New Variable Impact Test for Low-Volume Roads

G. King, P. R. Fleming, J. R. Boyce, and C. D. F. Rogers

The development of a new apparatus for routine testing of subgrades and pavement foundations is described. Potential applications include pavement design, material selection, and proof testing during construction. The main objectives were to develop a relatively low-cost, lightweight, and portable dynamic testing apparatus that has the capability of producing on-site resilient modulus values. A prototype swinging hammer apparatus (ODIN) has been built and proving trials have been in progress for 12 months. ODIN is designed so that the stress and area of impact can be adjusted to simulate various loading conditions to suit the materials and constructions under test. Under low impact stresses, quasi-elastic (resilient) behavior occurs, followed by plastic deformation and failure at higher stresses. Digital storage of the impact pulse facilitates processing of the signal to determine the maximum resilient deflection. By using double integration techniques and incorporating energy balancing equations, a composite modulus value can be determined, taking into account both peak deceleration and pulse time. The apparatus typically produces an impact pulse of 1 to 3 msec duration, with a transient deflection of 0.5 to 3.0 mm. Intensive field testing of various materials from soft clay subgrades to capping and subbase layers has yielded reasonable moduli that correlate well with other tests. The ability to test different materials and constructions, along with the capability for data capture and interpretation, indicates widespread potential applications.

Design of low-volume roads needs to be innovative. Materials testing to determine parameters associated with pavement design, and subsequent proof testing of compacted layers, need to be efficient because of economic constraints. Routine testing of the subgrade and subbase is an important feature of pavement design and construction. However, the economics of low-volume roads imposes strict limitations on the testing regime.

It has been recognized, particularly for thinly surfaced roads, that determination of the resilient modulus of the pavement foundation is necessary to indicate whether a pavement will withstand repeated loading during trafficking. The relative complexity and expense in measuring a resilient modulus has, however, proved to be prohibitive for routine testing of low-volume roads. Despite attempts to calculate resilient moduli from California bearing ratio (CBR) values and combinations of standard laboratory test results, it is suggested that no acceptable method is in present use.

It is, therefore, considered that the development of a low-cost, lightweight, and portable dynamic testing apparatus for regular in situ determination of resilient modulus for unbound material layers has great potential for use in the design and construction of low-volume roads. The new variable testing apparatus, ODIN, has been developed by a teaching company formed between Geotechnics Limited and Loughborough University of Technology. It has been designed to test a range of natural soils, stabilized soils, and granular materials that are generally used in highway and earthworks construction. ODIN (see Figure 1), can be used for the initial determination of resilient modulus during design, for compliance testing during construction, and for the determination of local material suitability for use in construction.

ODIN

ODIN consists of an impact head to which the interchangeable impact plates are secured. The head is raised by a swinging arm arrangement that has the advantage of allowing manual raising of masses up to 15 kg and that ensures a good contact between the impact plate and ground surface. Plates vary in diameter from 100 to 300 mm, allowing a range of impact stresses. The drop height can be varied up to 600 mm, with a stop facility to control drop height for simple repeated testing. An accelerometer mounted in the hammer head is used to measure deceleration on impact, with the signal being digitally recorded at 20-μsec intervals for a period of 5 msec from the moment of impact.

The impact stress can be controlled by variation of the diameter of the impact plate and the drop height. A stress range of 0.2 to 3.5 MPa can be achieved that simulates the stresses during wheel loading (typically 0.7 MPa for a single wheel load and standard axle), although the stress pulse is of much shorter duration. The stiffness of clays and granular materials is not generally dependent on rate of loading. However, it is recognized that the inertial stresses during testing can be significant and allowances are made during the analysis of results.

The diameter of the impact plate used during testing is important. Plate diameter will determine the depth to which a construction is stressed and influence the peak stresses acting during the test. It is also important that the area of the impact plate should be large enough to obtain a characteristic material response, without being overly influenced by individual aggregate particle size. For testing of homogeneous subgrade material, the larger plate sizes (200- and 300-mm diameters) have given consistent results at lower stress values. On subbase materials, both the smaller and larger plate sizes have been used with success. However, depending on the construc-

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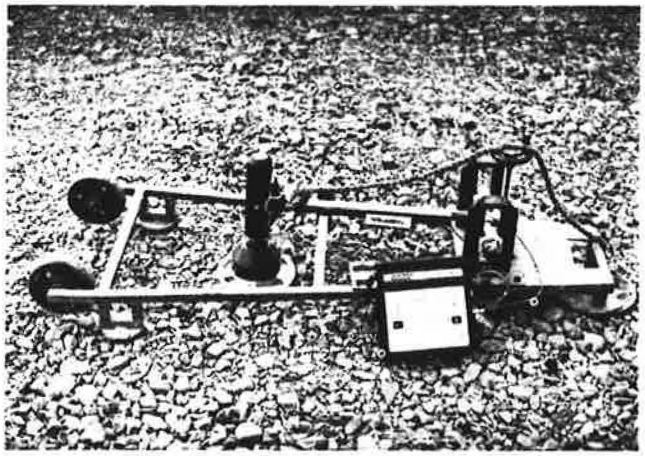

FIGURE 1 First ODIN prototype with data processor.

tion thickness and the plate sizes used, the surface modulus may be influenced by the subgrade stiffness.

The present test procedure involves testing at drop heights of 0.2, 0.3, 0.4, and 0.5 m, with generally four tests at each drop height. The accelerometer signals recorded at each height are generally repeatable, as shown in Figure 2, with the fourth drop used to calculate a resilient modulus, assuming repeatability. Note the straight-line loading and short transient loading pulse in Figure 2.

In a road construction environment, it is anticipated that full ODIN tests (i.e., testing at a number of drop heights and stresses) will be carried out at specified intervals to determine the elastic range of the material under test. More concise testing can then be carried out at much closer spacings from

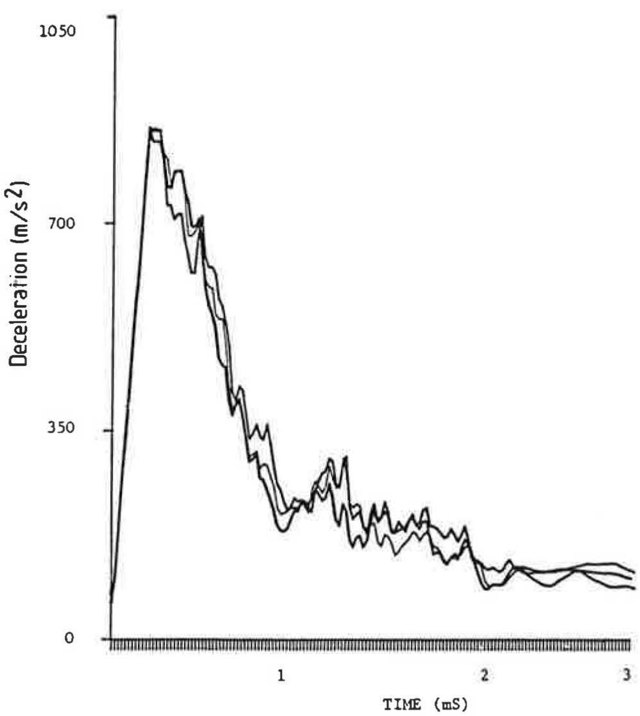

FIGURE 2 Accelerometer output for three successive tests demonstrating repeatability.

a specified drop height, allowing simple, quick, routine testing of subgrade and subbase.

The ability to vary the plate sizes allows ODIN testing to be designed for the particular materials and construction under test. With a small impact plate (100- and 150-mm diameters), testing of individual layers can be carried out, whereas larger plate sizes can be utilized to test either thicker homogeneous layers or to obtain a composite foundation modulus.

EXISTING APPARATUS

Existing methods of in situ pavement evaluation include static, wheel, and dynamic loading methods.

Static Loading

The in situ CBR test can be used to monitor individual layers, but is subject to increasing error with increased particle size. The CBR test is a bearing test that leads to shear failure and relates more to shear strength than resilient modulus.

The plate loading test involves the application of a load to a circular plate to obtain an elastic modulus (*1*). The duration of the loading is long compared to an actual wheel load. The large kentledge required and the time taken to carry out a single test restricts its potential for routine testing.

Moving Wheel Loading

Deflection beam testing is used to measure pavement deflection as a wheel load passes, but is often unreliable on granular materials because of significant movement during loading.

Dynamic Loading

The falling weight deflectometer (FWD) test involves a falling weight (of up to 400 kg) the impact of which is transmitted to a circular loading plate by a system of springs, giving a pulse time similar to that of vehicle loading. A series of geophones measures ground deflection at an increasing radial distance from the loading plate. Computer analysis techniques are used to calculate the resilient moduli of the separate pavement layers. The equipment and associated computer software are expensive, and hence, regular testing is not feasible in low-volume road situations.

The Clegg hammer apparatus (*2*) consists of a 4.5-kg mass, fitted with an accelerometer. The output from the accelerometer is in the form of a Clegg impact value (CIV). The hammer is dropped down a guide tube from a height of 450 mm four times, the CIV being the fourth or highest deceleration (1 CIV = 100 m/sec^2). The impact area is 50 mm in diameter and is similar in size to the coarser subbase aggregate particles. As a result of this small impact area, high stresses occur that cause localized bearing failure in all but the stiffest construction materials. It has been shown (*3*) that the CIV, which is overly influenced by properties of material close to the loaded area, is more likely to reflect the shear strength or CBR of the material rather than its resilient modulus.

THEORY AND ANALYSIS

The theory that has evolved during the development of ODIN is that under low impact stresses quasi-elastic (resilient) behavior occurs, followed by plastic deformation and failure at higher stresses (*3*). For a homogeneous material, the factors that influence deceleration on impact are the soil stiffness, the bearing capacity of the material under test, and inertia effects.

1. Stiffness. Laboratory testing (*4*) has indicated that resilient modulus is stress dependent, although not dependent on rate of loading, in the time range associated with transient vehicle loading of pavements.
2. Bearing Capacity. In situ testing with high stresses, as is the case with the Clegg hammer, can produce a bearing failure resulting in significant plastic deformation or compaction.
3. Inertia. Inertia effects are inherent in impact testing. The loading pulse produced by ODIN is rapid, of the order of 1 to 3 msec, and energy is required to accelerate the soil mass to the same velocity as the impacting plate. This inertial effect is allowed for in the calculation of the apparent modulus on impact (*5*).

By equating the impact energy to the work done in deflecting the ground under the impact area, relationships between peak deceleration (A_p), maximum deflection (s), drop height (H), and resilient modulus (E_r) can be derived.

Digital storage of the impact pulse facilitates simple signal processing. A typical unfiltered signal is shown in Figure 3 together with a filtered signal using a 4-kHz digital filter. Peak deceleration is obtained from the filtered signal, whereas velocity and peak displacement are obtained by integration (once and twice, respectively) of the unfiltered signal. In order to minimize inertia effects, peak displacement is used rather than displacement at maximum deceleration (*3,6*).

Using the relation that force is equal to mass multiplied by acceleration and assuming a uniform stress under the plate, maximum stress on impact (σ) is calculated from the peak deceleration value (A_p) as follows:

$$\sigma = \frac{4A_pMg}{\pi D^2}$$

where

M = mass of falling weight,
D = impact plate diameter, and
g = acceleration caused by gravity.

Resilient modulus (E_r) is calculated using a Boussinesq approach:

$$E_r = \frac{A_pM(1 - \nu_r^2)g}{sD}$$

where

ν_r = resilient Poisson's ratio, and
s = peak displacement.

Assuming a value for Poisson's ratio, 0.3 for a granular material and 0.5 for a clay, the resilient modulus can be calculated from the accelerometer output.

The calculated modulus is normalized to a stress of 0.7 MPa to relate to typical stresses acting on the foundation surface materials from construction traffic. Stress correction is made using the following relationship (*4*).

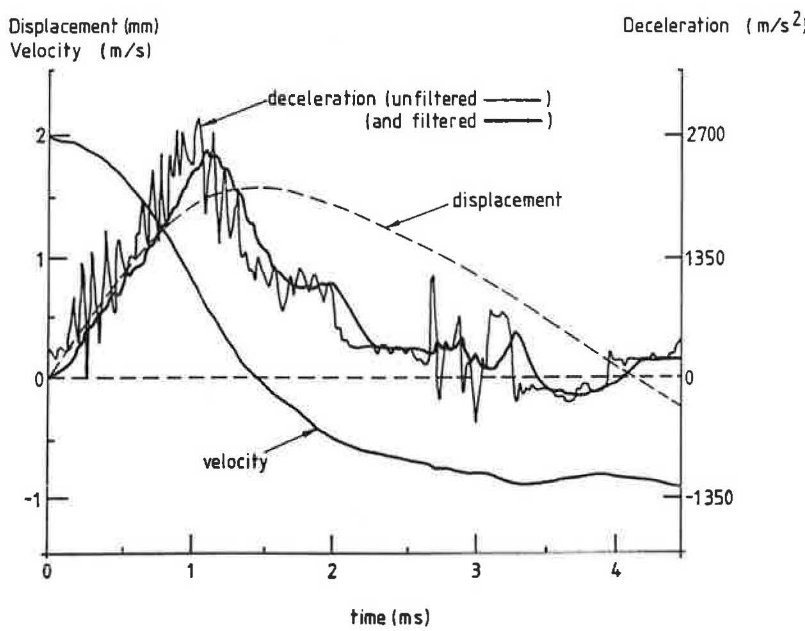

FIGURE 3 Typical unfiltered, filtered, and integrated accelerometer signal on impact.

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

where

k_1 = material constant,
k_2 = material constant, and
θ = sum of principal stresses.

The range of k_2 values is generally between 0.2 and 0.7; hence, assuming a value of k_2 of 0.5,

$$E \propto \theta^{1/2}$$

Moduli values are only calculated from tests demonstrated to be within the elastic range of the soil under test. Figure 4 shows peak deceleration (A_p) versus drop height (H) for impact tests carried out both using 100- and 50-mm plate sizes. The larger (100-mm) diameter plate size indicates A_p is proportional to H at A_p values of up to about 2500 m/sec^2, with a leveling or reduction in value above this stress level indicating possible bearing failure. The smaller 50-mm plate and Clegg hammer give peak deceleration (A_p) values that increase slightly with increased drop height. This is suggested to be a result of high impact stresses creating a failure condition at low drop heights, with only minor increases in impact resistance for increasing heights thereafter.

Because of inertia effects, however, an increase in contact stress is to be expected with increased drop height. Variations of peak decelerations alone, therefore, may not indicate failure conditions in all tests. Deflections recorded during testing will also increase with increased contact stress, although a significant increase in deflection will occur when the yield and failure conditions are reached. Variations in the moduli (uncorrected for stress) with increased drop height best indicate whether the elastic range of the soil has been exceeded, this condition being characterized by a limit or reduction in calculated moduli values.

RESULTS

ODIN has been specifically developed for use on variable subgrades and differing unbound pavement and earthwork materials. Attention has been given to correlation of values obtained by ODIN to values obtained by other in-situ testing apparatus, specifically the plate bearing test, the FWD, and the Clegg hammer.

Field testing at Bothkennar, Scotland, undertaken in connection with research work being carried out by the University of Nottingham, provided the potential for correlation between ODIN, FWD, and Clegg hammer for 12 pavement foundation constructions. Nine of the pavement foundations consisted of crushed rock aggregate (Type 1), having the same material and grading, and three consisted of sand and gravel. A 30-m length of subgrade exposed during construction was also tested with the Clegg hammer and ODIN apparatus only. The pavement foundations varied in thickness and many were reinforced, with different reinforcements being used for different constructions.

Testing of the thick, homogeneous subgrade was carried out using larger plate diameters to minimize the stress on impact. Moduli values of the order of 25 to 45 MPa were obtained and considered to be reasonable. A slight reduction in stiffness with increased chainage can be identified from Figure 5. At the time of testing, the subgrade at 70-m chainage had only recently been exposed to relatively hot conditions, whereas that at lower chainages had been exposed for some time, allowing the development of a thick drier crust reflected in slightly higher modulus values.

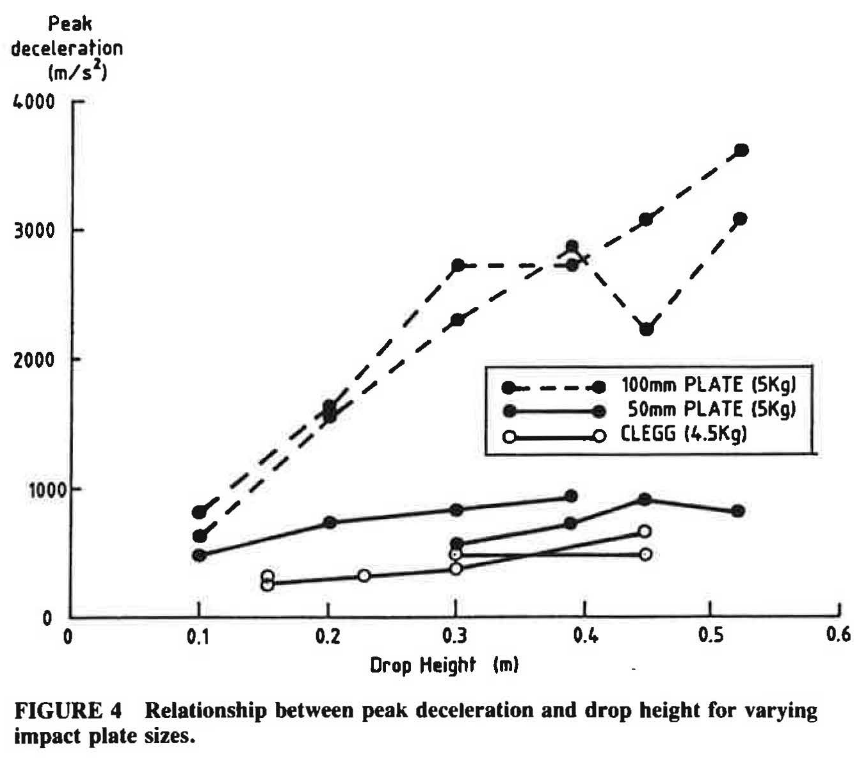

FIGURE 4 Relationship between peak deceleration and drop height for varying impact plate sizes.

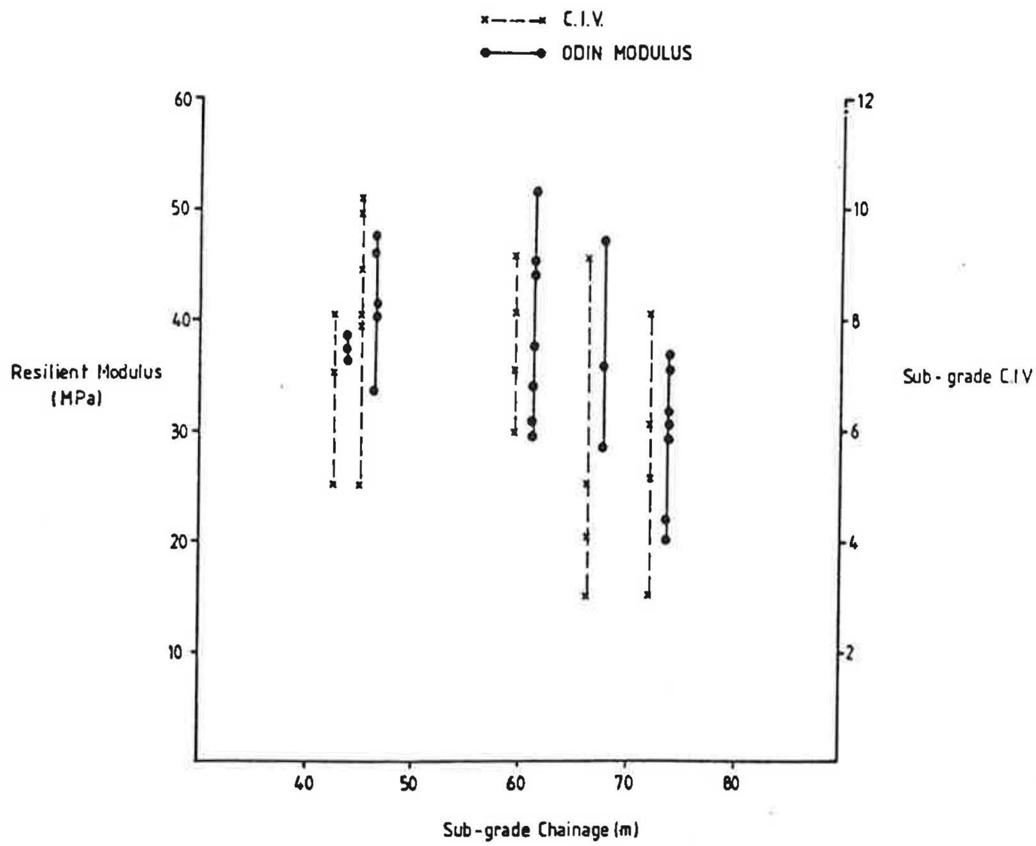

FIGURE 5 Variation of resilient modulus and CIV with increased chainage on clay subgrade.

Variations in CIV values indicate a similar trend (Figure 5); however, they are considered to reflect variations in CBR (or shear strength) rather than resilient modulus.

ODIN testing of the pavement foundations was carried out with smaller diameter plate sizes to control the depth of stressing. FWD testing was carried out using a 300-mm plate, with the stiffness of the subbase layer back-calculated for a normalized stress of 500 kPa. The respective back-calculated FWD subbase moduli and ODIN moduli obtained with a 200-mm plate are shown in Figure 6. It can be seen that a reasonable correlation exists between the FWD and ODIN moduli, although it is evident that specific correlations exist for particular material types. Within any test foundation a range of moduli was obtained with both the FWD and ODIN, and it is considered that this reflects the true variability of the granular constructions. No correlation was obtained between CIV and either FWD or ODIN moduli.

A detailed program of field testing was carried out on pavement foundation test bays at the Road and Railroad Research Department of Delft University, Holland. The constructions tested consisted of seven unsurfaced pavement foundations comprising 250 mm of subbase overlying a sand subgrade. The subbase materials varied from weak lava to stiff self-cementing slag materials. Testing was carried out using the ODIN apparatus and the Clegg hammer. Earlier work carried out at Delft included testing with a modified FWD (7). This dynamic plate bearing test measures only the central deflection, hence giving a composite modulus. Figure 7 shows the composite modulus values both for ODIN using a 150-mm impact plate and the FWD using a 300-mm loading plate for the various constructions tested, along with the CIV.

The moduli are generally comparable, although both tests show some scatter in particular bays. This relation is further demonstrated in Figure 8, which shows the correlation of composite modulus for ODIN and the FWD. Some scatter is inevitable when testing granular materials because of such features as surface texture and variations in density. When a significant range of moduli values was obtained with ODIN, as in the case for the phosphorous slag (FO), a comparable range of values is evident for the modified FWD.

No apparent correlation was found between surface modulus and CIV for the constructions. It is suggested that the Clegg hammer has differentiated between constructions with either loose surfaces or weak constituent aggregate particles and those constructions with a closed texture or high aggregate particle strength.

APPLICATIONS

In the United Kingdom and many other countries, the construction of formation, capping, and subbase layers relies on material gradings and method specifications for their placement and compaction. It has been recognized for some years that it is desirable to move towards a situation where the ability of the pavement foundation to support the pavement

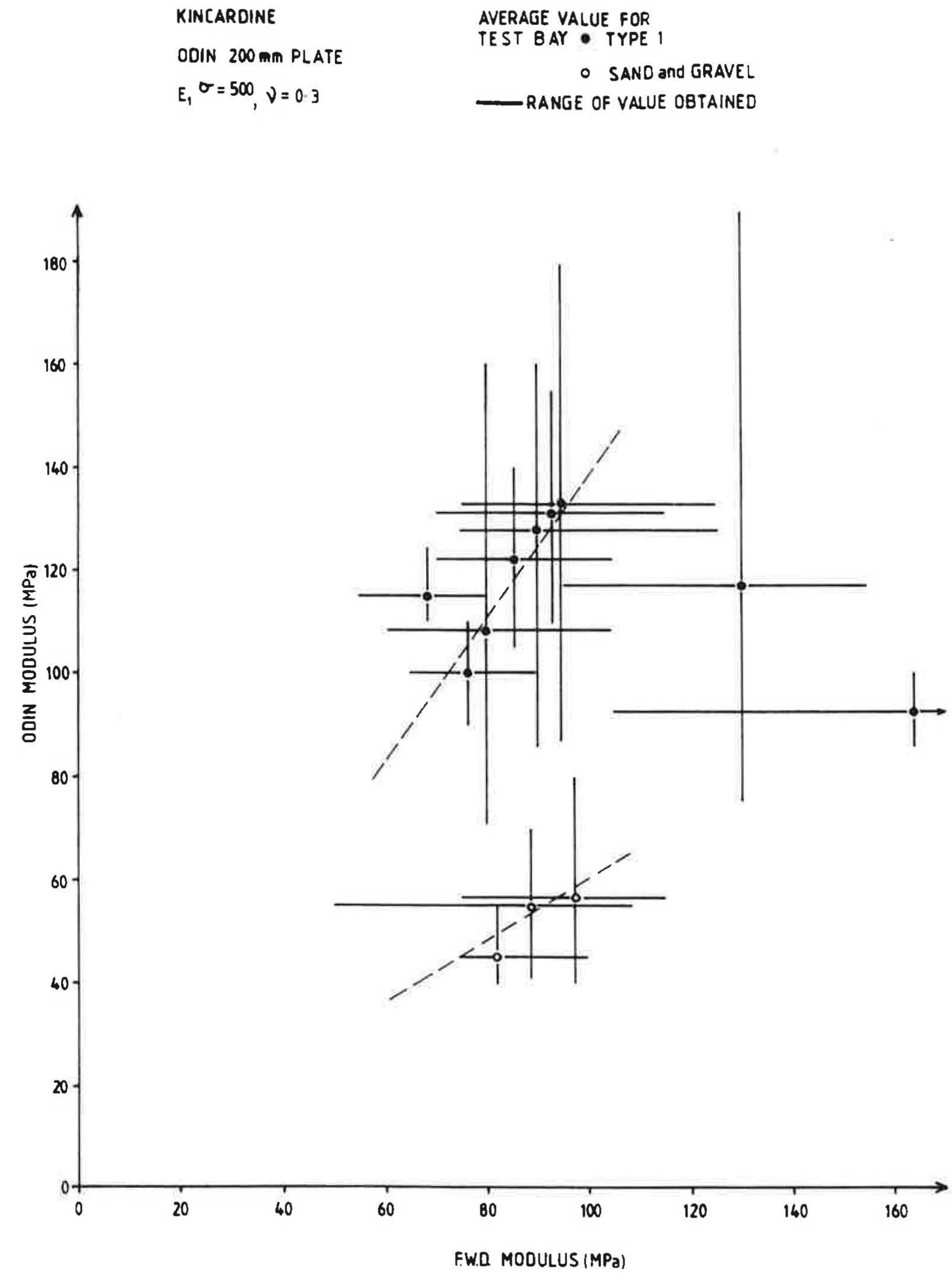

FIGURE 6 Resilient modulus and FWD back-calculated modulus for 12 subbase constructions.

structure is assessed more directly. Empirical tests such as the CBR, Moisture Condition Value (MCV), and CIV may give some assurance that the material is well compacted and unlikely to suffer permanent deformation, but they cannot show that the surface modulus is adequate to support a pavement subject to repeated loading.

It is believed that applications will be in two stages. The first stage is the testing of materials before a road contract commences. The second stage includes routine testing of subgrade and foundation layers as constructed to ensure that a consistent performance is achieved throughout the contract.

CONCLUSIONS

The new impact test apparatus is considered to have great potential for use in low-volume road situations. The low cost, robustness, and portability of ODIN, along with the ability to produce on-site resilient modulus values, enable use both for routine testing during the design and construction of pavements and the determination of material suitability for use in construction. The ability to vary the impact plate size and drop height also allows ODIN testing to be designed for the particular materials and construction under test. With appro-

OS Eastern Scheldt Sand (same as subgrade).
MG Crushed masonry.
FF 50% crushed Concrete/50% crushed masonry.
LA Lava.
SS Pelletised blast furnace slag.
ME Crushed masonry with 15% electro-furnace slag
FO Phosphorous slag.

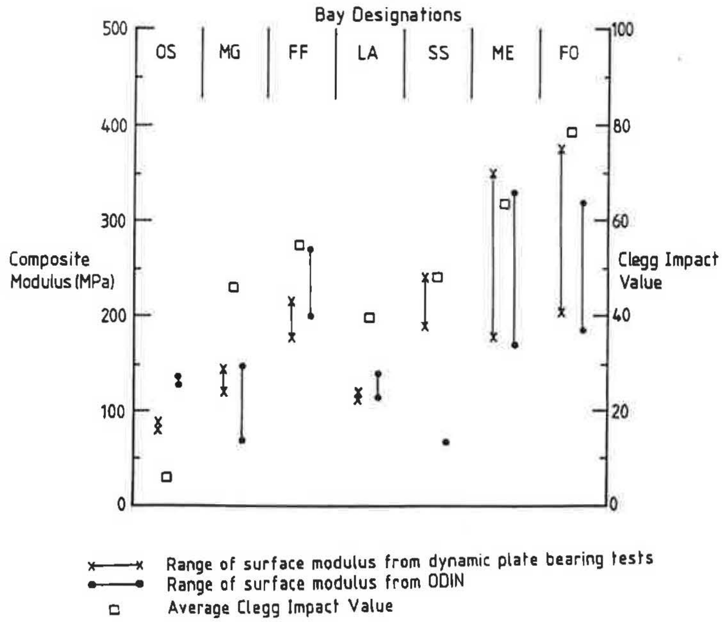

FIGURE 7 Composite modulus (ODIN and FWD) and CIV for seven construction bays.

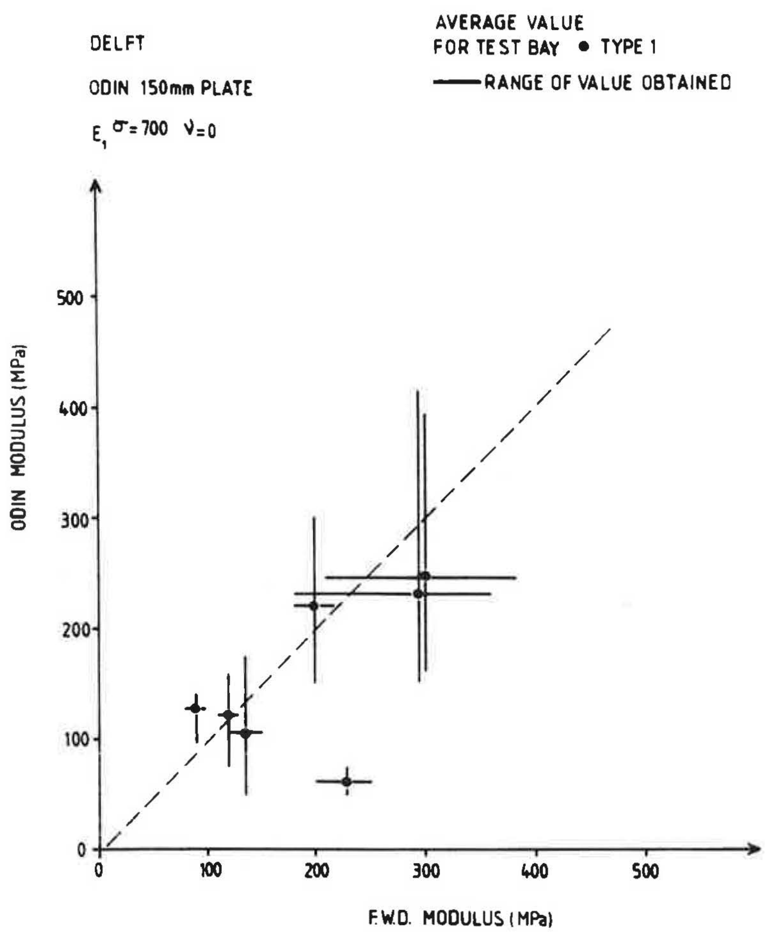

FIGURE 8 FWD and ODIN modulus values for bays tested.

priate analysis of the impact pulse, a modulus can be determined for a wide variety of soils and unbound materials.

By equating the impact energy to the work done in deflecting the ground under the impact area, relationships have been derived to calculate a resilient modulus. ODIN testing produces a repeatable and effective means of determining resilient modulus, which compare favorably with those values obtained by the FWD over a range of stiffnesses. It has also been suggested that although the Clegg hammer is often correlated with CBR, being a parameter more indicative of shear resistance it has no correlation with elastic moduli.

A second prototype is now under construction. This model will be used to further examine the sensitivity of the results to compaction, moisture content, and other construction variables, and refine analysis procedures. Current field test programs include specifically the study of correlations with other in-situ foundation evaluation procedures, both static and dynamic.

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