Evaluation of PFWD and DCP as Quality Control Tools for Sub-Grade of GW and SW Soils

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Abstract

The Stiffness modulus is one of the necessary inputs in mechanistic-empirical pavement design and Quality Assurance/Quality Control (Q_A/Q_C) of pavement layers construction. The use of Portable Falling Weight Deflectometer (PFWD) for measuring the stiffness modulus of unbound pavement layers is increasing worldwide. The modulus can also be indirectly calculated by the results of other available devices. The Dynamic Cone Penetrometer (DCP) is an easy-to-access device for evaluating the strength of unbound pavement layers in a cheap, easy and fast way. In this study, the stiffness modulus of PFWD and penetration rate of DCP was correlated for the sub-grades ranging from well-graded sand (SW), which is highly consisted of SiO_2 and Al_2O_3, and well-graded gravel (GW) classification. In addition, the results indicated that a good correlation exists between PFWD moduli and DCP results and also for the precise evaluation of the SW soil modulus with a considerable amount of SiO_2 and Al_2O_3, a coefficient factor, of $C = 2.39$, was presented.

Keywords: Stiffness Modulus; PFWD; DCP; mechanistic-empirical; Q_A/Q_C .

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1. Introduction

Quality pavement foundation layers are critical for achieving excellent pavement performance. Stiffness and strength of the soil are considered as essential and relevant engineering and mechanical properties in both design and construction of earthworks, while soil density and water content are necessary physical measurements during the construction process. However, soil prepared at the same density and water content may have different stiffness and strength, which are dependent on several factors, including the state of stress, strain level, boundary condition, and fabric of the soil [Chen et al., 2005, Cho and Santamarina, 2001, Duffy and Mindlin, 1956, Holtz, Kovacs and Sheahan, 2011, Hossain and Apeagyei, 2010]. The fundamental material property, stiffness modulus, is a key input in the new mechanistic empirical-based design, which cannot be obtained from density and moisture content measurements [Van Gurp, Groenendijk and Beuving, 2000]. This value can be determined in a direct or an indirect way depending on time and facilities. Since laboratory test procedures are expensive and complex, the direct field tests have been proposed [Ahmed and Khalid, 2011]. There is a wide range of devices such as Falling Weight Deflectometer (FWD) used for direct estimation of pavement layers stiffness. FWD as a direct measurement of the performance parameters of the foundation materials, as they are constructed in the field, provides a greater assurance of the design and efficiency of site operations [Brown, 1996, Fleming and Rogers, 1995, Lambert, Fleming and Frost, 2006, Rahim and George, 2003]. Some studies suggest that a Portable (PFWD) could as well accomplish the same objective as that realized by conventional FWD, at a fraction of the cost [Fleming, Frost and Rogers, 2000 , Fleming et al., 2002, Gudishala, 2004, Phillips, 2005]. The PFWD is gaining acceptance and popularity as an in situ spot-testing device for Q_A/Q_C of earthwork compaction [Mooney and Miller, 2009]. On the contrary, stiffness modulus value can indirectly be estimated by available equations and results of other tests like CBR or DCP. Several works have been conducted in the last decade to assess PFWD measurements, to evaluate the influence of some relevant parameters such as temperature, moisture content, grading and compaction, or to correlate the PFWD modulus with other test results such as FWD and CBR [Benedetto, Tosti and Di Domenico, 2012]. To cite a few of these studies, for a wide range of granular and cohesive materials, the US Army Corps of Engineers found a relationship described in Eq. (1) [Webster, Grau and Williams, 1992].

$$\mathrm{LogCBR} = 2.465 - 1.12\,\mathrm{LogPR}$$
$$\text{or} \quad \mathrm{CBR} = \frac{292}{\mathrm{PR}^{\frac{1}{12}}} \qquad \mathrm{R}^2 = 0.92 \tag{1}$$

Chen et al. (2001) used Eq. (1) to compute CBR and then used Eq. (2) to calculate FWD modulus.

$$M_R\ (psi) = 1500 \times CBR$$
$$or\ M_R\ (MPa) = 10.34 \times CBR \tag{2}$$

There is an acceptable relationship between E_{PFWD} and CBR for different soils [Nazzal, 2003]:

$$\mathrm{CBR} = -14.0 + 0.66\mathrm{E}_{\mathrm{PFWD}}$$
$$12.5\mathrm{MPa} < PFWD < 174.5MPa \qquad \mathrm{R}^2 = 0.83 \tag{3}$$

where PR is the penetration through the layer in millimeters. In this study, comprehensive field and laboratory experiments were performed to assess the engineering properties of well-graded sandy and gravelly soils using non-destructive and penetration tests. PFWD and DCP were conducted on the test materials and therefore a new empirical equation is suggested for estimating stiffness modulus of compacted soil. The main objective of the present work was to assess the limitation of previous works in modulus estimation of the SW soils with a high amount of SiO_2 and Al_2O_3. Therefore, a coefficient factor for the modification of PFWD modulus extracting from empirical equations based on CBR or PR was presented for this type of soil.

2. Experimental Program

All tests were performed on compacted and well-prepared sub-grades in the true scale of the field in order to reach a realistic and functional model for unbound pavement layer modulus evaluation. Through a series of tests, PFWD modulus, DCP penetration-rate, water content, density and soil classification of three strips of sub-grades, samples coming from 8 different points in each sub-grade, were measured.

3. Devices

3. 1. Portable Falling Weight Deflectometer (PFWD)

The elastic stiffness modulus of the sub-grade soil foundation is estimated from the measurement of the surface deflection due to impact loading applied to the sub-grade by Employing PFWD device[2] [George, 2006]. In the current test program, a 300-mm diameter rigid plate (with center opening of 40 mm) is employed, though in calculations the presence of the center hole is disregarded. While employing a 10-kg sliding hammer, the height of fall is adjusted to 7.7 (kN) and 10.9 (kN) forces, successively. The corresponding contact stresses underneath the bearing plate were about 109 (kPa) and 158 (kPa), respectively. The duration of the recorded force and deflection signals was set to 60 (ms). The peak values of load and deflection are employed in the software for calculating the elastic stiffness modulus, E from Eq. (4) [Fleming, Frost and Lambert, 2007].

$$E = \frac{A.P.r.\left(1-v^2\right)}{D} \tag{4}$$

Where:
E = stiffness modulus (MPa)
A = plate rigidity factor, default = 2 for a flexible plate, Π/2 for a rigid plate.
P = maximum contact pressure (kPa)
r = plate radius (m)
D= peak deflection (mm)
v = Poisson's ratio (usually in the range 0.3-0.45 depending on test material type)

3. 2. Dynamic Cone Penetrometer (DCP)

DCP was initially developed for in situ evaluation of pavements in South Africa [Kleyn, Maree and Savage, 1982]. This device is used as an acceptable test for evaluation soil strength in many parts of the world. In this study, the DCP was used as a standard test for comparison with the PFWD. The DCP is a simple, fast, and economical test that can provide continuous measurements of the in situ strength/stiffness of pavement layers and sub-grades. The test was conducted by dropping an 8 kg mass from 575 (mm) height and recording the number of blows versus depth. The penetration rate (PR) was calculated (mm/blows) based on PFWD influence depth.

4. Materials

Tests were performed on two sub-grades of GW (well-graded gravel and gravel-sand mixture) group and a sub-grade of SW (well-graded sands and gravelly sands) group, in accordance with Unified soil classification, in order to be suitable representatives of well-prepared sub-grades.

5. Experimental Results

The research was conducted on three compacted sub-grades, twenty four points. PFWD modulus, DCP penetration rate, and other physical properties were measured in eight points of each sub-grade. Every PFWD modulus on the Table1 is an average of five drops. The influence depth of PFWD based on the size of loading plate, drop height and falling weight is about 270-290 (mm) and DCP total penetration was considered in this range. ASTM E2583-07 and ASTM D6951 are applied for PFWD and DCP tests, respectively.

The X-ray test was done on the sub-grade from the SW range for figuring out the chemical components of the material. The test justifies the high values of PFWD module of the SW. The chemical property of the SW was determined by X-ray analysis and the result is reported on Table 2 and Figure 1, X-ray tests show that the SW soil is consisted of % 64.824 and %21.215 of SiO_2 and Al_2O_3, respectively.

6. 3D-FEM Verification

The finite-element technique proposes a robust tool for developing models for assessment of pavement deflections produced by FWDs. Even though three-dimensional (3D) finite elements models can handle the problem which can be solved by two-dimensional (2D) models, it is very expensive to develop 3D models in terms of data preparation and computational time [Desai, 2002]. With regard to the geometry and load conditions, asymmetric 2D model was developed and analyzed by the finite elements software, ABAQUS. The boundary conditions and the mesh size of the FE model are shown on the Figure 2.

Deflection is the response of pavement layers in the impulse non-destructive testing system. Comparing this response with the output from finite elements model is necessary for verifying the data collected in the field by PFWD. Therefore, Table (4) demonstrates all deflections derived from FE model and deflections measured by PFDW in the field. For example, at point No. sixteen, the difference between the deflection measured in the field by PFWD, 0.0921 (mm), and the deflection, calculated by the finite elements model, 0.1050(mm), was negligible. This little difference is because of the time gap between load and deflection peak which is shown in Figure 3(a).

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[2] TML Model Japan

Back-calculated modulus and as such finite elements analysis are influenced by this time gap.

7. Regression

The regression analysis for the GW soils, which was performed to find the best correlation between the E_{PFWD} values and PR_{DCP} yielded the following regression model:

$$E_{PFWD} = 240.32 - 82.92 \ln(PR) \quad 2.6 < PR < 11.8 \quad (5)$$

With R^2= 0.933, significance level < 99.9%, and standard error =5.524.

For the SW soil, the above equation can be used with a correction factor of C=2.39.

8. Discussion

Previous works were partial to estimate the correct E_{PFWD} values of the SW soils with stiff components. By having DCP values and Equations (1) and (2), the E_{PFWD} values are calculated. This estimation can prove that other previous studies are appropriate for estimating near values of E_{PFWD} except the SW soil which is studied in this research. According to X-ray test results, percentages of SiO_2 and Al_2O_3 are high in this SW soil, %64.825 and %21.215, respectively. These components can sharply raise the modulus values of this type of soil. The coefficient factor, C=2.39, presented by this paper, covers the error in module estimation of the SW with these constituents. As it is shown in the table3, there is a little difference between what were measured in the field by PFWD and what were estimated by previous equations for the GW. However, this difference is prominent for the SW which is abundantly made of SiO_2 and Al_2O_3. According to Table 3, after exerting the coefficient factor on the modulus values resulted from Equations (1) and (2), the results have become close enough to field modulus values measured by PFWD for the SW.

9. Conclusion

A series of tests was performed by using two portable devices for measuring soil in-situ module. Each test device was used on three different compacted and prepared sub-grades, two of which were from the same soil classification, GW, and the third one was from SW group based on unified soil classification. The SW is mainly consisted of SiO_2 and Al_2O_3.The conclusion from the results derived is summarized as follows:

- Existence of some materials in the soil can have serious effects on the elastic modulus of the material. It is found out that SiO_2 and Al_2O_3 are the cause of high range of PFWD module of the SW soil which is studied in this research.
- Former studies in the related field did not consider any coefficient for calibration of their proposed equations regarding different types of materials. The coefficient factor (C=2.39), which is presented in this study, covers the lack for calculating the correct module of the SW with a high amount of SiO_2 and Al_2O_3.
- DCP is a suitable and cost-effective tool for evaluating in-situ unbound pavement layers.
- As it is shown in Figure 4, the Equation (5) is appropriate for estimating in-situ modulus of by possessing penetration rate of DCP for different types of granular soils.

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