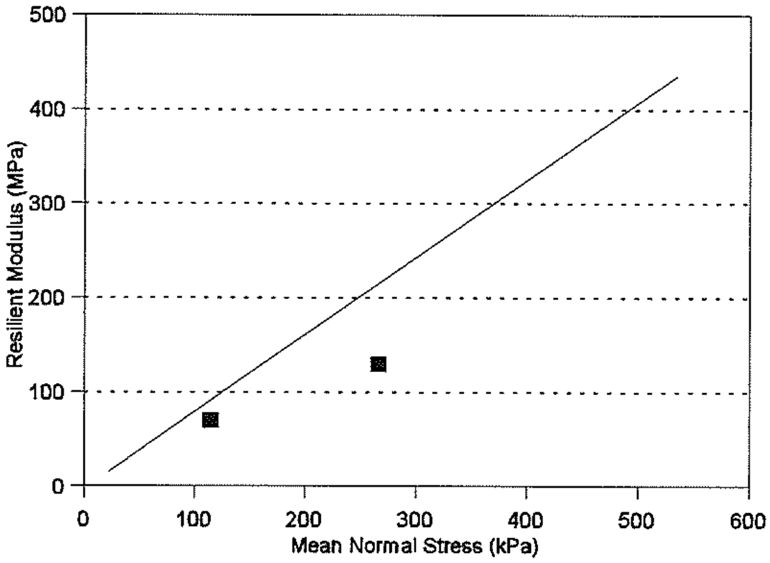


Figure 6.4
RLT test and laboratory Loadman test results for Drury AP65 (untreated) aggregate specimens.

Test configuration
● RLT Test
■ Lab Loadman

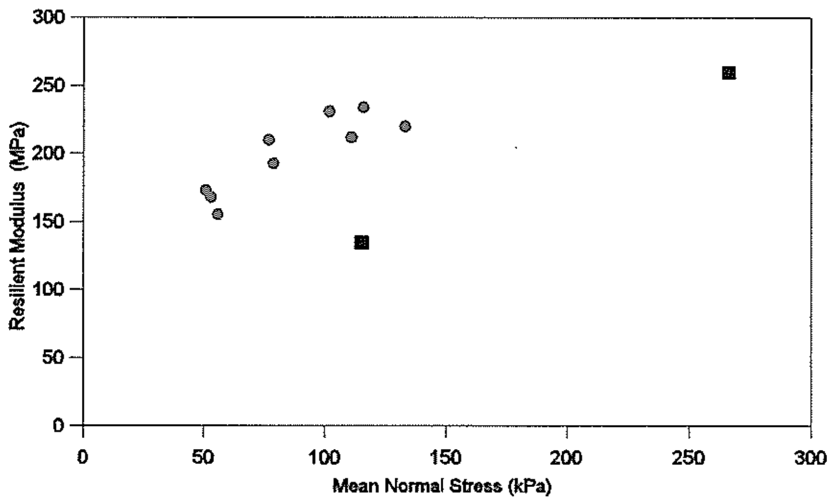
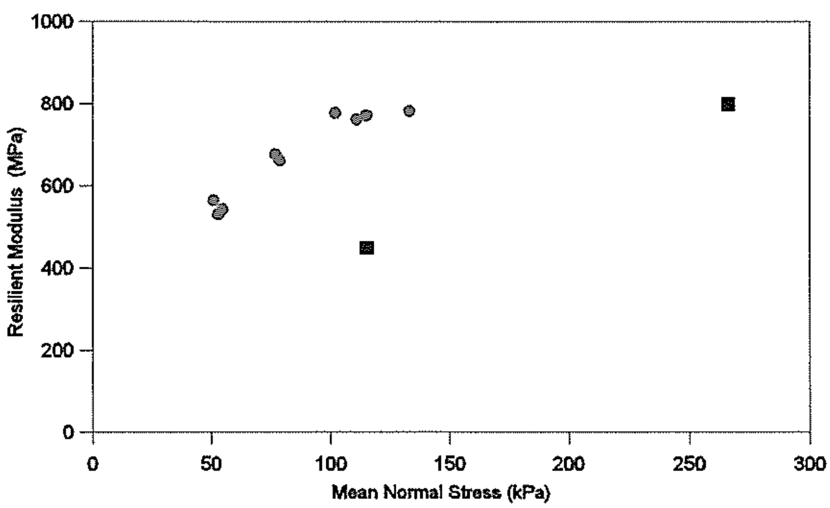


Figure 6.5
RLT test and laboratory Loadman test results for Drury AP65 (stabilised) aggregate specimens.

Test configuration
● RLT Test
■ Lab Loadman



6.4.2 Aggregate Specimens

Figures 6.3, 6.4 and 6.5 show that the mean normal stresses imposed by the Loadman are close to those typically used in RLT tests for aggregate materials. However, the stresses imposed by the Loadman with the 132 mm-diameter base plate are somewhat higher than desired.

A reasonably good correlation was found between the Loadman and RLT test results for each of the aggregate specimens. However, in general, the Loadman resilient modulus results were slightly lower than the corresponding RLT test values.

The Loadman tests performed on the aggregate specimens showed an increase in resilient modulus with increasing mean normal stress, as would be expected for these materials.

6.5 Discussion

The data shown in Figures 6.1 to 6.5 indicate that the Laboratory Loadman tests provide resilient modulus values that correlate reasonably well with the corresponding values obtained using RLT tests. In general, if the Loadman results do differ from the RLT results, the Loadman elastic moduli are slightly lower.

A source of error in the Loadman testing is the approximation of a constant dynamic load for all tests. The dynamic load applied by the Loadman varies depending on the response of the test material. However no experimental data are available at this time to establish the exact loading magnitude for each test. It is understood that a new Loadman apparatus is being planned and it includes a load cell to measure the applied dynamic load. Another portable FWD device (called the Phoenix Prima) has also been introduced recently to the market, and it has an integral load cell.

An inconsistency between the laboratory Loadman results and the RLT test results that should be noted concerns anisotropy. In the analysis of the Loadman tests, the material can be modelled as an anisotropic material whereas typical RLT tests do not include sufficient measurements to allow anisotropy to be considered. However, including anisotropy in the resilient modulus results causes the vertical resilient modulus values to increase, which is opposite to the trends shown in Figures 6.1 to 6.5.

Another important observation derived from Figures 6.1 to 6.5 is that the stresses imposed by the Loadman are significantly higher than those applied during typical RLT tests. This is especially true for subgrade soils which experience relatively low in-service stresses because of their low position in the pavement. This could be resolved by increasing the size of the Loadman base plates. The alternative device, the Phoenix Prima, allows the drop height of the falling weight to be varied from virtually zero height to 800 mm or more.

7. FIELD LOADMAN TESTING PROCEDURE

7.1 General

In this section, the procedures proposed for the laboratory Loadman testing are extended to the field testing environment. A test and analysis method is postulated for a simple single-layered structure as well as a two-layer structure.

The Loadman apparatus provides the ability to perform tests at a range of stress levels by attaching base plates of various sizes. The Loadman operator should endeavour to use a range of base plate sizes for any given test (see Section 5.2.2 of this report).

7.2 Single-layered Structure

The simplest field testing procedure applies to a single layered structure such as an in situ subgrade soil, although it could also apply to a thick layer of material overlying a subgrade. For the latter to be appropriate the layer would be required to act as if it were effectively semi-infinite, i.e. it would need to have a thickness of approximately 1.0 m or more.

The single-layer field test is equivalent to the laboratory Loadman test procedure except that the in situ test layer does not have a rigid base. Therefore, the procedures described in Section 5 of this report should be adopted except that the rigid base is excluded from the *CIRCLY* back-analysis model.

7.3 Two-layered Structure

In this context a two-layered structure is assumed to consist of some thickness of compacted unbound aggregate overlying a semi-infinite subgrade layer. For the purposes of this discussion it is assumed that the subgrade comprises a fine grained soil. Therefore, the elastic modulus of the upper layer can be expected to be dependent on the prevailing mean stress, and the elastic modulus of the subgrade can be expected to be dependent on the prevailing deviator stress. As the Loadman provides relatively simple data, the two layers must be analysed in two parts.

First, Loadman tests are performed on the surface of the upper layer. As for the other test procedures, a range of Loadman base plates should be used. As the upper layer experiences relatively high in-service stresses, the operator should generally use smaller diameter base plates. Test drops should be repeated until the Loadman deflection achieves a reasonably consistent value. The deflection and percentage of deflection recovery for at least five further drops should then be recorded. On completion of each set of Loadman tests progressively larger base plates should be used.

When the testing of the upper layer has been concluded that layer should be removed over an area of approximately 500 mm square. The Loadman test procedure should be repeated on the exposed lower layer to determine the mean elastic deflection at for a range of Loadman stress levels. As the lower layer experiences relatively low in-service stresses, the operator should generally use larger diameter base plates.

The two-layer structure should then be modelled using *CIRCLY*. However it should be noted that the analysis is complicated because the elastic modulus of the lower layer is dependent on the elastic parameters of the upper layer. Therefore, an iterative approach is required to determine the appropriate elastic modulus data for the upper layer.

The steps in the full analysis are as follows. Note that steps (a) to (c) are all applicable to the lower layer of the pavement structure which is initially treated as in a single layer model. The remaining steps are all applicable to the two-layered model.

(a) Use *CIRCLY* to obtain the anisotropic (or isotropic) elastic modulus values of the (single) lower layer for each stress level by matching the *CIRCLY* and mean recoverable Loadman deflections at the edge of the Loadman base plate.

(b) Use *CIRCLY* to calculate the deviator stress (σ_d) in the (single) lower layer at a point 0.3 m[5] below the centre of the Loadman load for each stress level. This establishes a relationship between deviator stress and elastic modulus for the subgrade soil. Note that if the subgrade comprises a granular material then the mean stress should be calculated instead of the deviator stress.

(c) Model the two-layered structure using *CIRCLY*, initially using assumed (anisotropic) elastic modulus values for both the upper layer and the subgrade. The upper layer should be sublayered using the AUSTROADS sublayering scheme.

(d) Determine the deflection of the initial *CIRCLY* model at the edge of the Loadman load. Compare the *CIRCLY* deflection with the mean recoverable (two-layered) Loadman deflection.

(e) Determine the deviator stress at a point 0.3 m below the top of the subgrade for the two-layered *CIRCLY* model. Use the relationship between deviator stress and subgrade elastic modulus obtained in step (b) to obtain the elastic modulus corresponding with the calculated deviator stress. Compare the assumed subgrade elastic modulus with the value defined in the E/σ_d relationship.

(f) Based on the deflection and deviator stress data obtained from steps (d) and (e), refine the upper layer and subgrade elastic modulus values.

[5] Estimated depth of significant stress - see Section 7.4.2 of this report for description.

Repeat this procedure until the *CIRCLY* deflections converge with the mean recoverable Loadman deflections and the assigned subgrade elastic modulus converges with the elastic modulus corresponding to the E/σ_d relationship obtained in step (b).

(g) Obtain a relationship between the elastic modulus of the upper layer and the mean stress at the mid-point of each sublayer for each level of Loadman stress. The result of the analysis will be two elastic modulus relationships with respect to states of stress, one for each layer. These relationships can be used to determine elastic modulus values that are appropriate for use in pavement design.

7.4 Discussion

The Loadman analysis procedures described above, particularly for a two-layered structure, are somewhat arduous. However it is considered to be a viable way of using the Loadman to determine elastic modulus parameters that are appropriate for pavement design. The factors that make the procedure arduous are the non-linearity of the materials and the relative simplicity of the Loadman data.

7.4.1 Relationships between Elastic Modulus and Stress

A drawback of the proposed analysis procedure for a two-layered structure is that it is difficult to establish elastic moduli for the test materials over a wide range of stress conditions. This is mainly due to limitations associated with the Loadman's deflection measuring equipment. While large diameter Loadman base plates could be used, they have the effect of reducing the applied stress and the resulting test deflection. This deflection may be so small that it falls within the resolution limits of the device. Conversely, if a small base plate is used the applied stress may be so great that the resulting deflection could be outside the range of the device. Taking these factors into account it may be necessary to make some assumptions regarding the relationships between elastic modulus and state of stress used in the analysis.

If the pavement engineer requires simply an approximate indication of the elastic moduli for a typical two-layered structure, the upper should be tested with the 200 mm-diameter Loadman base plate, and the subgrade should generally be tested using the largest base plate available.

7.4.2 Subgrade Characterisation

One aspect of the analysis presented above that warrants explanation is the location at which the deviator stress is calculated so that the subgrade layer is adequately characterised. Generally, when a layered structure is being analysed in a geotechnical context, stress levels are calculated at the mid-elevation of each layer. While this can be done for an upper pavement layer of finite thickness, it cannot be done for a semi-infinite subgrade layer.

One way of addressing this issue is to identify the *average depth of significant stress* (ADSS). The ADSS is defined as the distance from the pavement surface to one third of the depth where the deviator stress is reduced to 10% of the deviator stress occurring at the top of the subgrade.

To obtain a simpler alternative to the ADSS, a series of *CIRCLY* runs was performed using a two-layered structure comprising typical elastic parameters and aggregate layer thicknesses. The following variables were used in the analyses:

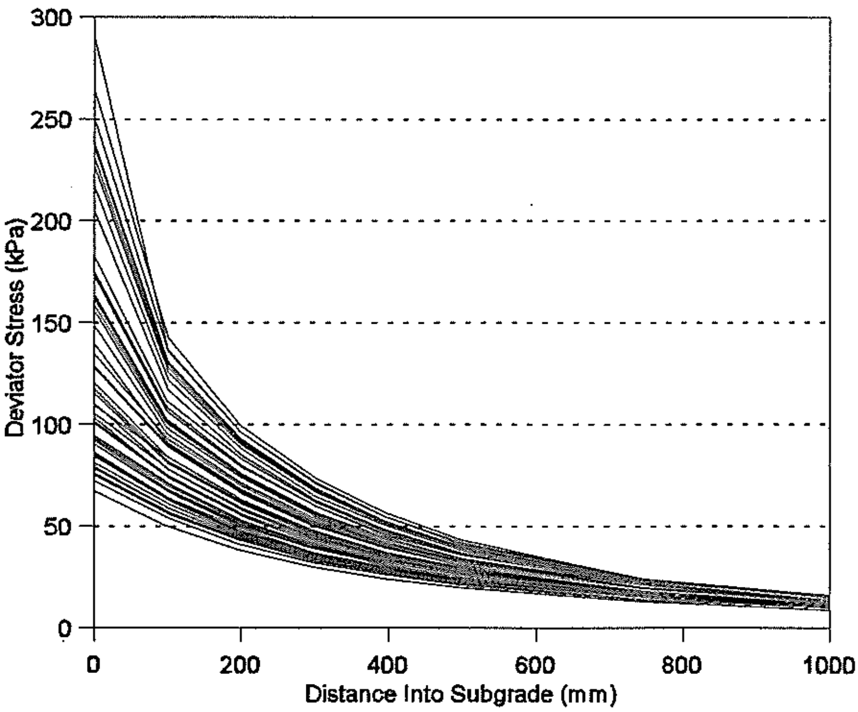
E_{AGG} : 200, 300, 400 MPa
E_{SG} : 30, 50, 70 MPa
h_{AGG} : 150, 200, 250, 300, 350 mm

where E_{AGG} : elastic modulus of the aggregate (top sublayer);
E_{SG} : subgrade elastic modulus; and,
h_{AGG} : aggregate layer thickness.

The deviator stress was determined at regular intervals of depth up to 1 m. A plot of deviator stress versus depth into the subgrade is presented in Figure 7.1. It is postulated that the centroid of the area under the deviator stress versus depth plot (up to 1 m depth) is an appropriate depth at which the subgrade layer can be characterised.

Analysis of the shapes of the plots in Figure 7.1 indicate that the centroids were all in the depth range of 280 mm to approximately 340 mm. Therefore a depth of 300 mm is considered to be reasonable. This is the basis on which the deviator stresses are calculated at a depth of 300 mm (0.3 m) in steps (b) and (e) in the Loadman analysis described in Section 7.3 of this report.

Figure 7.1 Deviator stress versus depth/distance (mm) into subgrade for typical unbound aggregate pavements.



8. CONCLUSIONS

The Loadman portable FWD is a device that shows considerable potential for use in pavement engineering practice, particularly since the AUSTROADS pavement design procedures were adopted by the road controlling authorities in New Zealand. Research has been carried out on ways of developing and improving the utilisation of the Loadman device.

The objectives of the project listed in S1.3 are as follows:

- to develop a set of constants for programming the Loadman to produce elastic modulus data that more realistically reflect the material properties;
- to develop both field and laboratory-based Loadman testing procedures that facilitate the establishment of anisotropic elastic modulus data; and
- to compare the results of laboratory-based Loadman tests with corresponding tests performed using the repeated load triaxial apparatus.

The first objective was achieved by considering the theoretical elastic solutions for both punch type loading and anisotropic material parameters. These conditions are thought to provide superior characterisation of the Loadman test and the response of typical pavement materials. A revised set of E_{modify} Loadman constants have been developed from this study.

The second objective has been achieved by considering the most appropriate procedures for carrying out Loadman tests in both the laboratory and 'field environments. The proposed laboratory Loadman test involves performing Loadman tests on 0.5 m x 0.5 x 0.5 m specimens compacted in a rigid steel box. The elastic deformation of the specimen produced by the Loadman testing is recorded and used in a back-calculation procedure that allows the anisotropic elastic modulus of the test material to be established. The back-calculation procedure has been verified using finite element modeling.

The proposed procedure for field Loadman testing has been developed taking into consideration the important issue of stress dependency of pavement materials. The procedure has been developed for both single and two-layered pavement structures. However the latter case may require a degree of judgement on the part of the engineer to supplement the data obtained in the analysis.

The third objective has been achieved by comparing the results of laboratory-based Loadman tests with resilient modulus tests carried out using the RLT testing apparatus. The results of the study indicate that the laboratory Loadman test shows great potential, although the test does suffer from imposing stress levels that may be higher than those occurring in-service, particularly for subgrade soils.

Notwithstanding this, the laboratory Loadman tests produced anisotropic elastic modulus results that tied in reasonably well with the corresponding results from the RLT tests.

The advantages of the laboratory Loadman test over the RLT test are that the Loadman test is very simple and it requires very little specialist equipment. It also allows complete specimens to be tested, e.g. aggregates with particle top sizes of 65 mm or even 100 mm can be accommodated. In most RLT tests these specimens would be "scalped" by removing all particles retained on the 19 mm sieve. This practice changes the particle size distribution and can produce misleading test results.

If the Loadman can be developed so that it can incorporate an internal load cell to measure the applied dynamic load, then the results would be even more favourable. This would result in a new method of determining (anisotropic) resilient modulus data that is simple, quick and cost-effective.

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APPENDIX

SUMMARY OF LABORATORY LOADMAN & REPEATED LOAD TRIAXIAL TEST DATA

1. Waitemata Group Soil

Test Point	Deviator Stress (kPa)	Elastic Modulus (MPa)
Laboratory Loadman Test		
1	308	45
2	682	65
Repeated Load Triaxial Test		
1	24.9	206
2	26.8	142
3	27.1	88
4	28.5	163
5	34.1	184
6	34.7	157
7	40.7	182
8	41.0	166
9	48.3	138
10	50.0	112
11	55.0	128
12	55.7	94
13	56.5	208
14	65.4	106
15	66.6	106
16	70.8	198
17	72.0	141
18	114.2	86
19	116.7	94
20	129.0	46
21	131.0	63
22	131.5	81
23	185.1	59
24	187.8	46
25	189.5	51
26	190.5	36
27	192.5	54

2. Kaingaroa Pumice Soil

Test Point	Deviator Stress (kPa)	Elastic Modulus (MPa)
Laboratory Loadman Test		
1	354	12
2	706	30
Repeated Load Triaxial Test		
1	13.8	62
2	13.8	58
3	13.8	65
4	27.6	60
5	27.6	45
6	27.6	60
7	41.4	60
8	41.4	60
9	41.4	63
10	55.2	69
11	55.2	70
12	55.2	68
13	69.0	76
14	69.0	77
15	69.0	77

3. Flat Top AP25 Aggregate

Test Point	Mean Normal Stress (kPa)	Elastic Modulus (MPa)
Laboratory Loadman Test		
1	115	70
2	266	130
Repeated Load Triaxial Test		
1	22.8	15
2	534.7	436

4. Drury AP65 (Untreated) Aggregate

Test Point	Mean Normal Stress (kPa)	Elastic Modulus (MPa)
Laboratory Loadman Test		
1	115	135
2	266	260
Repeated Load Triaxial Test		
1	51	173
2	53	168
3	56	155
4	77	210
5	79	193
6	102	231
7	111	212
8	116	234
9	133	220

5. Drury AP65 (Stabilised) Aggregate

Test Point	Mean Normal Stress (kPa)	Elastic Modulus (MPa)
Laboratory Loadman Test		
1	115	450
2	266	800
Repeated Load Triaxial Test		
1	51	564
2	53	530
3	55	543
4	77	677
5	79	661
6	102	777
7	111	762
8	115	771
9	133	782

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