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EVALUATION OF PFWD AS POTENTIAL QUALITY CONTROL TOOL OF PAVEMENT LAYERS

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Abstract. Portable Falling Weight Deflectometer (PFWD) that can be considered as simple equipment is mainly used to measure elastic moduli of pavement unbound layers. This paper evaluates the potential use of PFWD to reliably measure the elastic modulus of pavement layers. To achieve this, PFWD tests were conducted on highway sections selected from different projects in Tehran. The California Bearing Ratio (CBR) laboratory tests were also conducted on samples collected during field tests. PFWD testing parameters were varied while performing the field testing. These included drop weight, drop height, plate diameter and position of additional geophones. In addition, PFWD moduli were compared with those obtained from performing FWD testing on the same site. It was found that drop mass and loading plate size affect PFWD modulus significantly. In addition, the results indicated that good correlation exist between PFWD moduli and FWD and CBR results.

Keywords: Quality Control, Elastic Modulus, PFWD, CBR.

1. Introduction

Current criteria for pavement evaluation and design rely on characterizing pavement structural layers with either California Bearing Ratio (CBR) values or back-calculated moduli from Falling Weight Deflectometer (FWD) tests. However, CBR testing is time-consuming for rapid assessment and FWD is not commonly used on unsurfaced pavements, as the trailer-mounted device does not easily access construction sites (Fleming *et al.* 2000). Portable Falling Weight Deflectometer (PFWD) is a light device which can serve as possible alternative replacement. Due to its simplicity in design, portability, and the added advantages of providing quick and reliable estimates of the stiffness modulus, the use of PFWD is gaining popularity in the recent years (George *et al.* 2009). Although multiple versions of these devices have been evaluated in the U.S., Europe, and Japan for quality control during construction, the applicability of using this equipment is relatively unknown.

PFWD, shown schematically in Fig. 1, applies an impact load on the roadway surface and the induced pavement surface deflection is measured simultaneously. This device consists of three main parts: (a) A base with loading plate, sensors, and associated electronics, (b) A 5 to 20 kg sliding hammer, and (c) Upper frame including sensor housing, rubber buffers, and guidance rod (Lin *et al.* 2006). Users have the option of selecting the 100, 200, or 300 mm diameter loading plate to accommodate different soil types and unbound layers. In addition to the main geophone sensor which is located at the centre of the loading plate, two more geophones are located at selected distances from the loading point to measure the deflections of the pavement layers. The depth of influence of PFWD is up to 280 mm depending on the stiffness of the tested materials (Nazzal 2003). Hence, due to the small falling energy, the device can not distinguish between multiple layers greater than this depth.

Based on Boussinesq's theory and assuming constant loading (applied from a PFWD), Equation (1) was used to calculate the pavement composite modulus (Huang 1993):

$$E_0 = \frac{2(1-\upsilon^2)P}{\pi.a.D_0}, \qquad (1)$$

where: E_0 – composite modulus values (MPa); P – applied force at load plate (N); D_0 – deflection at the centre of loading point (mm); a – radius of loading plate (mm); and υ – Poisson's ratio.

However, PFWD elastic modulus depends on several parameters of the instrument including loading drop weight, drop height, plate diameter, plate surface contact and etc that may affect PFWD results (Lin *et al.* 2006; Steinert *et al.* 2006) and is aimed to be investigated in this research.

Several researches have attempted to find correlations between PFWD results with CBR values. Phillips and Freeman (2003), Nazzal (2003) and George *et al.* (2009) showed that there is good correlation between these parameters; whereas, poor correlation was reported in some other research works (Seyman 2003; Phillips 2005). In addition, different correlations have been determined between the PFWD and FWD back-calculation moduli (Steinert *et al.* 2006; George 2006). Hence, the

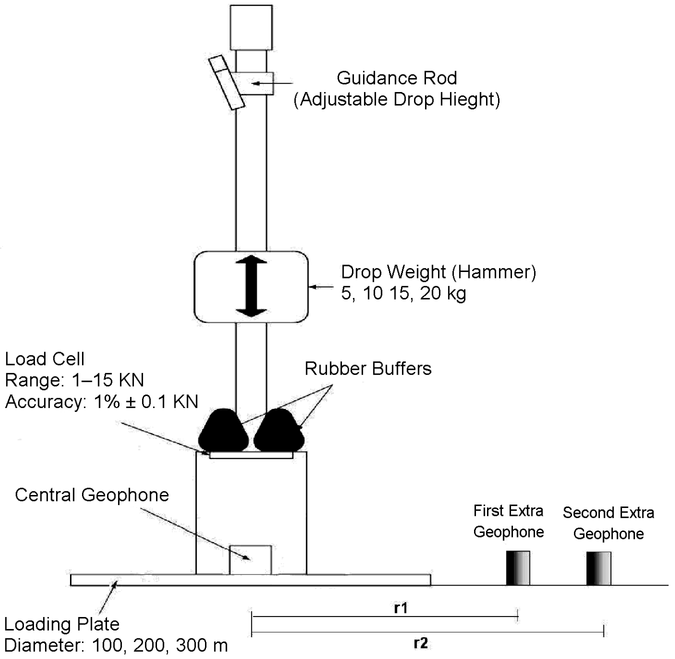


Fig. 1. Schematics of a Portable Falling Weight Deflectometer (Fleming *et al.* 2007)

other objective of this study is to assess the ability of PFWD to accurately measure soil strength in terms of traditional evaluation, namely CBR and FWD.

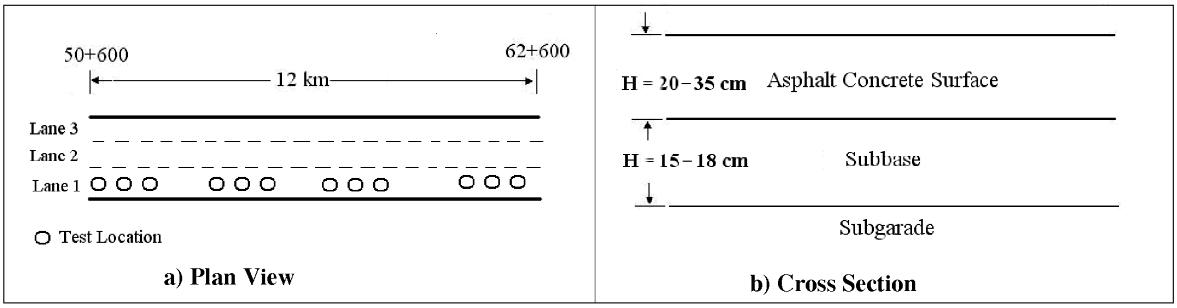
2. Field Testing Program

Field testing was carried out on different unbound base and sub-base layers on several highway construction sites in Tehran. Table 1 reports the general testing conditions and the material characteristics at various projects. The elastic moduli of the compacted layers were determined under PFWD (TML model from Japan) varying test parameters. These parameters included drop weight, drop height, loading plate diameter, and position of external geophones. At each condition, six drops was performed. The first three drops were ignored and the next three were averaged and the result was taken as the PFWD modulus of each layer. In addition, CBR laboratory tests were conducted on twenty five samples collected during field tests.

FWD and PFWD testing were performed separately on several locations of an asphalt surfaced road (Fig. 2). AC surface thickness in the test sections varied between 200 and 350 mm. Both of this devices had similar loading

Table 1. General testing conditions and the material characteristics at various projects

Project	Layer Type	Classification	Number of Test Points	Evaluated Parameters
Kahrizak	Subgarde	A-6	3	Drop Weight, CBR
Azadegan Expressway	Subbase	A-1-a	2	Drop Weight, CBR
Khalij Street	Subbase	A-1-a	2	Drop Weight, CBR
Amamali Expressway	Subbase	A-1-a	4	Drop Height, Plate Diameter
Yadegar Expressway	Subbase	A-1-a	11	Drop Weight, Drop Height Distances of Extra geophones, CBR
	Base	A-1-a	7	
Ghom Freeway	Subbase under AC	A-1-a	12	FWD Back-calculated Moduli



a) Plan View

b) Cross Section

Fig. 2. Test locations at FWD and PFWD testing

plate (300 mm) and geophone spacing (0, 200, and 400 mm), but their drop weight were different. Back-calculated layer moduli were used as the basis for FWD and PFWD comparison purposes.

3. Parameters affecting PFWD modulus

The effects of major parameters affecting PFWD modulus results are reported as it follows:

3.1. Drop weight

PFWD tests were carried out using 5, 10 and 15 kg drop weight in various project sites. The results indicated that for the three weights considered in this research, PFWD moduli were increased with increasing the drop weights as it is shown in Fig. 3.

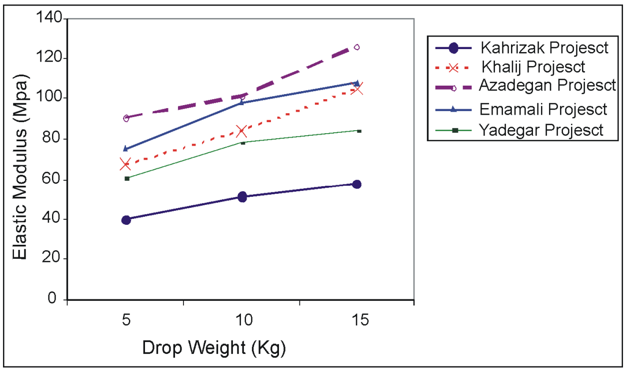


Fig. 3. Effect of drop weight on PFWD moduli

Theoretically, when the heavier drop weight is applied, the instrument weight and the confining stresses are also increased. It seems logical to consider that the greater in the confinement, the greater would be the soil modulus. A general model that can quantify the effects of confinement on the soil modulus is attributed to Kondner (Briaud and Seo 2003). According to this model, the modulus is proportional to a power law of the confinement stress. If it is assumed that the weight of PFWD is in proportion with the confinement stress, the secondary modulus derived from the instrument weight changes (from W_1 to W_2) can be determined from the primary modulus, using Equation (2):

$$E_2 = k(\frac{W_2}{W_1})^a E_1 . \tag{2}$$

Where, “k” and “a” are constant coefficients. The eight of PFWD instrument when a 5 kg drop weight was used was 26 kg. When the drop weight was changed to 10 and 15 kg, the instrument weight was increased to 31 and 36 kg respectively. In this research, based on the primary moduli, using 5 kg drop weight, the secondary moduli (i.e. determined from 10 and 15 kg drop weights) were just calculated using Equation (2) for twenty five testing location. Results from SPSS software showed that the least-squares differences between the calculated and the measured values will be minimized, when “k = 1” and “a = 0.966”. Fig. 4 shows a very good correlation between the calculated muduli and those measured in the field (i.e. $R^2 = 0.97$).

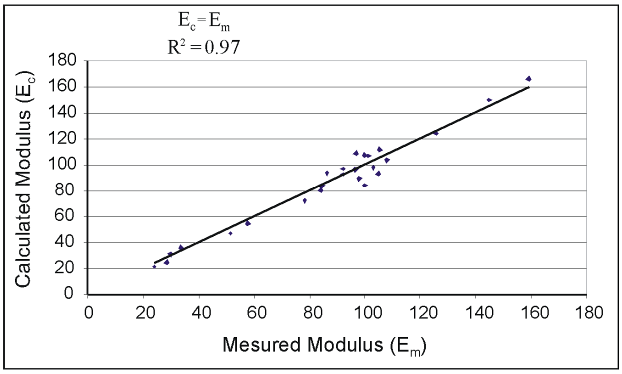


Fig. 4. Correlation between measured and calculated moduli

3.2. Drop height and loading plate diameter

The effects of changing the drop height on PFWD moduli was evaluated in one site using a fixed weight of 15 kg dropped on to a loading plate of 300 mm diameter. Three different drop heights, namely 515, 375, and 275 mm, and two sizes of loading plates, namely 100 and 300 mm diameters were used in another project. The test results illustrated that the moduli remained almost the same regardless of the above drop height variations (Table 2). In fact, the coefficient of variation (C_V) of the moduli were small in different drop heights (C_V <6.4%).

Table 2. The effects of changing the drop height on moduli results

Project	Location	Drop height (mm)			C_V
		515	375	225	
Yadegar Expressway	P1	91	93	N/A	1.50%
	P2	83	78	N/A	4.10%
	P3	96	94	N/A	1.70%
	P4	176	167	N/A	3.80%
	P5	155	150	N/A	2.50%
Amamali Expressway	P1 (Dia = 300 mm)	80	89	90	6.40%
	P1 (Dia = 100 mm)	118	128	121	4.20%
	P2 (Dia = 300 mm)	66	68	63	3.80%
	P3 (Dia = 300 mm)	62	60	58	3.30%
	P4 (Dia = 300 mm)	83	84	83	0.70%

For granular materials, the most significant parameter that influences modulus is the confining stress (Yoder and Witczak 1975). Lekarp *et al.* (2000) also reported that the confining pressure has more effect on granular soils stiffness than deviator stress. Since the variations of deviator stress are significant in different drop heights of PFWD testing, but the confining stress does not vary significantly due to fast rate of loading, the moduli remain almost the same.

The effects of varying the load plate diameters (100 and 300 mm) were evaluated using a fixed drop height of 500 mm and two drop weights of 5 and 10 kg on several locations in the laboratory testing box. As it is shown in Table 3, it was resulted that E_0 modulus determined from 100 mm loading plate was almost 1.85 times greater than that from 300 mm loading plate. In fact, the contact pressure for the 100 mm diameter loading plate is about 9 times greater than that from a 300 mm diameter. Hence, the contact area has a pronounced effect on elastic modulus results.

Table 3. The effects of plate diameter on PFWD moduli

Loading plate diameter (mm)	Point	Load (N)	Pressure (kPa)	Modulus (Mpa)
100	A	4022	512	343
		6080	774	353
	B	3943	502	245
		6091	776	274
300	A	4046	57	188
		6366	90	194
	B	4080	58	130
		6281	89	139

3.3. Position of geophones

In addition to the central geophone, two additional geophones were positioned at different distances from the loading application point. With this arrangement, composite modulus of a pavement with two-layer system can be measured. Sensor positioning on any pavement structure is a function of the layers stiffness and composition. SHRP suggests a uniform sensor configuration for FWD in order to minimize sensor location errors (Rada 1994).

In this research, two additional geophones were located at three different positions of 200–300, 300–450, and 200–450 mm from the centre point and PFWD testing was performed in these geophone configurations. The upper layer modulus (E_1) and the lower layer modulus (E_2) were then calculated based on peak loads and deflections. For this Evercalc computer program was used which has been widely used to back-calculate pavement layers moduli Fig. 5 shows E_1 and E_2 values in the three positioning of the additional geophones. E_1 values are approximately similar for the above three positions (Fig. 5a). This means that the upper layer moduli are independent on the positions of the additional geophones. As it can be seen from Fig. 5b, the moduli of the lower layer (E_2) are very close for both geophones location of 200–450 and 300–450 mm, in contrast with the values for 200–300 mm distances that are different. This implies that if the second geophone is positioned at 300 mm from the centre point, the modulus of the lower layers cannot be measured accurately. Hence, the lower layer modulus varies to some extent with changing the position of the second geophone and 450 mm positioning of the second geophones could be considered to be reliable.

4. Correlation between CBR and PFWD

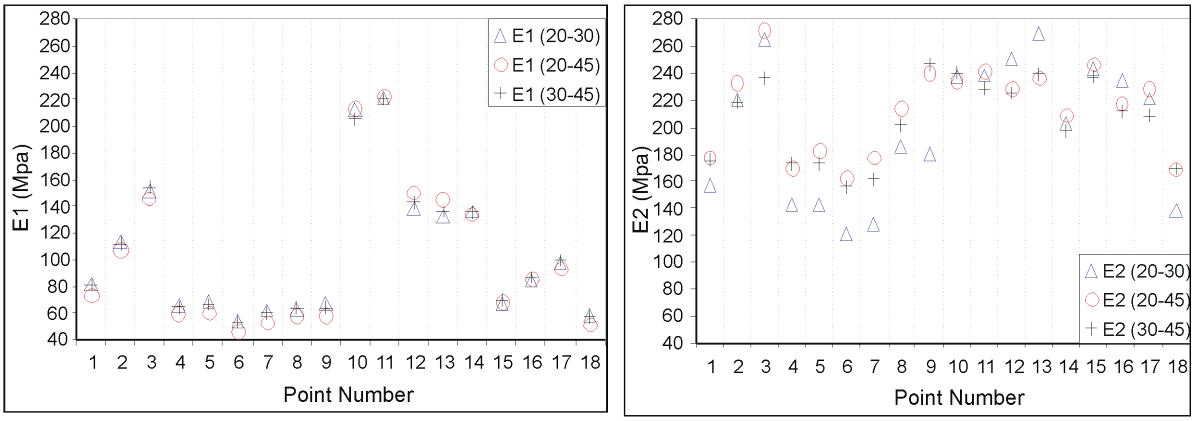
Statistical regression analysis was conducted to develop direct correlations between CBR testing results and PFWD elastic modulus. In this regression analysis, PFWD modulus with 10 kg falling mass and 300 mm plate diameter were considered.

The following linear regression model was obtained between CBR and E_{PFWD} for twenty five testing location:

$$CBR = -5.58 + 0.484\,E_{PFWD}\,, \tag{3}$$

$$R^2 = 0.88 \quad F = 177.54 \quad S_y = 4.59\,.$$

Where, E_{PFWD} is in MPa. R^2 of 0.88 and the calculated value of F = 177.54 being larger than the tabulated F (95, 1, 23) = 4.25. This indicates that there is a reasonably strong correlation between CBR and modulus variables



a) Upper layer modulus (E_1) b) Lower layer modulus (E_2)

Fig. 5. The effect of distances of extra geophones on layers modulus

Also, the calculated t of coefficient of modulus (t = 13.32) is more than the tabulated t (95, 23) = 2.807, indicating significance of this coefficient. A zero intercept regression analysis between CBR and E_{PFWD} resulted in the one-to-one relation of Equation (4):

$$CBR = K.E_{PFWD}. \tag{4}$$

Where, K is the tangent of fit line. With the results in this research a value of K=0.43 was obtained as shown in Fig. 6.

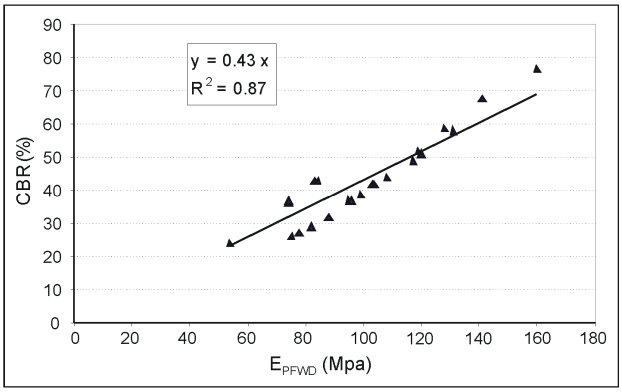


Fig. 6. A zero intercept regression analysis between CBR and E_{PFWD}

In order to compare the K values in different studies, it is necessary to consider two factors. First, PFWD modulus depends to the mass or the self-weight of the drop assembly of PFWD as discussed above. Based on this premise, Nazzal (2003) and Phillips (2005) studies which used 10 kg mass drop and 300 mm load plate of PFWD, are similar to this research.

Second, the number of samples and variations of the measured CBR values affect K value. Nazzal (2003) and Phillips (2005) obtained K = 0.52 and K = 0.32 respectively. It is evident that the values differ greatly with the K value that was obtained in this research (i.e. K = 0.42). Fig. 7 shows variations of CBR values in the above mentioned studies. As shown in Fig. 7, CBR ranges obtained in this study differ with the ranges obtained by the above researches. If the low and high extreme CBR values excluded from their data, this K value will be 0.43 that it is equal to the current study value. Finally, if the values of two previous studies (thirty five samples) are considered with the current research values (twenty five samples) in regression analysis, K value be 0.42 as shown in Fig. 8. With reference to this figure, R^2 of 0.60 and the calculated value of F = 85.46 being larger than the tabulated F (95, 1, 56) = 4.0, validate a good correlation between CBR and modulus. The calculated t = 9.245 is greater than the tabulated t (95, 56) = 2.669 which indicates the significance of modulus coefficient. Hence, K = 0.42 appears to be a reasonable value in regression analysis between CBR and E_{PFWD}.

In addition, if the CBR values of the samples less than 25% are only considered in two above studies, the correlation obtained between CBR and PFWD values will be poor. In other words, the relationship between CBR and PFWD modulus appears to be difficult to be defined for low-strength materials. This could be a reasonable agreement indicating poor correlation between CBR and E_{PFWD} in another study where seventeen samples of all the CBR tests (eighteen samples) had values less than 25% (Seyman 2003).

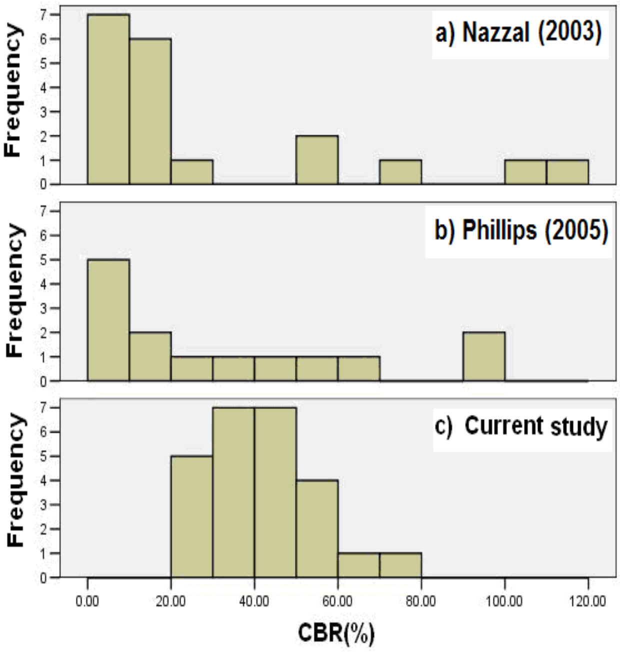


Fig. 7. Variation of CBR values in different studies

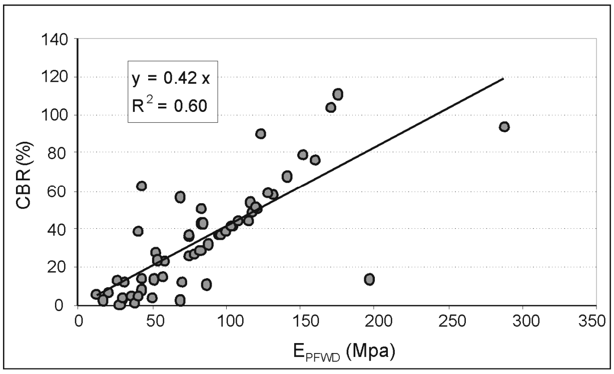


Fig. 8. Linear regression model based on different studies samples

Indeed, CBR test is a strength evaluating testing method for soft materials. This may not correlate well with stiffness parameter for these types of soils. However, for higher quality soils, this correlation improves.

5. Correlation between FWD and PFWD

Since E_{FWD} is generally considered acceptable for in-situ materials characterization, it could be used as a benchmark value for comparison purposes with PFWD results. Back-calculation of pavement layers moduli (AC surface and subbase) was calculated for FWD and PFWD tests and back-calculation subbase layer moduli were used as the basis for their comparison. Fig. 9 shows the results of the regression analysis between the PFWD and the FWD back-calculated moduli. R^2 of 0.74 and the calculated value of F = 25.6 larger than the tabulated F (95, 1, 10) = 4.96, indicates a significant relation between E_{FWD} and E_{PFWD}. This relation suggests that E_{PFWD} on average is 1.76 times the FWD modulus. Steinert *et al.* (2006) reported PFWD modulus was equal to 1.33 times FWD subbase modulus for the thin asphalt surfaced road. They showed that the correlation coefficients between the PFWD and FWD tended to increase as asphalt thickness decreased. However, it is not clear from the work, whether the comparative measurements were at the same contact stress, or to what extent this may influence the results.

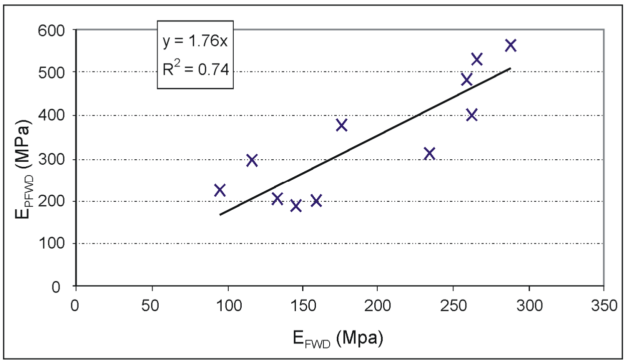


Fig. 9. Relationship between PFWD modulus and FWD modulus

A number of factors influence the measured moduli from the PFWD and FWD including differences in mass, plate diameters, deflection sensor configurations, and load pulse and they lead to variations among different research (Van Gurp *et al.* 2000). In current study, the loading mass parameter was different for the two devices. FWD set up produced 890 kPa contact pressure (applied load of 63 kN), but 90 kPa was the average contact pressure induced by PFWD load of 6.4 kN.

6. Conclusions

The objective of this study was to evaluate the PFWD testing as a potential method to measure in-situ stiffness of highway materials and embankments. Based on the testing results in field projects, the following conclusions can be drawn:

- PFWD moduli increase with increasing drop weight. For the tested drop weights of 5, 10, and 15 kg, the modulus was increased nearly proportional with the increased instrument weight.
- The effect of drop height on PFWD moduli was insignificant. The test results illustrated that the moduli remained almost the same regardless of the drop height variations.
- The size of loading plate has a pronounced effect on PFWD moduli. It was found that the moduli determined using a 100 mm diameter are approximately 1.85 times greater than that of 300 mm diameter.
- Based on back-calculation analysis, the upper layer modulus does not change appreciably upon changing the positions of the additional geophones. However, the lower layer modulus varies to some extent with changing the position of the second geophone.
- The results of the statistical analysis show that good correlation do exist between CBR and PFWD stiffness moduli for CBR within the range 20% to 80%
- A reasonable correlation exists between back-calculation subbase layer moduli of PFWD and moduli determined from FWD measurements on asphalt surfaced roads.
- PFWD can be used to evaluate the stiffness/strength parameters of the different pavement layers and embankments.

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PFWD TAIKYMO KELIO DANGŲ SLUOKSNIŲ KOKYBĖS TYRIMAMS ĮVERTINIMAS

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Santrauka

Nešiojamasis krintančio svorio deflektometras PFWD (angl. *portable falling weight deflectometer*) yra nesudėtingas prietaisas, dažniausiai naudojamas kelio dangų nesurištų sluoksnių tamprumo moduliui nustatyti. Straipsnyje apžvelgta, kaip PFWD naudojamas kelio dangų sluoksnių tamprumo moduliams matuoti. Taikant PFWD išbandyti skirtinguose projektuose Teherane (Iranas) panaudoti kelio dangų skerspjūviai. Bandiniams papildomai atlikti Kalifornijos santykinio atsparumo rodiklio CBR (angl. *California bearing ratio*) nustatymo eksperimentiniai tyrimai. Atliekant lauko tyrimus naudoti skirtingi PFWD bandymų parametrai: krintantis svoris, kritimo aukštis, plokštės skersmuo ir papildomai išdėstyti geofonai. PFWD nustatyti tamprumo moduliai palyginti su tamprumo moduliais, išmatuotais naudojant krintančio svorio deflektometrą FWD (angl. *falling weight deflectometer*). Nustatyta, kad PFWD matavimų rezultatams didelę įtaką turi kritimo masė ir apkrovimo plokštės matmenys. Gauti eksperimentinių tyrimų rezultatai parodė, kad PFWD, FWD ir CBR matavimai gerai koreliuoja tarpusavyje.

Reikšminiai žodžiai: kokybės kontrolė, tamprumo modulis, nešiojamasis krintančio svorio deflektometras, Kalifornijos santykinis atsparumo rodiklis.

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