STIFFNESS MEASUREMENTS AND CRITERIA FOR THE CONSTRUCTION OF ROAD FOUNDATIONS

Livneh M.
Emeritus professor–Technion-Israel Institute of Technology–moshliv@tx.technion.ac.il

ABSTRACT

Current Israeli practice for the construction of pavement foundations is based on a recipe approach, and their design entirely on the California Bearing Ratio (CBR) to characterize the subgrade, capping, and sub-base materials. CBR is used as an index of both martial strength and stiffness although it measures neither directly. Such an approach leads to the dependence of the degree of compliance with current common specifications and performance quality on two different elements that are not always directly related to each other. Thus, performance-based specification is required to control long-term functional and structural performance. This will facilitate quantitative evaluations of alternative construction practices and materials, such as reclaimed materials, with beneficial cost and environmental implications. Thus, quality-control and assurance testing would be expected to include stiffness along with density measurements.

The Falling Weight Deflectometer (FWD) and some additional small-scale dynamic devices are available for the measurement of elastic stiffness modulus on pavement foundations. However, various studies have indicated that different types of equipment can produce different values for foundation stiffness; furthermore, it is difficult to develop relationships between these different tests unless the comparison is conducted on a site-specific basis. These findings are validated in the present paper for a comparison of FWD and Light Drop Weight (LDW) outputs. In addition, this paper describes the DCP-accompanied tests that were conducted together with the FWD and LDW tests in order to correlate stiffness results with CBR values. The study concluded that it was also difficult to develop relationships between stiffness and CBR values. This finding highlights once again the need to specify stiffness target values, along with the required strength values, for the construction of pavement foundations.

Finally, in Israel, as in several other locations, preliminary target stiffness values have been suggested. These values are compared with those reported by several agencies around the world. The final conclusion emanating from Israeli practice is that the target values should be based on in-situ tests and site-specific trials.

Keywords: CBR, compaction, DCP, FWD, LDW, road foundation, performance-based specification, seating factor, stiffness, surface modulus, quality-control

1. INTRODUCTION

Current Israeli practice for the construction of pavement foundations is based on a recipe approach; their design is based entirely on the California Bearing Ratio (CBR) to characterize the subgrade, capping, and sub-base materials. CBR is used as an index of both martial strength and stiffness, although it measures neither directly. Such an approach leads to the dependence of the degree of compliance with current common specifications and performance quality on two different elements that are not always directly related to each other. Thus, performance-based specification is required to control long-term functional and structural performance. This facilitates quantitative evaluations of alternative construction practices and materials, such as reclaimed materials, with beneficial cost and environmental implications. Thus, quality-control and assurance testing would be expected to include stiffness along with density measurements.

In some of Israel's major projects, stiffness measurements of compacted subgrade, compacted fill, compacted sub-base, and base layers are now required along with the execution of conventional in-situ density tests. Obviously, the conventional Falling-Weight Deflectometer (FWD) is classified as a suitable device for these stiffness measurements, but it is sometimes considered unnecessarily sophisticated for formation and foundation testing; furthermore, it is not without limitations on weaker substrates in regard both to transducer range limits and portability as discussed by Fleming et al. (2000). Thus, the German Light Drop-Weight (LDW), also known as the German Dynamic Plate Test (GDP), which is lightweight, portable, and simple to apply for repeated testing, is used by various agencies around the world (see Zorn, 1995). Here, it should be mentioned that this lightweight portable device is one among several small-scale dynamic devices that are available for stiffness measurements (see Fleming, 2001). However, various studies have indicated that different types of equipment can produce different values for foundation stiffness; moreover, it is difficult to develop relationships among these different tests unless the comparison is conducted on a site-specific basis.

Given this background, the objectives of the present paper were formulated as follows: (a) To correlate the conventional FWD surface modulus (stiffness) of subgrades with their comparative CBR values and the recorded seating factors (to be defined later on); (b) To examine the above findings associated with conventional FWD testing in light of comparative findings reported in the technical literature for such testing; (c) To correlate the LDW deformation modulus of subgrades with their comparative CBR values; (d) To examine the above findings associated with conventional LDW testing in light of comparative findings reported in the technical literature for such LDW testing; (e) To compare conventional FWD surface moduli with comparative LDW surface moduli by conducting in-situ comparative tests and analyzing various data given in the technical literature; (f) To summarize the deflection and surface modulus (stiffness) target values available in the technical literature, to discuss the local target and the procedure for detecting weak points, and finally to point out the use of DCP tests for the final identification of weak spots in a given working lot or even for identifying a total weak lot.

The process of attaining these major six objectives is detailed in the following sections of the present paper.

2. FWD SURFACE MODULUS VERSUS CBR

Recently, a conventional FWD device was implemented at an airfield construction site in Israel for quality control and assurance operations. This FWD testing was conducted on top of each series of five compacted silty-clay fill-layers before the construction and compaction of the next series of five silty-clay fill-layers. The device, which was equipped with a 450 mm-diameter plate, had an impact of 22 kN force or 138 kPa contact stress for all layer measurements. As can be seen, a lower impact load was adopted for the subgrade and the fill-layers owing to the fact that the actual in-service pressure exerted on these layers is lower than that exerted on the surface of the finished pavement structure (a 1,041 kPa contact stress). Thus, in order to eliminate the non-linearity effects of the materials on the measured deflections as much as possible, it was essential to apply a lower impact load.

Experimental data indicate that the resilient modulus derived from FWD testing (M_{FWD} in MPa) is correlated with the CBR values in the manner shown in Equation 1. M_{FWD}, also known as the FWD surface modulus or stiffness, is calculated from the central deflection measurement by the well-known Boussinesq equation for a homogeneous elastic half-space stratum, for which the Poisson ratio is 0.5.

$$M_{FWD} = \alpha \times CBR_e^{1/1.41} \qquad \text{(Eq. 1)}$$

where CBR_e (in percentages) denotes the equivalent CBR value of the interpreted CBR values that vary along a depth of 1.0 meters, measured from the surface of the FWD test. This depth is equal to more than 2 times the FWD's plate radius. Thus it is assumed that the stratum's character along this depth exerts the major influence on the M_{FWD} results. Here it should be noted that the use of the 1.41 power function was previously suggested in (Livneh, 2007a), based on local experience. Finally, the equivalent CBR value (CBR_e) is calculated according the expression developred by Livneh (2007b).

Figure 1 shows the output data obtained at the Israeli airfield construction site examined for the compacted silty-clay materials. The data indicate that (a) the value of α in Equation 1 (i.e., the multiplier coefficient as derived from the restrained regression analysis of the 1.41 power function) is equal to 5.77; (b) the coefficient of determination (R^2) is rather low, which makes the significance of the proposed correlation very poor (the standard error obtained in this correlation is 24.5 MPa).

As for similar data from the technical literature, Livneh (2007a) recently analyzed the experimental data measured by Philips (2005). According to this analysis, α is equal to 12.7 for the FWD experimental data when the comparative CBR is measured by direct testing, or α is equal to 12.9 when the comparative CBR is measured by DCP testing. The standard errors obtained for these two correlations are 56.7MPa and 48.2MPa, respectively, which are both rather high values. The coefficient of determination (R^2) obtained for these two correlations are 0.56 and 0.61, respectively. These two latter statistical coefficients indicate a better statistical significance in comparison with the data of Figure 1. Moreover, a similar value of α=12.1 was obtained for the experimental data measured by Nazzal (2002). Here, it should be noted that the comparison conducted by Livneh (2007a) indicates that direct FWD testing on the subgrade leads to lower values of resilient modulus than those obtained from backcalculation of FWD deflections measured on the pavement surface.

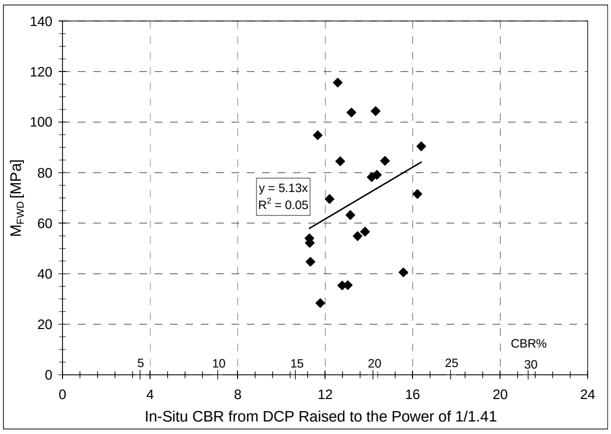

Figure 1. Surface modulus from FWD testing versus in-situ CBR, as obtained in compacted silty-clay material from the recent airfield project in Israel

The recorded wide range of α-values, from 5.8 to 12.9, is attributed to the variability of properties in the tested materials. Furthermore, this difference in the α-values can be attributed to utilizing different loading-pulse shapes, some of which may be attributed to the function of measurement transducers or the way in which the measurements are converted into displacement or even to utilizing improper test technique, such as improper plate seating, etc., as Fleming et al. (2000) state: "Results from different devices can be dramatically different." In any case, the above studies concluded that it was difficult to develop relationships between stiffness and CBR values. This finding highlights the need to specify stiffness target values along with the required strength values for the construction of pavement foundations.

3. LDW SURFACE MODULUS VERSUS CBR

Now, in order to evaluate M_{LDW} values (i.e., the resilient modulus values measured by the LDW device, also known as the deformation modulus E_{V1}, LDW surface modulus, or LDW stiffness), test-pits containing a silty-clayey stratum were excavated prior to construction at various locations at the above-mentioned Israeli airfield project site. Comparative LDW and DCP tests (for a description of the LDW device, see Livneh, 2007b) were carried out on staggered surfaces, arranged at depths of about every half meter. Restrained regression analysis of the 1.41 power function was conducted on the test data obtained as shown in Figure 2. It can be seen that the data of Figure 2 lead to the following expression:

$$M_{LDW} = \beta \times CBR_e^{1/1.41} \qquad \text{(Eq. 2)}$$

where CBR_e (in percentages) denotes the equivalent CBR value of the interpreted CBR values that vary along a depth of 0.5 meter, measured from the surface of the FWD test .

This depth is equal to about 2 times the LDW's plate radius. Thus it is assumed that the stratum's character at this depth exerts the major influence on the M_{LDW} results. Note: M_{LDW} in Equation 2 is given in MPa.

Figure 2 shows the output data obtained for the natural silty-clay material from trenches excavated in the tested airfield construction site. The data indicate that (a) the value of β in Equation 2 (i.e., the multiplier coefficient as derived from the restrained regression analysis of the 1.41 power function) is equal to 3.07; (b) the coefficient of determination (R^2) is negative, which makes the significance of the proposed correlation very poor. The standard error obtained in this restrained regression is 21.0 MPa.

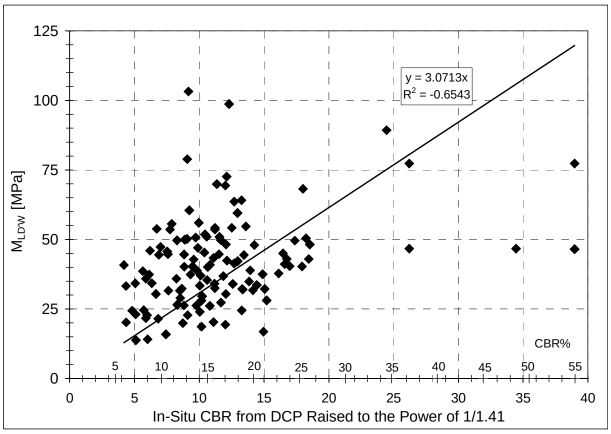

Figure *2*. Surface modulus from LDW testing versus in-situ CBR, as obtained in natural silty-clay material from the recent airfield project in Israel

As for other similar data, the data given by Livneh (2007b) indicate that the β-coefficient varies in the range of 3.07-6.02 at five different sites. It seems that the 6.02 coefficient is perhaps exceptional. For these values, all values of the coefficient of determination (R^2) are above 0.74, except for the -0.59 value obtained at one site and the -0.65 in the present study. The minus sign, which is possible in restrained regression operations, means that the restrained regression is not significant. For the other cases, however, the restrained regressions seem to be significant.

The recorded wide range of β-values, from 3.1 to 6.0, is attributed, again, to the variability of properties in the materials tested. In other words, these findings indicate that the results are material dependent and that correlative equations should be used with care and only with a full understanding of the material properties of the soils on which the expressions are developed and of the soil being tested. Thus, it is very much recommended that any correlative expression should be implemented only after its validity is checked against limited in-situ testing.

Here, it should be pointed out that according to German railway practice, the β value equals to (a) 3.73 for CBR values lower than 10% and (b) 10.74 for CBR values higher than 10%. For case (b), a constat value of minus 35.81 exists in Equation 2. Thus, the outputs of the local β values reported above can be compared to German railway practice. This comparison indicates that the local outputs reported above in regard to lower bound compare well with the German outputs. Moreover, it seems that the local results for the range of higher CBR values are more realistic than those corresponding to German railway practice.

Here it should be noted that German railway practice refers originally to E_{V2} values, and so the corresponding M_{LDW} values have been calculated according to equation given by Zorn (1995). The original E_{V2} value is termed the dynamic deformation. This term is defined by German railway practice (see German DIN No. 18 134) as the surface modulus, calculated from the amount of central deflection caused by the second loading cycle in a static plate-bearing test.

4. FWD MODULUS VERSUS LDW MODULUS

A practical question now arises as to whether a complete equivalency exists between the FWD surface modulus (M_{FWD}) and the LDW surface modulus (M_{LDW}). As the α coefficient of Equation 1 and the β coefficient of Equation 2 have variable values, no complete equivalency can exist between these two surface moduli. In more detail, the ratio of these two moduli is given by the following expression:

$$\frac{M_{FWD}}{M_{LDW}} = \frac{\alpha}{\beta} \qquad \text{(Eq. 3)}$$

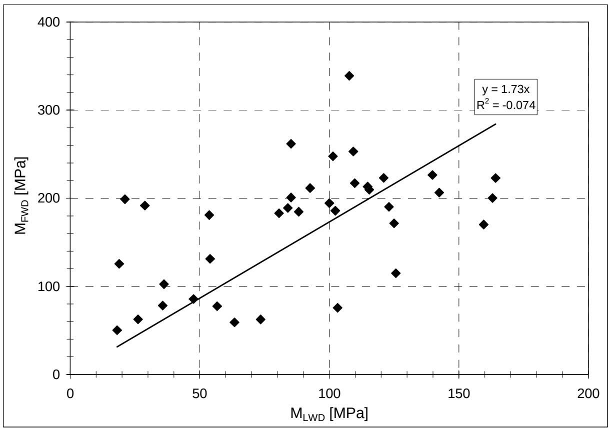

Figure 3. Surface modulus from FWD testing versus surface modulus from LDW testing, as obtained in compacted chalky-marl material in Israel

For the present study of silty-clay material, the α coefficient is equal to 5.13 (see Figure 1) and the β coefficient is equal to 3.07 (see Figure 2). Thus, the moduli ratio is equal to 5.13/3.07=1.67. To check this analysis, direct comparative FWD and LDW tests were recently performed on compacted chalky-marl material in Israel. Figure 3 shows the output data obtained for these tests, indicating that (a) the ratio of M_{FWD} to M_{LDW} value (i.e., the multiplier coefficient as derived from the restrained regression analysis) is equal to 1.73 (similar to the moduli ratio of 1.67 mentioned above); (b) the coefficient of determination (R^2) is negative, thus making the significance of the proposed correlation very poor. The standard error obtained in this correlation is a very high value of 70.5 MPa.

At this juncture, it should be noted that Fleming et al. (2000) conducted comparative studies that contained the use of several portable deflectometers, together with the conventional FWD device. The data from these studies for M_{FDW} versus M_{LDW} were analyzed by Livneh (2007a). This analysis indicated that the ratio of M_{FWD} to M_{LDW} equals 1.73. In an earlier study, Fleming et al. (1988) demonstrated that this correlative ratio increased to about 2.0, and in a later study (Fleming, 2001) that it decreased again, to 1.63. The three values for the M_{FWD} to M_{LDW} ratio are much lower than those obtained recently by Livneh (2007b), 2.77.

5. SEATING FACTOR EFFECTS

In the FWD measurements, a seating factor (SF) is calculated according to a similar approach proposed by van Gurp et al. (2000). According to Israeli practice, the expression for calculating this seating factor is:

$$SF = \frac{d_4}{d_2} - 1 \qquad \text{(Eq. 4)}$$

where d_i denotes the maximum (center plate) FWD deflection at drop i. The goal of van Gurp et al. (2000) was to investigate the feasibility of relating degree of compaction to seating factor values. The basis for this investigation is the hypothesis that a well compacted foundation would exhibit close to zero SF values, as the d_4 value would be identical with the d_2 value. On the other hand, an increasing SF value would indicate a "soft" foundation that is further compacted with every successive drop of the FWD mass. Van Gurp et al.'s finding indicates, however, that SF is not a satisfactory indicator for prediction of degree of compaction.

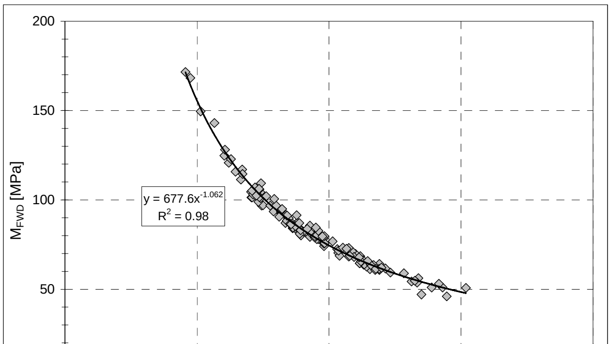

Figure 4. Surface modulus from FWD testing versus the seating factor for a compacted sandy material at a major road construction project in Israel

To support the above-mentioned argument, Figure 4 shows the dependency of FWD surface modulus (M_{FWD}) on the measured seating factor (SF) as defined by Equation 4. The measurements were performed on a compacted fill material of A-2-4 or A-3 type, at a major road construction project in Israel.

In addition to the previous paragraph, Hoffman (2004) reports that his SF data (with a somewhat different definition employing eight successive mass drops) illustrate the complex mechanical behavior of unbound materials. He believes that factors like the material's cohesion, internal friction, moisture content, gradation etc. also affects the SF values. This is probably why a single and meaningful correlation between SF and degree of compaction may not be feasible. In contrast to unbound materials, FWD tests, the results obtained on bound materials by Substand (2002) showed very small drop-to-drop variations and also several different load levels from which to choose. This is because the FWD sensors and the load plate are always better "seated" on bound (versus unbound) layers.

Figure 4 indicates the strong and significant dependency of M_{FWD} values on SF values in granular and semi-granular materials. Moreover, the reduction of M_{FWD} values with the increase of SF is very remarkable, from 150 MPa for SF equals 4 to 50 MPa for SF equals to 12. In this case it is believed that the major reason for this “dramatic” behavior is the rate of development of confining pressure with the load plate seating situation on the unbound layers. Thus, it seems that for high values of SF, say 6% and above, stiffness measurements in unbound materials should be re-taken. Another possible explanation, however, can be suggested for the phenomenon associated with Figure 4. When a significant relationship exists between M_{FWD} and SF, high deflection readings occur, not as a result of a poor plate-seated situation, but as a result of a poor material state. If this explanation is adopted, no re-measuring of deflections is required.

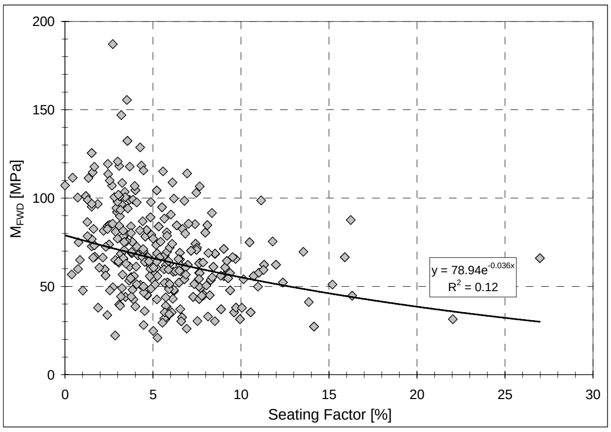

Figure 5. Surface modulus from FWD testing versus the seating factor for a compacted silty-clay material at the recent airfield project in Israel

As for cohesive materials, Figure 5 shows the dependency of FWD surface modulus (M_{FWD}) on the measured seating factor (SF) in a compacted silty-clay material from the recent airfield project in Israel of Figure 1. This figure indicates the poor and non-significant dependency of M_{FWD} values on SF values in bound materials. In this case, the variability in the state of the material is believed to govern the remarkable scatter of the results at the low range of SF. At the high range of SF, a poor plate-seated situation may lead to highly erroneous deflections. Thus, the recommendation here is that for higher values of SF, say 12% and above, stiffness measurements should be re-taken in cohesive materials.

Finally it should be noted that according to Fleming et al. (2000), the operational procedure recommended in order to provide a single value of stiffness for the LDW and the FWD is six drops on the same spot. The first three drops, termed pre-compaction, are to remove any bedding errors and are ignored. The deflections of the next three drops are recorded and displayed on the readout, together with the computed average stiffness. This may be a better operating procedure than the one employed now in Israel; i.e., utilizing four drops, with the first drop ignored and the average of the next three drops calculated.

6. SURFACE MODULUS (STIFFNESS) TARGETS

Several agencies around the world specify target stiffness (surface moduli) to characterize the formations and foundations of pavement structures. The proposed target values derived from the reported values (see Livneh, 2007b) are shown in Table 1, using an M_{FWD}/M_{LDW} ratio of 1.75 (shown to be a representative value for the range of values discussed earlier) and the conversion of moduli shown by Zorn (1995). The reference values for the proposed values are presented in bold in Table 1.

Table 1. Target values for surface moduli as a result of a liturature survey

Structure	**Traffic**	**Target of Minimum Moduli Values**		
		$\mathbf{M_{LDW}}$	$\mathbf{E_{V2}}$	$\mathbf{M_{FWD}}$
Formation	----	45	90	**80**
Foundation	Light	60	**120**	105
	Heavy	75	**150**	130

In Table 1 formation here means the part of the pavement structure that contains the natural, compacted subgrade and the capping layers laid on this subgrade; foundation means the part of the structure containing the formation and the granular sub-base layers laid on the above formation.

Along these same lines, some agencies in Israel include the following clauses in their mandatory construction specifications: The subgrade or capping-layer compaction will be measured for central deflections with an FWD device in accordance with ASTM D4694-96. The test will be conducted by means of four weight drops in each test station with a device equipped with a 450 mm-diameter plate and having an impact of 22 kN, on the basis of which test the deflection results will be normalized. For each carriageway, the tests will be carried out at every design cross section (at a maximum spacing of 10 meters). The representative central deflection for each test-station will be the average of the last three weight drops. For each lot, every representative central deflection should be less than the following: (a) 0.60 mm (corresponding to a surface modulus of 80 MPa), and a coefficient of variation of less than 40% for a natural subgrade after its reworking and compaction, provided that the fill height is 0.5 meter and above; (b) 0.50 mm (corresponding to a surface modulus of 95 MPa), and a coefficient of variation of less than 40% for a natural subgrade after its reworking and compaction, provided that the fill height is less than 0.5 meter; or for a subgrade in cut after its reworking and compaction; (c) 0.40 mm (corresponding to a surface modulus of

115 MPa), and a coefficient of variation of less than 30% for fill and capping layers, provided that the fill height is 0.5 meter and above; (d) 0.25 mm (corresponding to a surface modulus of 175 MPa), and a coefficient of variation of less than 30% for the upper sub-base layer.

For A-3 material and A-2-4 material with a maximum of 20% passing through sieve #200 and a minimum of 90% passing through sieve #4, no FWD testing should be executed directly on these materials. FWD testing should, however, be executed on the first capping layer or sub-base layer spread directly on these materials. This is in full correspondence with the findings of Figure 4.

It seems that the requirements listed above are more stringent than those given in Table 1. Furthermore, it is not understood why the criteria are not dependent on a particular type of soil and traffic. For example, the requirement for the compacted silty-clay material in the recent airfield project in Israel described in Figure 1 has been increased to 0.8 mm (corresponding to a surface modulus of 60 MPa) as a result of FWD testing, conducted along in-situ trial strips.

Here, it should be pointed out that the results of the FWD measurements are also used to locate localized weak-point areas in the lot tested. These weak-point areas should be tested further by additional routine tests (gradation, plasticity, moisture content, degree of compaction, DCP, etc.) to detect the reasons for their deviation. Following this detection, all necessary work should be carried out to raise the deviant sections to the required standards.

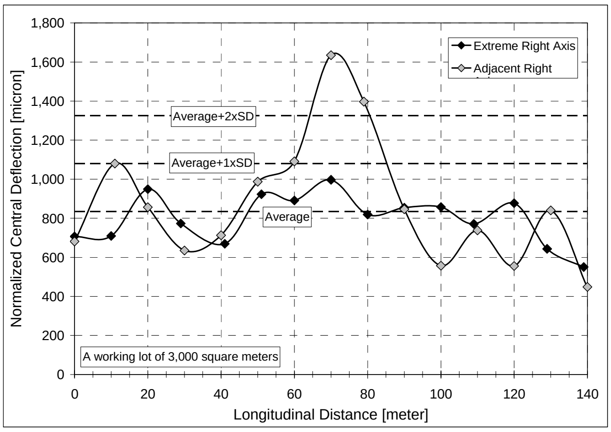

Figure 6. FWD measurements of central deflection (normalized to 22 kN), made along a working lot of compacted silty-clay material

An example of detecting weak points is given in Figure 6. This example is taken from a working lot tested for compacted silty-clay material at the recent airfield project in Israel, shown in Figure 1. The testing was carried out along two longitudinal axes, located 10 meters apart, at a spacing of 10 meters. The average central deflection obtained for all these measurements was 835 microns, which is higher than the maximum target value of 800 microns. This target value was specifically assigned to this airfield project site. Now, a Grubbs analysis for detecting outliers (odd results) reveals that the measurements in Figure 6 contain two such weak measurements, characterized by a central deflection, respectively, of 1,397 and 1,635 microns. Without these two values, the average deflection of the rest of the measurements can be decreased to an acceptable value of 786 microns. Thus, the whole working lot can be accepted, except for the localized weak area of the two odd points, which should be explored further for its state and treatment.

Finally, it should be mentioned that the State of Minnesota (see Siekmeir et al., 2000) suggests the use of DCP testing, along with some other tests, including the elastic stiffness measurements, for in-situ subgrade and granular-base characterization. In light of this suggestion, supplementary requirements have been formulated for the QA/QC procedure at the Israeli airfield project. According to these supplementary requirements, a working lot that does not comply with the FWD criteria should be rejected only after checking that additional DCP testing in the particular lot does not comply with specifically defined DCP criterion. A reasonable DCP criterion is a minimum CBR value, as obtained along the test cross-section, that is higher than twice the design value. It is also recommended in the context of these supplementary requirements that the final definition of the target values for the central deflections measured be arrived at by conducting calibration tests in representative in-situ sections.

7. CONCLUSIONS

The FWD and several additional small-scale dynamic devices are available for the measurement of elastic stiffness modulus on pavement foundations. However, various studies have indicated that different types of equipment can produce different values for foundation stiffness. Furthermore, it is difficult to develop relationships among these different tests unless the comparison is conducted on a site-specific basis.

In light of the above, this study concentrated on the possible use of FWD and LDW devices for measuring the mechanical properties of the formation of pavements. The main findings derived from this study are as follows: (a) It is difficult to develop relationships between FWD or LDW surface modulus (stiffness) and CBR values; this finding highlights the need to specify stiffness target values, along with the required strength, for the construction of pavement foundations; (b) It seems that LDW outputs for dynamic deformation (E_{V2}) are of the same magnitude as those obtained from the second loading cycle in German static plate-bearing tests; thus, the LDW device can be used as a substitute for the German static plate-bearing; (c) The ratio of FWD surface modulus (M_{FWD}) to LDW surface modulus (M_{LDW}) is equal to 1.67 in one set of analyses and 1.73 in a second set of analyses; these values are in the range of those previously published; (d) For sandy materials, there is strong dependency between the seating factor and the measured FWD surface modulus, and poor dependency for cohesive materials; thus, it is suggested that deflections be re-measured when the seating factors exceed limiting values, on the one hand, and that six consecutive mass-drops be employed, ignoring the first three and averaging the last three, on the other hand; (e) It seems that the target values of surface moduli proposed by some agencies in Israel are more stringent than those recommended by some agencies in the UK and Germany. Since, moreover, these targets are not soil-type and soil-state dependent, it is recommended that specific target values be assigned to each given project after local in-situ trial sections are conducted.

Finally it is proposed that a working lot that does not comply with the FWD criteria should be rejected only aftehecking that additional DCP testing in this lot does not comply with specifically defined DCP criteria.

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ACKNOWLEDGMENTS

The results presented in this paper were obtained in the course of projects performed by the author for various Israeli governmental agencies. Thanks are therefore due these agencies. The paper was prepared with the assistance of Mr. Arieh Aines, graphics editor of the Transportation Research Institute at the Technion, to whom thanks are also due.