



## ASSUMPTIONS TO ROAD PAVEMENT TESTING BY NON-DESTRUCTIVE MEANS

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**Abstract.** Road transport is by far the most convenient way of transportation these days, offering the highest mobility and flexibility. While road transport is gaining popularity, the increased amount of traffic requires proper improvements and maintenance of the road network. The increasing usage of roads requires highest levels of maintenance of the road network. To ensure that, new methods with the ability of rapid, non-destructive monitoring and testing of the construction properties are on demand. Review and analysis of flexible road pavement testing means and methods are presented in this paper to introduce the problem and current technology. 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 with application possibilities in a new advanced non-destructive pavement structure research device.

**Keywords:** road, pavement, testing, shock and vibration.

### 1. Introduction

The aim of this study is to provide the analysis of road pavement testing methods and means as well as development of methodology for non destructive pavement testing (NDT) using a new approach based on the effects of shock and vibration.

One of the most important factors of pavement behavior during its usage is the effect of loads applied by the vehicles moving along it. Finding an optimal solution for a specific road requires knowledge of traffic conditions and predictions for the design period as well as selection of the right design and maintenance.

Construction of road pavement consists of the designed pavement layers placed on the subgrade. The construction base is designed to withstand the loads of traffic as well as distributing the loads to the subgrade. Therefore the construction base has to be continuous and stable. The loads effecting the pavement can be either short-term or long-term, and can be static or dynamic. Applied loads deform the pavement layers, e.g. loads generated by a vehicle deform the subgrade in the active zone, so the thicker and stiffer the pavement the better the loads are distributed on the subgrade, therefore the effect on the subgrade is reduced to minimum (Mallick 2013).

Once pavement is laid it deteriorates gradually due to the vehicle loads, environmental conditions (such as temperature, humidity, direct sunlight, etc.) and installation failures. There are methods developed to determine the influence of climate conditions. Though the behavior of the pavement structures is quite well known in theory, it still differs from the practical situation. This happens due to the different effect of deterioration factors.

Knowing the actual state of particular pavement structure 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.

To ensure proper pavement performance during the period it is designed for, it is essential that there are no plastic deformations in any pavement layer, the continuity of the monolithic layers is not interrupted and the elastic deflection does not exceed the maximum design deviation after applying the design load (Tarawneh, Sarireh 2013).

The two main characteristics for pavement are strength and the rigidity of the road. If the pavement is not strong enough, defects, such as rutting, start to appear. This leads to not only resistance to the traffic and to increasing costs of using the transport system, but also, the

dynamic impacts caused by the wheel contact with an uneven surface increase the pace of pavement deterioration.

While the proposed method concentrates on load-bearing of the road structure, possibilities of using it for other parameter testing, such as searching for pavement defects is also possible.

## 2. Review of methods and means for pavement characteristic determination

To ensure proper pavement performance during its lifetime, pavement structure must be designed to be able to withstand the predicted traffic and the loads it bears. Future traffic is predicted based on current yearly traffic data, social and economical factors of the area (Bertulienė 2011). The effect on the pavement of different loads generated by different types of vehicles is unified using the Equivalent Standard Axle Load (ESA) indicator (Mallick 2013). This indicator shows the impact on the pavement compared to the impact generated by a standardized 80 kN axle load. ESA is expressed as follows:

$$ESA_{80} = \sum_N \left( \frac{A_i}{80} \right)^{k_{d,s}}, \quad (1)$$

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

Due to the impact of environmental conditions and vehicle loads the characteristics of pavement structure tend to degrade. This is caused by pavement structure deterioration. Although the degradation at a certain stage of operation can be predicted, it has been proved that 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, quality of materials used in the pavement and other special conditions, such as natural disasters or accidents, which affect the performance of the construction (Paliukaitė, Vaitkus 2011).

Many different methods are developed to know the present condition of pavement structure. 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 (Bertulienė 2008).

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

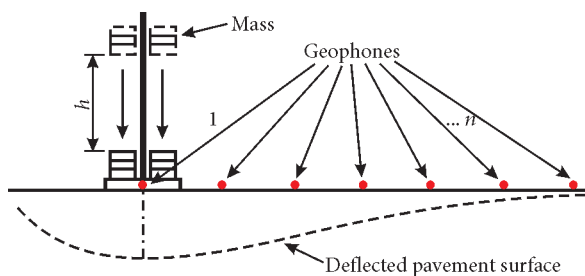


Fig. 1. General layout diagram of FWD

To simplify the research process and increase the pace, a group of NDT methods are being implemented in the road research (Nazarian *et al.* 1993). These methods are based on the theory of elasticity and the phenomenon of elastic deflection 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 deflections that would eventually disappear and the pavement would get back to its initial state.

First, static NDT methods were developed. 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:

$$E_i = \frac{PD}{\Delta l} (1 - \mu^2), \quad (2)$$

where  $P$  – vehicle wheel load to pavement, Pa;  $D$  – wheel and pavement contact diameter, m;  $\Delta l$  – forced pavement deviation, m;  $\mu$  – Poisson's coefficient.

Apart from the advantages of rapid testing, static methods showed one main disadvantage: static methods are unable to evaluate the response of pavement to dynamic load generated by traffic in reality. This leads to the inability to define the reasons of pavement degradation.

This problem is solved in dynamic testing methods (Bertulienė *et al.* 2010). Dynamic methods are able to generate dynamic loads that affect pavement very similar to moving traffic. The dynamic effect on pavement is expressed (Bertulienė, Laurinavičius 2008) as follows:

$$Q_d = Mg \sqrt{\frac{2H}{\delta}} k_d, \quad (3)$$

where  $M$  – mass of falling weight, kg;  $g$  – gravitational acceleration,  $m/s^2$ ;  $H$  – height from which the load is dropped, m;  $\delta$  – coefficient assessing the stiffness of suspension;  $k_d$  – falling weight energy loss rate.

The non-destructive methods involve special machinery to initiate the deviations 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 methods, they observe different factors to provide strength characteristics, e.g. a static method of Benkelman 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 (FWD) analyzes the decrement of deflections along the pavement structure once a dynamic impact load is applied.

While Benkelman Beam method gained its popularity as a static non-destructive method in the 2<sup>nd</sup> half of the XX century, it was soon pushed away by a series of new dynamic methods evolved from FWD, an invention of Danish Road Laboratory (Fig. 1). The main advantage of this method is that instead of measuring the pavement reaction to a static force it generates dynamic impulse load

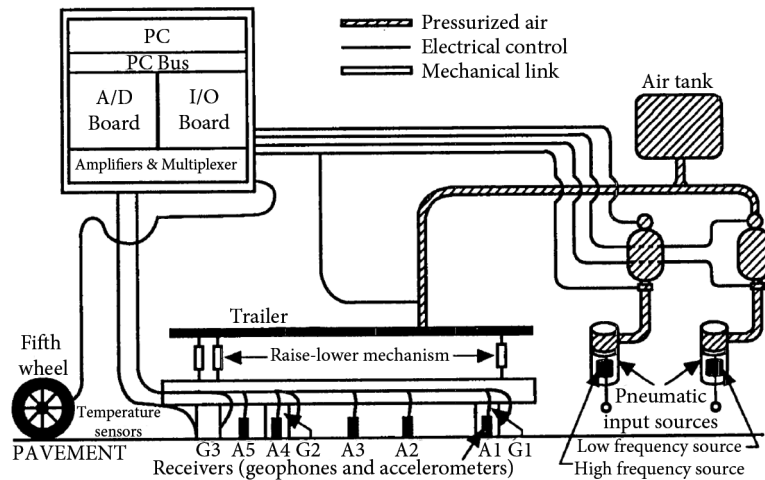


Fig. 2. General layout scheme of the Seismic Pavement Analyzer

on the pavement of known force. It allows simulating the effect of the vehicle load to the pavement. An element of certain weight is dropped from certain height on a special plate that would transfer the impact force to the pavement. A special beam with sensors (geophones) detects the deflections of the pavement structure in several distances from the center of the impact. The deflection data is then recalculated to the load-bearing capacity of construction (Kaulfers 2011).

The modern modifications of FWD are automatic, computer driven systems operated with a simple interface. There are also special variations, such as Light Weight Deflectometer (optimized for loose soils), Heavy Weight Deflectometer and even Rolling Wheel 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, e.g. pavement moisture, fine cracking, subsurface problems, and loss of support under rigid pavements, overlay delamination and asphalt aging.

To monitor these factors a vibration based method, called the Seismic Pavement Analyzer (Fig. 2) or simply SPA has been developed in University of Texas, US (Nazarian *et al.* 1993; Uddin *et al.* 1985). It is capable of detecting all of the problems presented above, except for the subsurface problems. A vibration-based method for damage detection is also being developed, showing strength in accuracy (Huang 2012). These two projects show great potential of vibration-based pavement testing tools as a versatile method, used in pavement design as well as structural constructions.

This method is very convenient because it requires minimal data reduction in the office, as it is mostly done in the field. It also allows easy data manipulation and graphical presentation. Moreover, the system design empowers the user to maintain the SPA easily and cheaper.

The equipment consists of pneumatic excitators and multiply sensors detecting response on excitation by pavement.

### 3. New approach to pavement testing

There are methods and means developed for the state of initial stress detection and elimination in metal structures, bridge and building constructions as well as frames and beddings of machines and metal cutting tools. Process is described in US patent 3741820. 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 (Hornsey 2006) 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 a tensometer, inductive gauge, 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 (Hornsey 2006) show 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. This is described in a patent by one of the co-authors Giniotis *et al.* No. 621749 *Method for Stress Relieving Metal*.

Area of stress in the construction can be characterized by constituent of stress  $\delta$  that causes deformation  $E$ . Stress that appears due to initial friction can be expressed by the coefficient of damping  $\psi = \frac{\Delta W}{W}$ , where  $\Delta W$  – is energy dissipation in the all volume of the frame per period of deformation,  $W$  – energy of oscillation of the whole frame. Also  $\psi \approx 2\delta$ , where  $\delta$  is logarithmic decrement of free damped oscillations, and

$$\delta = \ln \frac{E_n}{E_{n+1}}, \quad (4)$$

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

In addition, it can be stated that the energy  $W$  dissipation during the free oscillations can be expressed as a function of residual stress and deformations:

$$\delta = F(\psi) = f_\psi(\sigma, E), \quad (5)$$

where  $\sigma$  – initial stress along the pavement structure.

Eqs (4) and (5) give a functional relation between the residual stresses, deformation and amplitudes of damped oscillations. It is obvious that by measuring the logarithmic decrement information about the existence and value of residual stress in the construction can be received. Eqs (4) and (5) give no values of the residual stress, thus, as it was pointed out before, 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  $z$  is used as characteristics 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 structure with known condition can be used as reference data later on.

Oscillations transferring along the surface of the pavement extinguish (fade) according to the exponential law

$$y(t) = Ae^{-\zeta\omega_n t}, \quad (6)$$

where  $A$  – normalized amplitude;  $\zeta$  – relative attenuation;  $\omega_n$  – frequency of free oscillations,  $t$  – time. Time constant of the system's extinguishing oscillations and relative attenuation is expressed as:

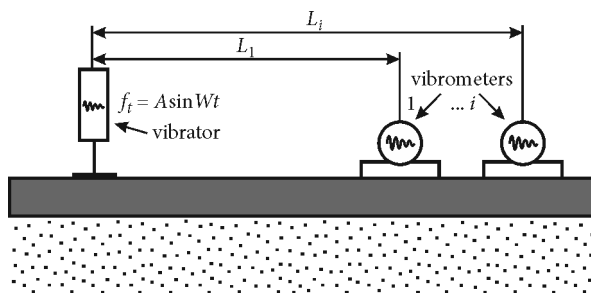


Fig. 3. General diagram of layout of the pavement testing

$$\tau = \frac{1}{\zeta\omega_n}. \quad (7)$$

Value of the time constant and its deviations can also be used to determine the rigidity properties of the surface. As it is difficult to determine a fixed value of the time constant, comparison measurements of the reference pavement or comparison of these measurements with measurements by other methods can be applied.

The main diagram of vibration testing of the road pavement is shown in Fig. 3. A vibrator (electromechanical, pneumatic or other) is placed on the surface of pavement structure. It is supplied with a plate, placed on the pavement. Vibrations of sinusoidal or quasi-sinusoidal oscillations are generated in short time intervals and registered by a vibrometer, placed at a strictly determined distance  $L_1$  and  $L_i$  from the vibrator. After an excitation of vibrations the vibrometer registers the pattern of free oscillations transferred by the surface of the pavement. It is registered as a logarithmic decrement  $\delta$  of fading oscillations which character will be dependent on the mechanical characteristics of the pavement – homogeneity, stiffness, adhesion between the layers, strength and initial stresses. Its analysis gives plenty of information on the mechanical characteristics of the pavement. By applying this method there are 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 pavement testing is performed by several methods:

- registering the pattern of logarithmic decrement at different distances from the point of oscillations and comparing it with the reference pattern fixed on the known pavement;
- the same registration made at different depth of penetration of the tip of the vibration;
- spectral analysis of response signal from vibro-excitation 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;
- the same procedure can be performed using a wide known method of shock testing, such as FWD, by dropping weight on the pavement and registering the vibrations by a seismic sensor (vibrometer) instead of deformation measurement.

Methodical approach to road pavement quality analysis by vibration method can save the time and efforts of research significantly (Silva 2006). Equipment and accessories for this operation are cheaper and simpler in operation.

#### 4. Conclusions

1. Analysis of road pavement characteristics measurement and testing shows some inconveniences in the use of known and widely applied methods.

2. Vibro-excitation based method and pavement response to it by logarithmic decrement analysis offer more simple method of testing and data evaluation, also it is cheaper in application.

3. The proposed vibration method significantly saves time and effort of research. Equipment and accessories for this method are cheaper and simpler than other methods.

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