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Comparison of in situ devices for the assessment of pavement subgrade stiffness

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***Abstract* – The subgrade is the top surface of a roadbed upon which the pavement structure is constructed. The purpose is to provide a platform for construction of the pavement and to support the pavement without unwanted deflection that would reduce its performance. For those reasons subgrade bearing capacity have to be investigate during the construction process as a quality control, based on the design results. The dynamic in situ Falling Weight Deflectometer (FWD) tests are nowadays widely used and considered the most reliable and suitable approach to determine bearing capacity of road pavements and elastic moduli. In addition, the use of the Light Weight Deflectometer (LWD) takes the advantage of the dynamic application of load, and the flexibility of the handling of the equipment on construction area and unbound layer. In the present paper, a wide literature review is presented on the topic of correlation between different subgrade bearing capacity in situ tests. In order to assess the transferability of LWD measures, these results were compared with FWD test and Dynamic Cone Penetrometer (DCP) test. Soil samples, taken from the site, have also been investigate in laboratory to relate geotechnical and in situ test results.**

I. INTRODUCTION

In recent years, mechanistic-empirical design procedures have attracted the attention of both pavement engineers and researchers. These design procedures require knowledge of the mechanical properties of the materials that make up the pavement structure. In this framework, the resilient modulus (M_r) has become the basic parameter to characterize unbound pavement materials because a large amount of evidence has shown that the elastic (resilient) pavement deflection provides a better correlation to field performance than the total pavement deflection [3]. Resilient modulus is defined as the ratio of deviator stress, σ_d, to the recoverable strain, ε_r: $M_r = \sigma_d/\varepsilon_r$.

Meanwhile, the complexity of the laboratory test procedures has prompted highway agencies to explore other test methods, especially in-situ field tests. Deflection measurements with the Falling Weight Deflectometer (FWD) and Light Weight Deflectometer (LWD) and penetration test with Dynamic Cone Penetrometer (DCP) have been routinely employed in evaluating pavement layers, and the underlying subgrade. On the other hand, considering the differences between on situ test and laboratory tests, the modulus of a multilayer system, calculated from surface deflections employing a backcalculation routine, is referred to as "backcalculated modulus," E_{back}, in contrast to "resilient modulus," Mr, which results from a laboratory test. When using forward calculation, employing surface deflections and Boussinesq equations, the modulus resulting is designated "elastic modulus," E [10].

In the Minnesota Research Road Project (Mn/ROAD), Van Deusen et al. [10] reported difficulties in analyzing FWD measurements performed directly on subgrade surfaces. Their results showed a weak correlation between laboratory and backcalculated (E_{back}) moduli. On the contrary, an investigation, conducted by George (2003) [10], showed that E_{back} moduli obtained from testing directly on the subgrade are in satisfactory agreement with the laboratory values with certain restrictions. In this framework, Nazzal et al (2007) [8] conducted a linear regression analysis on collected field test data to relate the elastic modulus calculated by using the Light Weight Deflectometer (ELWD) and the FWD back-calculated modulus (MFWD), by obtaining the following regression model:

$$MFWD = 0.964\ ELWD \qquad (1)$$

With a coefficient of determination (R^2) of 0.94. This result suggests that the LWD and FWD yield close modulus values. This model is similar to the one proposed by Fleming [2] based on the results of several field tests conducted on different subgrade soils, which is:

$$MFWD= 1.031\ ELWD \qquad (2)$$

As the Dynamic Cone Penetration (DCP) test is concerned, a number of correlations have been developed between the penetration index (DPI) and the Elastic modulus of subgrade.

Chen et al. (2005) found a strong correlation between 30 DCP test results and E_{back} elastic modulus from FWD in mostly clayey and silty soils in Kansas. The DCP results were corrected to take into account the effect of overburden pressure in case of conducting the test through a drilled hole in the asphalt layer [1] with equation 3:

$$Es= 537.8*(DPI)-0.664 \qquad (3)$$

Siekmeier et al. (2009) proposed the minimum required DCPi values to be used for construction quality assurance based on tests conducted on granular and fine-grained soil samples for different range of moisture contents and densities [12] and for those found the relationship with E reported in Equation 4

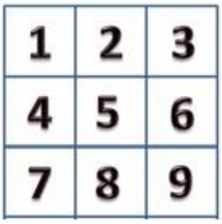
$$E_{DPI}=10^{3.04758-1.06166\log(DPI)} \qquad (4)$$

In this framework, the focus of the present research work is to investigate the viability of in situ tests performed with FWD, LWD and DCP for deriving the Elastic modulus of pavements' subgrade. To this aim via the correlation between FWD, LWD modulus and DCP index was tested and validated. The interpretation of in situ tests were supported by laboratory tests.

II. IN SITU TESTS OF SUBGRADE MODULUS

The tests were carried out at the University of Catania Campus. The site is characterized by alluvial deposits of different depositional environments, consisting in an alternating sequence of silty-clayey layers of alluvial plain and volcanic rock at the basement.

The test area has a surface of 2.5 x 2.5 m subdivided in 9 sampling points as described in Figure 1.



1	2	3
4	5	6
7	8	9

Fig. 1. Test point codes

Several conventional laboratory tests were performed. These include determination of grain size distribution, index properties, shear strength and resilient modulus. The gradation characteristics of each sample were investigated by performing sieve analysis, according to ASTM method. Figure 2 shows the grain size distribution curves for all samples tested

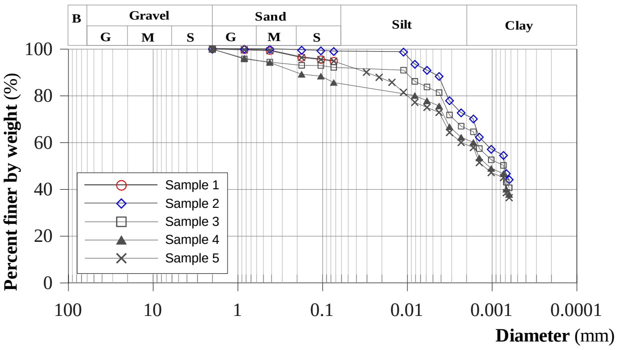


Fig. 2 Grain size distribution curves of sample tested.

The specific gravity Gs is varying from 2.71 to 2.74. The values of the natural moisture content wn range from between 18.46 and 24.04 %. Characteristic values for the Atterberg limits are: wL = 58.07 – 61.91 % and wP = 30 - 40 %, with a plasticity index of PI = 23 - 30 %. The laboratory results indicate a reasonable degree of homogeneity of the deposit.

III. THEORETICAL BACKGROUND

To define subgrade soil stiffness dynamic loading plate test were performed. These include Falling Weight Deflectometer (FWD) Light Weight Deflectometer (LWD).

Boussinesq developed a set of equations to calculate the stress, strain and displacement conditions in a homogeneous, isotropic, linear elastic semi-infinite space under a circular loading area. The modulus of a semi-infinite space may be evaluated from:

$$E=\frac{f\cdot\left(1-\nu^{2}\right)\cdot\sigma_{0}\cdot a}{d_{0}} \qquad (5)$$

where: E is the surface modulus, f is a factor that depends on the stress distribution, ν is the Poisson's Ratio, σ0 is the pressure under loading plate, a is the radius of the loading plate and d0 is the deflection at the center of the circular load.

If the subgrade is non-linear elastic then using a linear elastic approach may result in incorrect layer moduli. A typical outcome is that the modulus of the subgrade is overestimated.

Mallela & George (1994) [6] showed that when measured stresses and strains were compared to theoretical values it was found that a static analysis, assuming a non-linear subgrade, gave the best agreement.

Subgrade non-linearity was investigated by Ullidtz [9] and can be expressed by using the following formula:

$$E=C\cdot\left(\frac{\sigma_{1}}{p_{a}}\right)^{n} \qquad (6)$$

In Equation (6) σ_1 is the major principle stress from the external loading, i.e. excluding any static stresses due to the weight of the material, and pa is a reference stress, often taken equal to atmospheric pressure (0.1 MPa). The purpose of the reference stress is to avoid having units raised to a power different from 1. C and n are constants.

Under this assumption, it was also found that the strains and displacements in the non-linear elastic half-space could be calculated using Boussinesq's equations for the center line, under a point load P, with the modulus substituted by a non-linear function of the major principal stress. As result, a plate loading test on the surface of a material with the modulus described by Equation (5) would give the surface modulus:

$$E_0 = (1-2n)\cdot C\cdot\left(\frac{\sigma_0}{p_a}\right)^n \qquad (7)$$

where σ_0 is the uniformly distributed stress under the plate.

The nonlinear behavior of the subgrade was investigated by the way of triaxial test in the laboratory.

Since the pavement subgrades are subjected to a series of distinct load pulses, a laboratory test duplicating this condition is desirable. In the laboratory tests that were carried out, cylindrical specimens of soil were subjected to a series of cyclic loading with different deviatoric stress, simulating the multiple wheels moving over the pavement. A constant confining pressure applied on the specimens simulated the lateral stresses caused by the overburden pressure and the applied wheel load. The recoverable axial deformation of the specimens due to the cyclic loading was used to calculate the resilient modulus of the material. Axial deformation of the specimen was recorded by two externally mounted Linear Variable Differential Transducers (LVDT). Some plots of cyclic triaxial laboratory tests relating axial strain and deviatoric stress are shown in Fig. 3.

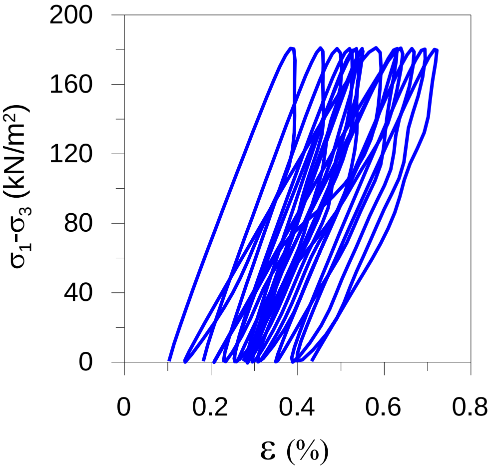


Fig.3. Triaxial test results. stress-strain curves

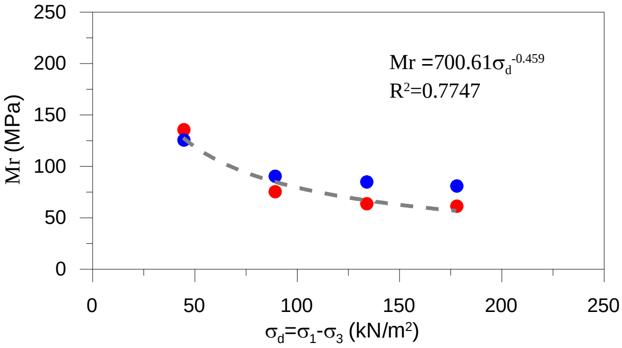


Fig.4 Triaxial test results. Resilient Modulus vs. Deviator Stress

Fig. 4 shows the variation of the resilient modulus with the applied deviator stress, ranging from 50 to 180 kPa.

A reduction in the resilient modulus is out lied by the regression curve.

IV. LOADING PLATE TEST

Both FWD and LWD test were performed in the present study (Figure 5a and 5b).

The FWD is a non-destructive field test which is designed to simulate deflection of a pavement surface caused by a fast-moving truck. The device simulates the load conditions of a heavy vehicle and estimates the pavement's response by measuring the basin of deflection using sensors fixed on a beam. The conventional FWD is able to apply loads in the range of 7-140 kN, even if the standard load used for structural pavement analysis is usually 30-50 kN that giving about 700 kPa pressure under the load plate. The device allows a variable weight to be dropped from a variable height and the load is applied to the pavement through a circular loading plate and weights from 50 to 450 Kg. The generated duration of the half sine pulse is typically 30 ms, corresponding to the loading time produced by a truck moving at 40 Km/h. The FWD used in the present study is the Dynatest 8000 equipped with a loading plate of 300 mm diameter and 15 geophones with a different offset from the loading plate (the farthest is located at 2100 mm on the beam), a load of 150 kg and heights able to produce a stress of 230-240 kPa.

Due to the dimension of the equipment only position 2, 5 and 8 were tested with FWD.

The light weight deflectometer (LWD) [4] is a hand portable device that was firstly developed in Germany to measure the soil in situ LWD dynamic modulus. The standard LWD device is equipped with one geophone positioned in the center of the plate. Typical load varies from 10 to 20 kg, while the plate diameter can be of 15, 20 or 30 cm. The advanced devices used in the present work (Dynatest 3031) is equipped with 2 additional geophones that can be used for measurement of deflections outside the loading plate and an additional load cell positioned under the loading plate. The LWD tests were conducted with two configuration of plate diameter: 150 mm and 300mm with a weight of 15 Kg and respectively a height of 13” and 17”.

The types of devices provided with the load cell and geophone are able to acquire the load-deflection time histories, sampling data every 0.25 ms, with a great level of accuracy. LWD data are mainly used to calculate Surface Modulus of the tested materials by means of Boussinesq equation; more recently some particular procedures, specifically developed to estimate the material compaction level achieved on site, are also starting to be used [5].

LWD test was performed in each of the 9 positions.

Basing on the triaxial laboratory tests, a no-linearity for the subgrade was assumed for determining the elastic modulus E with loading plate in situ tests.

From the exponent of the regression equation reported in figure 6b, a value of n=-0.46 can be assumed as seed value in the calculation of the moduli. Seed values are the start values in the iteration procedure that uses the results of load and deflection of FWD and LWD in situ test. It is therefore important to enter these values as realistic as possible.

Analogously, the stress distribution factor f was assumed equal to π/2, according to the literature for stress distribution on cohesive soils.

C. Dynamic Cone Penetrometer

The Dynamic Cone Penetrometer (DCP) consists of two 16-mm diameter shafts coupled near midpoint. The lower shaft contains an anvil and a pointed tip which is driven into the soil by dropping a sliding hammer contained on the upper shaft onto the anvil (Figure 5c). The soil deformability is determined by measuring the penetration of the lower shaft into the soil after each hammer drop. This value is recorded in millimeters (inches) per blow and is known as the DCP penetration index (PI). The penetration index can be plotted versus depth to identify thicknesses and strengths of different pavement layers or can be correlated to other soil parameters such as the California Bearing Ratio (CBR) [7] and the Modulus of subgrades. DCP test was performed in each of the 9 positions.

D. Result of in situ tests

The results of in situ tests are reported in Table 1 for the test positions n. 2, 5 and 8 as regards to FWD and for the test positions from 1 to 9 for LWD and DCP.

Looking at the results, there is good agreement between the moduli computed with FWD and LWD tests. This latter was used in a double configuration with plate diameters of 150 or 300 mm. Figure 6 reports the correlation between FWD and LWD calculation of moduli. Both the FWD and LWD moduli were computed by using a no-linear response of the subgrade. Load, deflection at the center of the plate recorded for each of the test positions and E modulus with parameters C, n carried out by the back-calculation are reported in Table 1.

As far as the DCP test is considered, Table 1 reports the results of the DCP tests on the same test position of the LWD tests.

Equations 8 and 9 and Figure 7 show the correlation between the LWD with the 300 and 150 mm plate configuration respectively and the penetration index (DPI) evaluated from DCP test. According to ASTM D6951-03, a cumulate of penetration each 5 blows for normal soil was used for the computation of DPIs. The average value of DPIs for a total depth of 60 cm (excluding the first series of seating blows) was considered for comparison with LWD.

In agreement with the literature, acceptable correlations were identified between log(E) and log(DPI):

$$E_{DPI(300mm)}=10^{1.528-0.0841\log(DPI)} \quad (8)$$

$$E_{DPI(150mm)}=10^{1.6433-0.2098\log(DPI)} \quad (9)$$

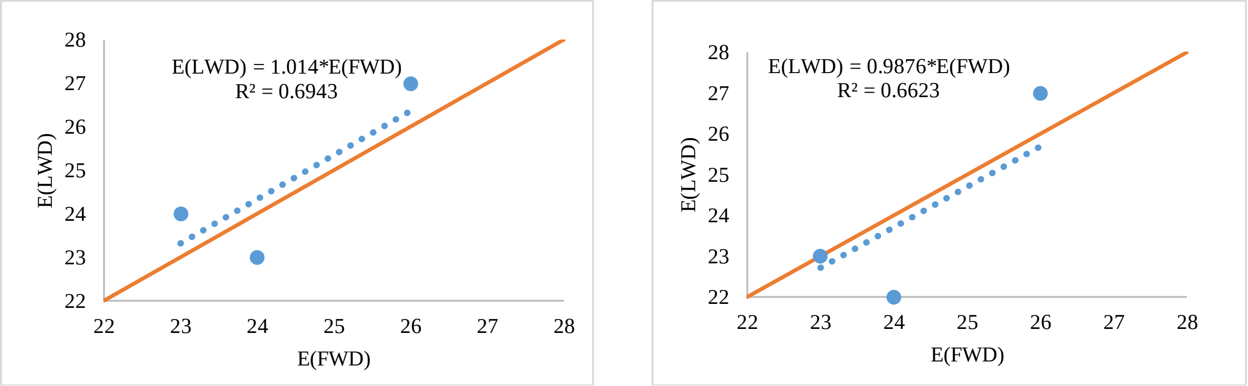
The highest R^2 was found for the correlation with the 300 mm loading plate. This result can be justified by the deeper stress distribution produced by larger plates which involves a subgrade depth more comparable with the DCP penetration in the soil.

a) *b)* *c)*

Fig.5. Equipment used for in-situ tests a) FWD; b) LWD and c) DCP

Table 1. FWD and LWD results based on Boussinesq Theory.

	FWD (300)				LWD (150)				LWD (300)				DCP
Position	Stress (kPa)	E (MPa)	C	n	Stress (kPa)	E (Mpa)	C	n	Stress (kPa)	E (MPa)	C	n	DPI (mm/blow)
1	-	-	-	-	397	26	55	-0.55	159	34	42	-0.43	-
2	238	26	30	-0.15	404	27	50	-0.45	151	27	30	-0.28	28.50
3	-	-	-	-	414	27	50	-0.43	159	20	23	-0.35	25.00
4	-	-	-	-	410	28	45	-0.34	158	21	25	-0.34	19.00
5	234	23	31	-0.36	406	24	44	-0.42	159	23	27	-0.33	13.00
6	-	-	-	-	390	22	42	-0.49	153	17	20	-0.4	-
7	-	-	-	-	412	31	65	-0.52	161	36	46	-0.5	3.45
8	239	24	28	-0.18	398	23	27	-0.33	158	22	42	-0.49	31.00
9	-	-	-	-	158	35	50	-0.26	159	26	32	-0.47	15.00



a)

b)

Fig. 6. Subgrade moduli: a) Comparison of FWD and LWD (150); b) Comparison of FWD and LWD (300).

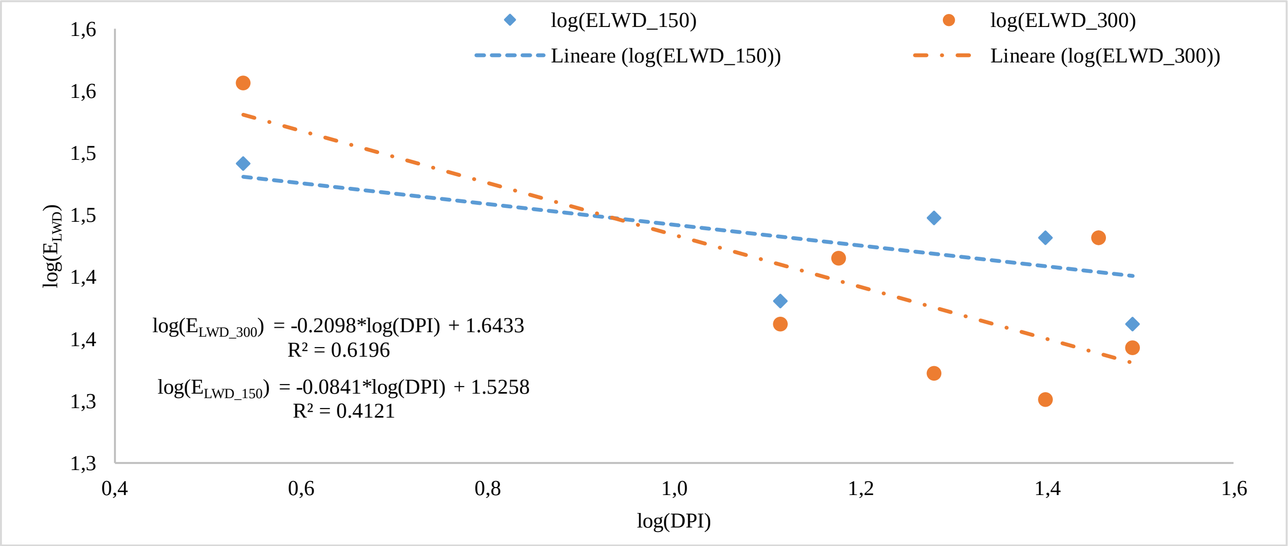


Fig. 7. DPI-Modulus correlations.

V. CONCLUSIONS

Resilient modulus of subgrade soil is an important material property, a requisite parameter to input in the design of pavements with mechanistic approaches. equation.

For many years the repeated load triaxial compression test (AASHTO TP 46) has been the basic test procedure to evaluate resilient modulus of cohesive and granular materials for pavement design applications. Despite several improvements made over the years, Seed et al. [11] cited a series of uncertainties as well as limitations associated with the test procedure. Because laboratory resilient modulus sample is not completely representative of in-situ conditions because of sample disturbance and differences in aggregate orientation, moisture content and level of compaction, an in situ determination test may be more representative.

Results pointed out a good correlation among different in situ devices which can be used to determine directly (e.g. FWD, LWD) or indirectly (e.g. DCP) the subgrade modulus. The use of triaxial laboratory test can be complimentary to the in situ test as proposed in the present paper to determine the soil proprieties and behavior. It is possible, also, to check the assumption that the measurements are done on a semi-infinite, linear elastic half space by measuring the deflections at different distances from the load. For this application, the system must be equipped with more geophones than the center plate one. This configuration is typical for FWD but less diffused for LWD. LWD equipment showed its high usability in sites with accessibility restrains for heavier and larger equipment like FWD. DPI, has the advantage to explore the soil more in depth, but needs an in site pre-calibration to determine the subgrade modulus. To this aim LWD test with larger loading plates (e.g. 200-300 mm diameters) are recommended.

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