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ROAD PAVEMENT TESTING BY VIBRATION MEANS

J. Janulevicius[1], *L. Siaudinyte*[2] *and V. Giniotis*[† 3]

[1] Dept. of Road Engineering., Vilnius Gediminas Technical University, Sauletekio al. 11, LT- 10223, Vilnius-40, Lithuania, Justinas@janulevicius.lt
[2,3] Institute of Geodesy, Vilnius Gediminas Technical University, Sauletekio al. 11, LT- 10223, Vilnius-40, Lithuania, Lauryna.Siaudinyte@vgtu.lt

Abstract: Review and analysis of road pavement testing means and methods are presented. Complexity of these methods is pointed out. New approach to pavement testing using vibro-excitation and logarithmic decrement analysis of extinguishing free oscillations is proposed and its advantages are shown.

There are two main groups of methods to find the actual strength characteristics of the pavement: destructive and non-destructive. The latter are divided into static and dynamic types of methods.

Nevertheless, some disadvantages exist in application of those methods, and a new application of vibration testing method is proposed.

Keywords: Pavement testing, non-destructive, vibrations, logarithmic decrement.

1. INTRODUCTION

Road networks play a significant role in modern transportation system. To ensure proper journey quality as well as best travel cost economy it is essential that the overall road network condition is always at the highest point.

Pavement condition monitoring is essential when exploiting a road network. Based on the data, gathered from different segments of the road, certain conclusions can be made about the further exploitation of a road. What is more, assumptions on suitability of certain materials used for the pavement constructions in given climate conditions can be made [7].

Pavement constructions are designed based on the elastic deflection theory. It claims that when a load, not exceeding the design load, is applied to the surface it deflects in an elastic way, so when the load is taken off, the construction eventually returns to its initial stage. Therefore the main criterion, describing the overall strength of pavement condition is the ability of construction to withstand applied loads without structural changes (plastic deflections).

What is more, once pavement is installed it deteriorates gradually due to the vehicle loads, environmental conditions (such as temperature, humidity, direct sunlight, etc.) and installation errors. There are methods developed to determine the influence of climate conditions [3].

So, knowing the actual state of particular pavement construction is not only useful in determination of the best performing designs in given climate but also for optimal scheduling of repaving and maintenance of the road network.

2. PAVEMENT CHARACTERISTIC DETERMINATION METHODS

Proper pavement performance during its operation period is ensured by the ability of the construction to withstand the predicted traffic loads. Future traffic predictions are based on current yearly traffic data, as well as social and economic factors of the area. The impact to pavement, generated by different types of vehicles is expressed in a unified indicator, called *Equivalent Standard Axle load (ESA)* [1]. It shows the impact generated by any vehicle, compared to the impact, generated by a standardized 80 kN axle load. The *ESA* indicator is expressed as follows (1):

$$ESA_{80} = \sum_{N} \left(\frac{A_i}{80} \right)^{k_{d.s}} \tag{1}$$

here: ESA – equivalent standard axle load; A_i – load of vehicle axle, kN; N – number of vehicle axis; $k_{d.s.}$ – pavement thickness and structure factor.

Due to the impact of environmental conditions and vehicle loads, the characteristics of an installed pavement construction tend to degrade. Although the degradation can be predicted at a certain stage of operation, there is no exact mathematical method to predict the exact condition of pavement. It is impossible due to the influence of too many factors including altering climate conditions, uneven traffic loads, properties of materials used in the pavement and other special conditions, such as natural disasters or accidents that affect the performance of the construction [6].

Many different methods are developed to determine the present condition of pavement construction. These methods are classified into two main groups: destructive and non-destructive. The latter are divided into static and dynamic types of methods [2].

Destructive methods are based on taking of samples of the pavement and putting them in a number of physical and chemical tests in a laboratory. This is a very accurate but harmful and time consuming group of methods.

A solution that overcomes the negative aspects of destructive methods is a group of non-destructive testing (*NDT*) methods, which are being implemented to the road research [8]. These methods are based on the theory of elasticity and the phenomenon of elastic deviation of asphalt construction as a response to applied loads during the design period. Based on these methods, it is considered that if the load of any vehicle does not exceed the design limits, the pavement would only react with elastic deviations that would eventually disappear and the pavement would get back to its initial state.

The first section of NDT is static methods. These methods are based on generating a load, equal to the one generated by vehicle wheels and transferring it to the pavement in an area similar to the wheel and pavement contact area. Then the modulus of elasticity is calculated as follows (2):

$$E_i = \frac{P \cdot D}{\Delta l}\left(1 - \mu^2\right) \tag{2}$$

here: P – vehicle wheel load to pavement (*Pa*)*;* D – wheel and pavement contact diameter, (*m*); Δl – forced pavement deviation, (*m*); μ – Poisson's coefficient.

Although these methods provide advantages of rapid testing, they one main drawback: static methods are unable to evaluate the response of pavement to dynamic load generated by actual traffic. This makes impossible to define the reasons of pavement degradation.

To overcome these shortcomings dynamic testing methods are developed [2, 3]. They are able to simulate dynamic loads that effect pavement very similar to moving traffic. The dynamic effect on pavement is expressed as follows (3):

$$Q_d = Mg\sqrt{\frac{2\mathrm{H}}{\delta}}k_d \tag{3}$$

here: M – mass of falling weight, (*kg*); g – gravitational acceleration, (m/s^2); H – height from which the load is dropped, (*m*); δ –coefficient assessing the stiffness of suspension; k_d – falling weight energy loss rate.

The non-destructive methods involve special instruments to initiate the deflections by applying either static or dynamic load. The pavement reaction to the load is the main factor in the evaluation of pavement condition.

Depending on the method, each observe different factors to provide strength characteristics, e.g. a static method of *Benkelmann beam* is based on the evaluation of time it takes for the pavement to recover to its original state once the load is taken off, while the dynamic *Falling Weight Deflectometer* analyzes the decrement of deviations along the construction once a dynamic impact load is applied.

While *Benkelmann beam* method gained its popularity as a static non-destructive method in the 2nd half of the XX century, it was soon pushed away by a series of new dynamic methods evolved from *Falling Weight Deflectometer*, or FWD, an invention of Danish Road Laboratory. This method showed one essential benefit: it is able to simulate dynamic impulse load on the pavement of known force and falling duration. It allows simulating the effect of the vehicle load to the pavement.

The method is based on an element of certain weight being dropped from certain height on a special plate that would transfer the impact force to the pavement. A beam with sensors (geophones) detects the deflections of the pavement construction in several distances from the center of the impact. The deflection data is then recalculated to the strength characteristics of construction.

The modern modifications of a FWD are automatic, computer driven systems operated with by a simple interface. There are also special variations, such as *Light Weight Deflectometer* (optimized for loose soils), *Heavy Weight Deflectometer* (used on very strong constructions, such as airport runways) and even *Rolling Weight Deflectometer*. The latter is able to collect data while traveling non-stop at relatively high speed.

In 1990 *Strategic Highway Research Program* of the United States has performed a research of the main factors contributing to pavement deterioration and have found that there are six broad elements to cause it. They are: pavement moisture, fine cracking, subsurface problems, loss of support under rigid pavements, overlay delamination and asphalt aging.

3. NEW APPROACH TO PAVEMENT TESTING

There are methods and means developed for the state of initial stress detection and elimination in metal structures constructions, bridge and building constructions as well as frames and beddings of machines and metal cutting tools [10]. These methods are based on applying a wide range of frequency oscillations to special points of the structure, registering the spectrum of this effect, analyzing it and applying vibrations of frequency close to the resonating frequency or the one nearby to the construction [10, 11].

After a certain period of performing this action, initial stress in construction tends to decrease and even disappear. After vibration treatment initial stress is measured by tensiometers, inductive gauges, etc. A significant influence of this action is noticed on welded metal frames. The effect is so significant that this method is widely applied in frames or beddings of most precision machines and metal cutting tools. In devices, such as coordinate measuring machine, the effect of this treatment is so strong that the initial stresses can be minimized to an insignificant value so the machine is able to perform measurements without noticeable deformations and errors implied. Experiments performed have shown an initial spectrum of vibro-excitation and resonance peaks occurrence in the frequency range. Choosing frequency points and applying vibrations there shows that residual stresses in the construction recede and are significantly smooth in their distribution. Control of the process of vibro-treatment of the construction was developed using registration of logarithmic decrement of free oscillations of constructions after impact has been applied. It is significant that a total value or amplitude of the impact has no significance, the only relevant parameter is the logarithmic decrement curve and its comparison with reference or the curve before the vibro-treatment of the construction [11]. Area of stress in the construction can be characterized by constituent of stress δ that causes deformation E. Stress that appears due to initial friction can be expressed by the coefficient of damping $\psi=\Delta W/W$, where ΔW - is energy dissipation in the all volume of the frame per period of deformation, W – energy of oscillation of the whole frame [11, 12]. Stress is expressed as follows (4):

$$\delta = ln\frac{E_n}{E_{n+1}} \tag{4}$$

and E_n , E_{n+1} are amplitudes of damped oscillations.

In addition, it can be stated that as the energy W dissipating during the free oscillations is a function of residual stress and deformations that can be expressed as (5):

$$\delta = F(\psi) = f_{\psi}(\sigma, E) \tag{5}$$

Here σ is initial stress in the pavement volume.

Formulas (4) and (5) provide a functional relation between the residual stresses, deformation and amplitudes of damped oscillations. It shows that by measuring the logarithmic decrement, information about the existence and value of residual stress in the construction can be extracted. Equations (4) and (5) give no values of the residual stress, so only comparison of the curve can be used for assessment of damping features of the pavement, as well as the evaluation of pavement layer quality.

The relative damping coefficient can be utilized as a characteristic of the system damping parameters. Its determination will show how the vibrations are transferred along the road pavement. Registration of logarithmic decrement at various distances from the excitation point on a known pavement construction with known condition can be used as reference data later on.

Oscillations transferring along the surface of the pavement extinguish (fade) exponentially (6):

$$y(t) = Ae^{-\varsigma\omega_n t} \tag{6}$$

here A – normalized amplitude, ζ is relative attenuation, ω_n is frequency of free oscillations, t – time. Time constant of the system's extinguishing oscillations and relative attenuation is expressed (7):

$$\tau = \frac{1}{\varsigma\omega_n} \tag{7}$$

Value of the time constant and its deviations show road pavement's rigidity measure. As there is no basis for fixed-value time constant determination, comparison measurements of the reference pavement or comparison these measurements with measurements by other methods can be applied.

A vibration-based method for damage detection is being developed, showing strength in accuracy [5]. It shows great potential of vibration-based pavement testing tools as a versatile method, used in pavement design as well as structural constructions.

4. SETUP FOR THE EXPERIMENT

To realize this newly proposed method, a certain setup is required. It consists of an oscillation source that is placed on the surface of pavement construction. It generates and transfers vibrations by a contact plate, placed on the pavement. Vibrations of sinusoidal or quasi-sinusoidal oscillations are generated in short time intervals. Their response on a pavement construction is registered by vibrometers, placed at a precisely determined distance L_1 and L_i from the source. After an excitation of vibrations, vibrometer registers the pattern of free oscillations transferred by the surface of the pavement. It is registered as a logarithmic decrement δ of fading oscillations which character is dependent on the mechanical characteristics of the pavement – homogeneity, stiffness, adhesion between the layers, strength and initial stresses. Its analysis give plenty of information on the mechanical characteristics of the pavement. Applying this method gives great possibilities to determine various features of the pavement varying an excitation, changing the point and depth of its application and by analysis of these characteristics with spectral analysis of reference pavement with the pavement under the testing. The main diagram of vibration-based pavement testing device is shown in Fig. 1.

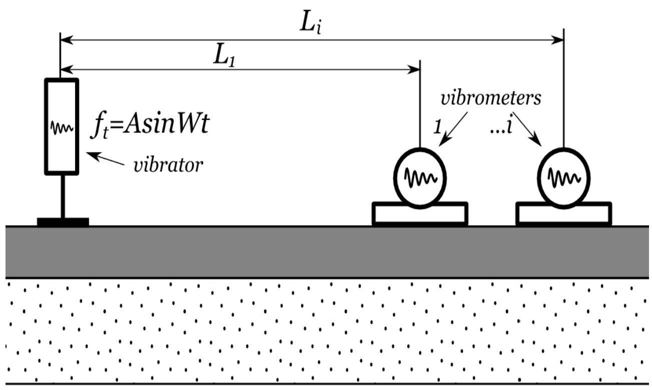

Fig. 1. General diagram of layout of the pavement testing

The pavement testing is achieved by:

- registering the pattern of logarithmic decrement at different distances from the point of oscillations and comparing it to the reference predetermined pattern acquired on a pavement with known properties;
- registering the same pattern at different depth of penetration into the pavement construction;
- performing spectral analysis of response signal from vibro-excitation source and comparison of its harmonics with signal from reference pavement;
- combining spectral analysis with logarithmic decrement analysis would present more information on pavement quality characteristics;
- comparison of amplitudes of the signal of excitation and the response signal and analysis of hysteresis pattern of the two signals;

Development and application of this method lead to time saving, less effort solution [12]. Equipment based on this method would be cheaper and simpler to operate.

5. CONCLUSIONS

Vibration-based pavement testing method offers a simpler method of testing and data evaluation. It also provides economic benefits.

The proposed vibration method is less time consuming and requires less effort. Equipment used for this method research is cheaper and simpler to operate.

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