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ASSESSMENT OF PAVEMENT STRUCTURAL STRENGTH BY THE FALLING WEIGHT DEFLECTOMETER

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Abstract. The main objective of the research project was to derive the equation for calculating the pavement equivalent E-modulus on the basis of the Falling Weight Deflectometer (FWD) deflection measurement data to be used in the Estonian Pavement Management System (EPMS) for network and project level analysis so, that the determined values are comparable with the Estonian flexible pavement design procedure 2001-52. In 1999, 32 and in 2001 additional 19 FWD test sites were chosen on actual pavement structures to perform FWD measurements annually, once or twice per month from early spring until late autumn. FWD measurement data were analysed mathematically and the results were compared with the Estonian flexible pavement design procedure.

The research project results in the following:

- The quantitative methodology for evaluating the qualitative characteristics of the pavement is determined on the basis of the Cobb-Douglas equation, taking into account at a time practically an unlimited number of factors influencing the pavement structural condition.
- The relationship between the pavement equivalent elastic modulus calculated according to the Estonian flexible pavement design procedure 2001-52 and based on the FWD measured deflection is determined. The equation for calculating of the pavement equivalent E-modulus on the basis of the FWD deflection data to be used in the EPMS is derived.

The correction factors for the pavement equivalent E-modulus, taking into account the month of the FWD measurement performance, moisture conditions and road embankment height at the FWD test site, are mathematically based on statistical data determined for Estonian conditions.

Keywords: flexible pavement, E-modulus, Falling Weight Deflectometer (FWD), Cobb-Douglas equation.

1. Introduction

Since 1996 the Falling Weight Deflectometer (FWD) is used to characterise the bearing capacity of pavement structures in Estonia. Pavement equivalent elastic modulus is calculated based on the measured deflection using the formula, which was developed at the time when the experience and knowledge about the FWD operation and performance in Estonia were insufficient. That led to big differences in the results of the calculated pavement equivalent E-modulus values on the basis of measured deflections and values calculated using the Estonian flexible pavement design procedure 2001-52 [1]. The main objective of the research project is to derive an equation for the calculation of the pavement equivalent E-modulus on the basis of the FWD deflection measurement data to be used in the Estonian Pavement Management System (EPMS) for network and project level analysis so that the determined values were comparable with the Estonian 2001-52 procedure.

In 1999, 32 test sites were selected and in 2001 additional 19 sites were selected to perform FWD trial measurements on actual pavement structures. Such measurements were performed annually from early spring until late autumn once or twice monthly. The purpose of the these measurements, performed throughout a year (except for the period when the road structure is frozen) was to find a correlation between the deflections measured at any time of the year and the deflection at the weakest period (usually in spring just after the road structure had thawed). Also, a need exists to calculate the pavement equivalent E-modulus values using FWD deflection measurement data compatible with the Estonian 2001-52 procedure, as those deflection-based back-calculated equivalent E-modulus values are used by the EPMS in the pavement condition evaluation, using criteria determined by the requirements compatible with the Estonian 2001-52 procedure.

2. Pavement equivalent E-modulus calculation

The basic equation for back-calculation of pavement equivalent E-modulus (E_{eq}) used by the most flexible pavement procedures is based on the derivation of Boussinesq's equations [2], which is expressed in the VSN 46-83 (the previous Soviet Union flexible pavement design procedure, which derivation of the Estonian procedure 2001-52 is) as follows (in the case the loading plate is used for determining the deflection) [3] (Eq (1)):

$$E_{eq} = \frac{0{,}25\pi FS(1-\nu^2)}{d_0}, \tag{1}$$

where E_{eq} – pavement equivalent E-modulus at the centre of the loading plate, MPa; F – contact pressure under the loading plate, kPa (measured by the FWD); S – diameter of the loading plate, mm (for the Dynatest FWD 8000 device $S = 300$ mm); ν – Poisson's ratio (in Estonian 2001-52 procedure $\nu = 0{,}3$); d_0 – deflection at the centre of the loading plate, mm (measured by the FWD).

2.1. Calculation of pavement equivalent E-modulus according to the procedure 2001-52 [1]

The VSN 46-83 [3], which is the basis for the procedure 2001-52, includes the equation for the calculation of the equivalent elastic modulus of consecutive pavement layers (E^*_{eq}) (Eq (2)):

$$E^*_{eq} = \frac{E_1 \times \left[1{,}05 - 0{,}125 \times \frac{h}{d} \times \left(1 - \sqrt[3]{\frac{E_2}{E_1}}\right)\right]}{0{,}71 \times \sqrt[3]{\frac{E_2}{E_1}} \times \arctan\left(1{,}35 \times \frac{H}{d}\right) + \frac{E_1}{E_2} \times \left(1 - \frac{2}{\pi} \times \arctan\left(\frac{H}{d}\right)\right)}, \tag{2}$$

where

$$\frac{H}{d} = 2 \times \frac{h}{d} \times \sqrt[3]{\frac{E_1}{6 \times E_2}}, \tag{3}$$

h – thickness of the top layer of the two-layer system, cm; d – diameter of the tire print, cm; E_2 – (equivalent) E-modulus of the neither layer of the two-layer system, MPa; E_1 – E-modulus of the top layer of the two-layer system, MPa.

The calculations of the E^*_{eq} by the equation (2) did not provide the same results as those performed by the nomograph presented in the same VSN 46-83. Prof Maano Koppel from Tallinn University of Technology performed numerous calculations to adjust the equation (2) to the VSN 46-83 nomograph and suggested the use of the modified Mazurov's equation (4) for the calculation of the coefficient M_m for adjusting pavement equivalent elastic modulus:

$$M_m = 1 - 1{,}1e^{-2.5\frac{E_2}{E_1}}\left[\frac{0{,}045}{0{,}4 + \frac{h}{d}}\sin\left(\frac{3{,}58\frac{h}{d}}{e^{0{,}65\frac{h}{d}}}\pi\right) + \frac{0{,}1}{e^{\frac{10h}{d}}}\right] +$$

$$0{,}05 - 0{,}05\left(\frac{h}{d} - 1{,}1\right)^2. \tag{4}$$

As a result, pavement equivalent elastic modulus E_{eq}, used in the procedure 2001-52 can be calculated using equations (2), (3) and adjusted with coefficient M_m, calculated by equation (4):

$$E_{eq} = M_m \times E^*_{eq}. \tag{5}$$

2.2. Influence of different factors on the pavement E-modulus

2.2.1. Influence of FWD loading time on the pavement E-modulus

It is established in the VSN 46-83 procedure that the loading time of the specimen during the laboratory determination of its E-modulus is 0,1 seconds. The VSN 46-83 procedure also describes the device of dynamic loading of the pavement (UDN) with the loading time 0,02–0,03 seconds. The loading times of two different E-modulus determination methods differ about four times. German norms are stipulating that the loading time during the E-modulus determination influences the E-modulus value of bituminous pavements – the FWD deflection based E-modulus value is to be reduced to achieve the E-modulus value comparable with the value determined at the loading time 0,1 seconds, using the correction factor K_{lt} calculated by [3]:

$$K_{lt} = \left(\frac{0{,}1}{t}\right)^{0{,}33}, \tag{6}$$

where t – loading time of the FWD, sec.

According to the manufacturer of the Dynatest FWD 8000 device no “definite” procedures for determining the loading time are available. A method used involves the calculation of a period between two times where the load signal recorded by FWD passes 5 % of its peak value (Anders Sorensen, Dynatest Denmark A/S, unpublished data). For example, if the load peak value is 746 kPa, 5 % of it is approx 37 kPa. Using the FWD recorded load development data imported into the Microsoft Excel file, the table line numbers closest to 37 kPa are 75 and 195. The difference is 120, and, as FWD is recording load development data after every 0,2 milliseconds, loading time can be calculated as 120 × 0,2 = 24 msec.

Technical Centre of Estonian Roads Ltd has determined the loading time of FWD measurements on several occasions and has found that in all cases the loading time for the FWD device used is in the range of 0,025–0,027 sec (Tiit Kaal, unpublished data). Using 0,026 seconds as the determined average value of the FWD loading time, the correction factor K_{lt} calculated by the equation (6) is 1,56. Taking into account that $K_{lt} = 1{,}56$, we can calculate the pavement equivalent E-modulus using FWD measured deflection values by the equation:

$$E_{eq} = \frac{0{,}25\pi FS(1-\nu^2)}{d_0 \times K_{lt}} = 137{,}37 \times \frac{F}{d_0}. \qquad (1a)$$

2.2.2. Influence of mean temperature of bituminous layer on the pavement E-modulus

As the mean temperature of the bituminous layers varies with FWD measurements, and as according to the procedure 2001-52, the pavement is calculated to the elastic deformation at the temperature +10 °C [1], the E-modulus value calculated by the equation (1a) is to be corrected with by temperature correction factor K_t. Temperature corrected pavement equivalent E-modulus:

$$E_{eqt} = 137{,}37 \times \frac{F}{d_0 \times K_t}. \qquad (1b)$$

2.2.3. Influence of FWD measurement execution time on the pavement E-modulus

FWD measurements at 51 FWD test sites were performed annually from early spring until late autumn once or twice during every month. The purpose was to find the tendency of annual change of the calculated pavement equivalent E-modulus, based on the deflections measured with the FWD, and to use the possible existing relationship to transfer the deflection measured at any time of the year and the calculated pavement equivalent E-modulus to the value corresponding to the weakest period of the pavement structure (usually in spring after thawing).

To decrease the variance of different years and to find the annual seasonal pavement equivalent E-modulus correction factor to the weakest period, every year the minimum value of calculated pavement equivalent E-modulus is to be determined. The determined annual minimum value of the calculated pavement equivalent E-modulus is to be used for calculating the annual seasonal pavement equivalent E-modulus correction factors to the weakest period by dividing the calculated pavement equivalent E-modulus value, measured on different dates, with the determined minimum value of the year, when FWD measurements took place:

$$K_D = \frac{E_{eq}}{E_{eqMIN}}, \qquad (7)$$

where K_D – seasonal pavement equivalent E-modulus correction factor; E_{eq} – pavement equivalent E-modulus at the centre of the loading plate, (MPa) (measured during the measurement season from spring until late autumn); E_{eqMIN} – annual minimum value of the pavement equivalent E-modulus at the centre of the loading plate, MPa (usually measured in spring).

2.2.4. Influence of FWD measurement site moisture conditions and embankment height on the pavement E-modulus

Strength characteristics of soils (E-modulus, angle of internal friction and cohesion) are dependant on their moisture content and, as a result of this influence, also on the value of the whole pavement E-modulus. By the Estonian pavement design norms [4], there are three different moisture condition area types (Table 1).

Also it is found by the author [5] that the FWD test site embankment height has a significant influence on the FWD based pavement equivalent E-modulus value comparability to the pavement equivalent E-modulus value calculated by the 2001-56 procedure [3] – consideration of the embankment height at FWD test site is improving the determination coefficient (R^2) by 10 %.

2.3. Conclusion

The back-calculated pavement equivalent E-modulus at the centre of FWD loading plate compatible with the procedure 2001-52 $(E_{eq2001-52})$ depends on numerous factors such as loading time of the FWD device, mean temperature of the bituminous layer at the moment of FWD measurement, date of FWD measurement, test site moisture conditions and embankment height. All these factors change the value of back-calculated pavement equivalent E-modulus. As the analysis above shows, the determination of the individual influence of those different factors on the value of pavement equivalent E-modulus is quite ambiguous and does not always provide the expected result with a satisfactory correlation. Thus, a simplification is to be achieved trying to take the influence of all separate factors into account at once.

Table 1. Characterisation of area types by moisture conditions [4]

Number of area type	Nature of area	Description of the area type
1	Dry	Run-off of ground water is assured; soil water is deep and not influencing the vegetation. Main soil types are gravelly sands, sands and clayey sands, also somewhat clayey soils are represented, but their relative moisture content (w) is less than 0,7. If the height of the embankment is 1,5 times higher than required by norms, the number of the area type is always 1, not depending on other circumstances.
2	Moist	Run-off of ground water is not provisionally assured; it is characterised with the 0,3 % (or close to this) natural slope of the ground surface. Short-term (less than 30 days) standing water is observed. Soil water is just a little bit deeper than the freezing depth, and influencing the vegetation (growing moisture-laving plants); signs of ground swamping can occur. Mainly somewhat clayey soils with relative moisture content (w) less than 0,8 are represented. It is possible to improve the moisture conditions by vertical planning of ground surface and trenching, and to achieve the conditions of the 1st area type. All grooves and 0-profiles (also embankments lower than required by norms) of the 1st area type belong to the 2nd area type.
3	Over-moist (wet)	Run-off of ground water is complicated; long-term (more than 30 days) standing water is observed. Because of the soil water close to the ground surface, obvious signs of swamp are present. Level of the soil water is higher than the freezing depth. Mainly somewhat clayey soils with relative moisture content (w) over than 0,8 are represented. Change of the number of area type is possible just with a comprehensive drainage. All grooves and 0-profiles (also embankments lower than the required by norms) of the 2nd area type belong to the 3rd area type.

Presence of just one of the area type features (except for soil type) is determining the area type number

3. Determination of pavement equivalent E-modulus $E_{eq2001-52}$ comparable with the procedure 2001-52 using the FWD deflection measurement data and the theory of Cobb-Douglas

3.1. Implementation of the production function of Cobb-Douglas for determining the pavement equivalent E-modulus based on the FWD measurement data

As it was previously concluded, we should find an approach to the calculation of the pavement equivalent E-modulus on the basis of the FWD deflection measurement data. To achieve this, quite a large amount of variables, influencing the pavement equivalent E-modulus, is to be handled at once.

The production function of Cobb-Douglas (Eq (8)) [6] used in economics suits very well for that purpose as it enables to take into account a large number of variables influencing the calculable value. The equation

$$y = a_0 \times x_1^{a_1} \times x_2^{a_2} \times ... \times x_n^{a_n} \tag{8}$$

can be expressed in the form

$$\log y = \log a_0 + a_1 \log x_1 + a_2 \log x_2 + ... + a_n \log x_n , \tag{8a}$$

where y – calculable value; $a_0 ... a_n$ – constants; $x_1 ... x_n$ – variables influencing the calculable value.

Using similarity, we can express the pavement equivalent E-modulus comparable with the procedure 2001-52 $(E_{eq2001-52})$ in the form

$$E_{eq2001-52} = a_0 \times x_1^{a_1} \times x_2^{a_2} \times ... \times x_n^{a_n} \times E_{eq}^{a_m} , \tag{9}$$

where E_{eq} – pavement equivalent E-modulus at the centre of the FWD loading plate, MPa (calculated by equation (1)); $a_0 ... a_n$ – constants to be determined; $x_1 ... x_n$ – variables influencing the calculable value (for example, date of FWD measurement, water condition area type of measurement site, height of embankment etc).

The equation for calculating the pavement equivalent E-modulus comparable with the procedure 2001-52, taking into account possible different known influencing variables, can be written in the form:

$$E_{eq2001-52} = C \times E_{eq}^{e} \times T^{t} \times M_i \times H_j , \tag{10}$$

where E_{eq} – pavement equivalent E-modulus at the centre of the FWD loading plate, MPa (calculated using equation (1)); T – mean temperature of the bituminous pavement at the moment of FWD measurement, °C; C, e, t – constants; M_i – factor taking into account the month when FWD measurement is performed (i = 4, …, 10, April – October); H_j – factor taking into account the height of embankment at the FWD measurement site (j = < 0,5m; 0,5–1 m; > 1 m).

Constants C, e, t and factors M_i, H_j can be determined using the Linest function of the Microsoft Excel, which returns an array that describes a straight line $(y = ax + b)$ that best fits the data, calculated by the least-squares method. Results of the Linest function use are presented in Table 2.

Regression equation is generally expressed in the form

$$y = b + a_1 x_1 + a_2 x_2 + ... + a_n x_n , \tag{11}$$

where $a_n, a_{n-1}, ..., a_2, a_1$ and b – empirical parameters found with the Linest function; $se_n, se_{n-1}, ..., se_2, se_1$ and se_b – standard deviation values of the parameters $a_n, a_{n-1}, ..., a_2, a_1$ and b; R^2 – determination coefficient, indicating the range of influence of independent variables on dependent variables; se_y – standard deviation of the variable y; F – value of the Fisher's statistic for evaluating the reliability of relation between independent and dependent variables; d_f – number of freedom degrees; ss_{reg} – sum of regression squares; ss_{resid} – sum of residual squares.

To calculate the values presented in the Eq (10) by Linest function it is to be rewritten in the form of Eqs (11) and (8a):

$$\log E_{2001-52} = \log C + e \log E_{eq} + t \log T + m_i \log x_i + h_j \log x_j, \qquad (12)$$

where $x_i = 10$ for the month i ($i = 4, \dots, 10$) when the FWD measurement took place ($\log 10 = 1$) and $x_i = 1$ for all other months used in analysis ($\log 1 = 0$); $x_j = 10$ for the embankment height at the FWD test site matching to the determined range (< 0,5 m; 0,5–1 m; 1–1,5 m or > 1,5 m) and $x_j = 1$ for all other determined ranges of embankment heights used in analysis; $E_{eq2001-52}$ – pavement equivalent E-modulus calculated using the 2001-52 procedure, MPa (known y values in the relationship $y = ax + b$); E_{eq} – pavement equivalent E-modulus at the centre of the FWD loading plate, MPa (calculated by the equation (1)); T – mean temperature of the bituminous pavement at the moment of FWD measurement, °C; $\log C, e, t, m_i, h_j, w_k$ – constants, which are determined by the Linest function of Microsoft Excel.

The factors M_i, H_j and the constant C in the equation (10) can be calculated using the values of constants $m_i, h_j, w_k, \log C$ determined by the Linest function:

$$M_i = 10^{m_i}, \;\; H_j = 10^{h_j}, \;\; c = 10^{\log C}. \qquad (13)$$

3.2. Determination of factors and constants for different pavement conditions

Chosen 51 FWD test sites can be divided into groups based on the:

- Moisture condition area type:
  - 1st type – 20 test sites;
  - 2nd type – 21 test sites;
  - 3rd type – 6 test sites.
- Pavement type:
  - asphalt concrete (AC) with thickness 130–160 mm – 7 test sites;
  - asphalt concrete (AC) with variable thickness – 6 test sites;
  - asphalt concrete + bitumen-stabilised base (AC + BS) with variable thickness – 20 test sites;
  - Cold bituminous mix (CBM) pavements with variable thickness – 6 test sites.

From FWD test sites grouped by the moisture condition area type, 4 test sites were left out from analyses as the moisture condition area type was not clearly defined and from test sites grouped by the pavement type were eliminated 12 test sites because of the variable nature of the pavement structure.

Table 2. Linest overall printout [7]

Column Line	A	B	C	D	E	F
1	a_n	a_{n-1}	…	a_2	a_1	b
2	se_n	se_{n-1}	…	se_2	se_1	se_b
3	R^2	se_y				
4	F	d_f				
5	ss_{reg}	ss_{resid}				

Initial FWD measurement data of different test site groups were processed with the Linest function of the Microsoft Excel and the reliability of results evaluated using values of the determination coefficient (R^2), Fisher criteria (F) and Student t-criteria.

As a result of the initial data analyses, values of constants e, t, C and factors M_i, H_j to be used in the equation (10) for calculating the pavement equivalent E-modulus comparable with the procedure 2001-52 were determined (Table 3).

3.3. Calculation of pavement equivalent E-modulus using FWD measurement data and determined factors and constants

Using the values presented in Table 3 and the Eq (10), it is possible to calculate the value of pavement equivalent E-modulus comparable with the value of the pavement equivalent E-modulus calculated by the procedure 2001-52 $(E_{eq2001-52})$. Comparison of pavement equivalent E-modulus values at FWD test sites calculated using the Estonian 2001-52 procedure $(E_{2001-52})$ and equation (10) $(E_{eq2001-52})$ is presented in Fig 1.

We have to bear in mind that there will always exist the difference between the back-calculated pavement equivalent E-modulus at the centre of the FWD loading plate, compatible with the procedure 2001-52 $(E_{eq2001-52})$ and the pavement equivalent E-modulus calculated according to the procedure 2001-52 $(E_{2001-52})$ as the 2001-52 procedure is fully based on the theoretical characteristics of pavement materials. At the same time, the back-calculation of pavement equivalent E-modulus at the centre of FWD loading plate is based on the realistic pavement deflection data under a certain load at a certain pavement condition at the time of the FWD measurement. The question is – how close can we get or what value of the determination coefficient (R^2) between those two pavement equivalent E-modulus values ($E_{eq2001-52}$ and $E_{2001-52}$) we will reach.

Table 3. Values of constants e, t, C and factors M_i, H_j to be used in the Eq (10) for determining the pavement equivalent E-modulus comparable with the procedure 2001-52

		Moisture condition area type			Pavement type			
		1	2	3	AC	AC 130–160 mm	AC + BS	CBM
Empirical constants	e	0,721	0,461	0,548	1,152	0,414	0,503	0,665
	t	0,053	0,030	0,204	0,117	0,052	0,028	0,105
	C	2,580	1,035	3,228	1,883	18,484	9,204	1,668
M_i Factor considering the month when FWD measurement is performed	M_4 – April	1,000	1,000	1,000	1,000	1,000	1,000	1,000
	M_5 – May	0,955	0,962	0,837	0,991	0,983	0,961	0,826
	M_6 – June	0,929	0,940	0,796	0,996	0,967	0,934	0,736
	M_7 – July	0,908	0,942	0,802	0,927	0,953	0,927	0,738
	M_8 – August	0,907	0,943	0,756	0,945	0,967	0,931	0,708
	M_9 – September	0,871	0,914	0,766	0,933	0,974	0,898	0,702
	M_{10} – October	0,866	0,921	0,836	0,936	0,963	0,893	0,707
H_j Factor considering the embankment height	$H_{<0,5} \le 0,5$ m	1,000	1,000	1,000	–	1,000	1,000	1,000
	$H_{0,5-1}$ = 0,5...1 m	0,867	0,913	1,447	–	1,007	0,880	1,724
	$H_{>1}$ >1 m	1,081	1,368	1,795	–	1,077	1,225	1,591
R2		0,666	0,956	0,728	0,700	0,753	0,800	0868
Fisher F-criteria (95 % probability)		2,31	2,31	2,74	2,73	2,74	2,31	2,73
Fisher statistic (is to be > F-criteria)		67,16	116,5	9,551	54,3	43,6	200	113,2
Student t-criteria (95 % probability)		1,97	1,97	1,97	1,97	1,97	1,96	1,96
a_i/se_i (Table 2) (is to be > t-criteria)	e	26,33	36,67	22,01	21,9	32,52	29,6	27,45
	t	2,36	2,31	2,06	2,17	2,39	2,18	2,55
	C							
	M	∞	∞	∞	∞	∞	∞	∞
	H	∞	∞	∞	∞	∞	∞	∞

(–) insufficient initial data; AC – asphalt concrete with a variable thickness; AC 130–160 mm – asphalt concrete with thickness 130–160 mm; AC + BS – asphalt concrete + bitumen-stabilised base with a variable thickness; CBM – cold bituminous mix pavements with a variable thickness.

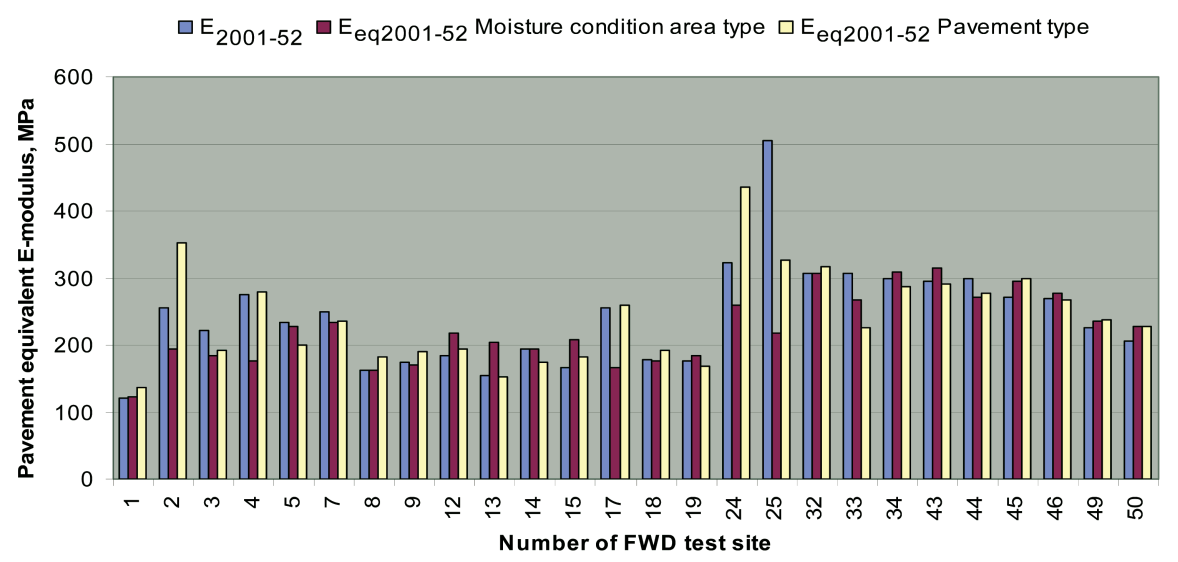

Fig 1. Comparison of pavement equivalent E-modulus values calculated using the procedure 2001-52 ($E_{2001-52}$) and the Eq (10) ($E_{eq2001-52}$) according to the FWD test site moisture condition area type and pavement type (using factors and constants from Table 3)

4. Conclusions

1. On the basis of the Cobb-Douglas equation a quantitative method for evaluating the qualitative characteristics of the pavement (Eq (10)) was developed, which can be used for the calculation of the pavement equivalent E-modulus to be used in the Estonian Pavement Management System for an objective evaluation of the structural condition of a pavement.

2. For the following qualitative variables, influencing the pavement equivalent E-modulus calculated on the basis of the FWD deflection measurements and comparable with the procedure 2001-52, values of correction factors of pavement equivalent E-modulus were calculated for different pavement moisture condition area types and pavement types (Table 3): month when the FWD measurement took place (M_i); embankment height (H_j) on the FWD measurement site.

3. For the following quantitative variables, influencing the value of pavement equivalent E-modulus, comparable with the procedure 2001-52, values of empirical constants were calculated for different pavement moisture condition area types and pavement types (Table 3): pavement equivalent E-modulus at the centre of the FWD loading plate calculated by the Eq (1) (*e*); mean temperature of the bituminous pavement at the moment of FWD measurement (*t*).

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