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TRAFFIC LOAD IMPACT ON THE INITIATION AND DEVELOPMENT OF PLASTIC DEFORMATIONS IN ROAD ASPHALT PAVEMENTS

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Abstract. The up-to-date road pavement structure research methods and application computer programmes are based on the theory of elasticity. This theory is most widely used in the model of road pavement structure response where the load under the action of vehicle wheel causes stresses and strains in pavement structure. When determining the bearing capacity of existing pavement structures and the need for their strengthening the most often used are the research data collected and/or engineering experience gained. This article presents the initiation and development of plastic deformations in asphalt pavement layers that were evaluated knowing the real loading conditions of tested structures. Research was accomplished in 12 structures with the different asphalt layers during the road exploitation period for 5 years used at identical conditions: under the same traffic load, weather conditions and hydrothermal regime of pavement structures

Keywords: experimental asphalt pavement structures road; Benkelman beam, mobile laboratory RST 28, rut depth, economic evaluation.

1. Introduction

Roads of the Republic of Lithuania, making part of the transport system of Lithuania, are one of the most important fields of national economy having a large effect on the development of economy, international trade, tourism and cultural communication. Since road network is the most widely developed network all over the world, the road transport is also most intensive. The roads and streets are used not only as the routes to travel to and from home, working place and shops, to carry passengers and goods but they are also used in the everyday life. Data on traffic volume and axle loads is very important for designing a new road as well as reconstructing the old ones. Different roads and locations have a different traffic volume and traffic-generated loads.

In the period 2000–2011, the total traffic volume on the roads of national significance has increased by 46%, the volume of heavy traffic – by 48%.

Various investigations showed that the properly designed and laid asphalt pavement has a very long service life. Pavements are most often designed in a way to serve 20 years, however based on the calculated assurance factors (providing for the growing loads and traffic volumes, climatic changes, deterioration of materials, etc.) the service life of pavements is extended.

To seek for the most suitable and cost-effective road pavement structures, in autumn 2007 a 710 m long experimental road pavement section was constructed and opened to traffic, comprising 27 different structures (there were analysed 12 structures with the different asphalt layers). When the sections are affected by the same conditions (same loads, temperatures and weather conditions) a longer service life of road pavement structures (which could better withstand initiation of plastic deformations, occurrence of defects and decrease in bearing capacity) could be determined more accurately and substantiated more properly. It is possible to more accurately define the cause of one or another defect and to take more accurate solutions for the reconstruction, repair or other works, where the research was started in the very beginning of road operation.

2. Durability factors of road pavement structure

Asphalt concrete in road pavements disintegrates due to the following reasons: due to destructive impact of heavy vehicles – causing fatigue cracks in asphalt pavements (Sanchez-Silva *et al.* 2005; Žiliūtė *et al.* 2010); due to the impact of climatic factors (sudden freeze-up in winter, frequent temperature variations, solar radiation) (Bhattacharjee, Mallick 2012; Leonovič, Melnikova 2012); due

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to insufficient strength of road pavement structure; due to the fast disintegration of road pavement structure (due to destructive impact of vehicles (especially that of heavy vehicles), due to climatic factors, groundwater effect, nonconformity of physical and mechanical properties of materials used to the current requirements (Breakah *et al.* 2011; Vaitkus *et al.* 2012); due to delayed maintenance and repair (Ferreira, Santos 2012; Sanchez-Silva *et al.* 2005).

Investigations (Jongwon, Sandhyeok 2006; De Solminihac *et al.* 2003) showed that the pressure of vehicle wheels on the road pavement and its structure is the main load to be taken into consideration in pavement design. When the load of vehicle travelling along the road exceeds the design load only slight plastic deformations occur, but when the accumulation of these deformations exceeds the permissible deformation, during the period when pavement structure becomes most weak, the road pavement and its structure start to disintegrate. The impact of heavy vehicles on road pavement depends not only on their wheel loads, the number of axles and their configuration but also on the number of wheels in the axle (Romero, Lozano 2006; Salama *et al.* 2006).

One of the main criteria allowing to describe vehicle impact on road pavement is the number of equivalent standard axle loads (*ESAL*). The use of the *ESAL* index makes it possible to efficiently predict durability of road pavements and to plan the repair and reconstruction works of roads.

The equivalent of standard axles assesses the impact of vehicle axles on road pavement. In practice, the standard axle load is the load of 100 kN and its impact is equal to one. The impact of axle, the load of which varies from the standard, on road pavement disintegration is called the equivalent of standard axles and is calculated by the formula (Čygas *et al.* 2008):

$$ESAL_{100A} = \sum_{i}^{n} N_i \left(\frac{A_i}{100} \right)^4,$$

where $ESAL_{100A}$ – number of equivalent standard 100 kN axle loads, units. It is possible to calculate the *ESAL* of each typical vehicle and to multiply it by the number of this type of vehicles in the flow or to multiply straight by the *ESAL* of the whole vehicle flow; n – a potential number of the variations of vehicle axle loads (of one vehicle or vehicle flow), units; N_i – number of axles with the equal load (of one vehicle or vehicle flow), units; A_i – vehicle axle load, kN.

3. Theoretical modelling of the impact of traffic flow on asphalt pavement structure

Roads and streets are affected by the static and dynamic vehicle loads. The static loads are caused by standing vehicles, the dynamic – by the constantly moving, braking, accelerating vehicles (Green 2008; Saad *et al.* 2005). Depending on the type of load, the frequency of load repetition and the combination of loads the following pavements are designed: flexible, semi-rigid and rigid. A flexible pavement is asphalt pavement, a semi-rigid – with the asphalt wearing course and the underlying concrete, a rigid – concrete pavement.

Under the action of traffic loads, three types of stresses are formed in asphalt pavements: vertical, horizontal (tangential) and shear.

The analysis of methods and models to determine traffic-generated impacts on asphalt pavements has been carried out for the last several decades. Previous investigations show that the scientists used to model the static, dynamic, two-dimensional and three-dimensional asphalt pavement loading. Asphalt pavement modelling was performed by using the linear elastic, non-linear elastic, viscoelastic, stress-dependent, plastoelastic compound models. The values of calculations were compared to the data of measurements taken by correspondent equipment. Asphalt concrete is a viscoelastic material. This means that under the effect of different ambient conditions, asphalt concrete may take a different physical state: viscous, viscoelastic, plastoelastic, elastic and brittle.

Based on the literature overview, when modelling asphalt pavement behaviour under traffic loads using the non-finite element method (Chen *et al.* 2004; Wu *et al.* 2006), the finite element method (Fang *et al.* 2004) and the compound (Kim, Tutumluer 2006; Oh *et al.* 2006; Wang *et al.* 2005) models, also when monitoring the impact of tyres and/or loads on road pavements (Erlingsson 2012; Maina *et al.* 2006; Yoo *et al.* 2006), and having made the analysis of experimental data conformity to the modelling results (Huang *et al.* 2002; Ullidtz, Zhang 2002), it was noticed that the values obtained by computer calculations and field tests were very similar. However, there were scientists who proposed to perform a more comprehensive scientific research and to assess additional circumstances (e.g. dynamic loading, bonding of layers, material properties) using the appropriate models.

Under the action of long-term and repeated traffic loads, and other factors (temperature variations, pavement aging, exceeded axle loads, studded tyres used in winter, frequent braking, design errors, improper technology of production works, improper maintenance, insufficient pavement structural strength) the plastic deformations are formed (ruts, corrugations, heaves), defects (cracks: structural, thermal, reflection, edge, joint and extrusion) and other surface deformations (fretting, ravelling, potholes, patches, bleeding potholes).

4. Experimental research of traffic-generated impact on asphalt pavement structures

Seeking to determine the suitable and cost-effective road asphalt pavement structures, a longer service life of which could be defined more accurately and substantiated more properly and which could better withstand initiation of plastic deformations, occurrence of defects and decrease in the bearing capacity, in autumn 2007 the test section of experimental road pavement structures (further – test section) with the length of 710 m was constructed and opened to traffic, comprising 27 different pavement structures. Research of the change in the bearing capacity and

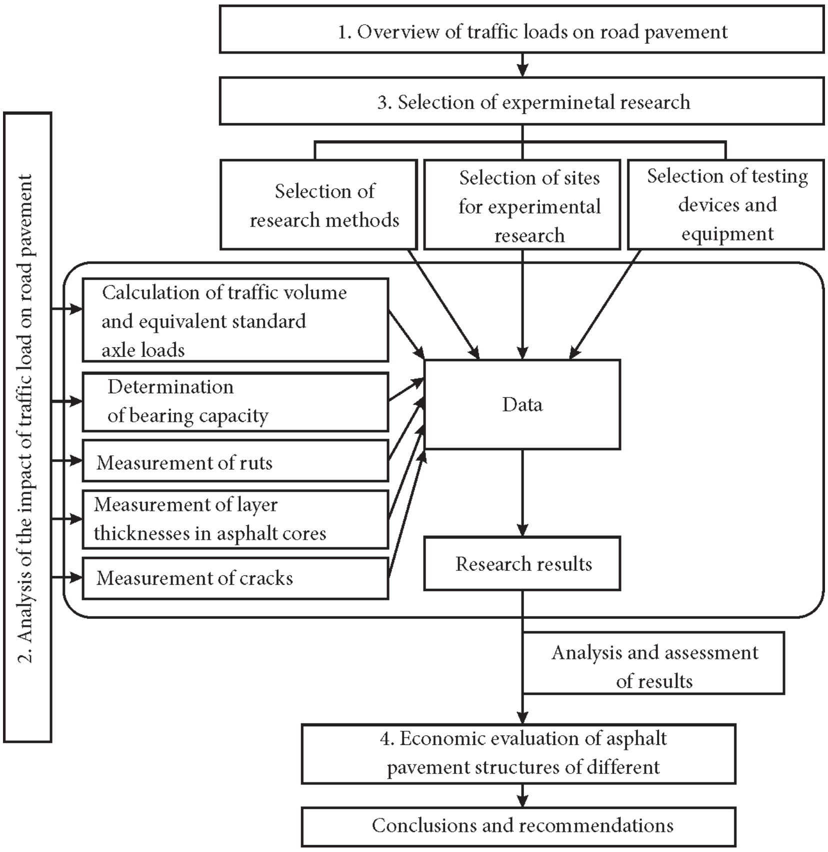

Fig. 1. The process of experimental research

Table 1. Materials used to construct asphalt pavement layers

No. of pavement structure	Asphalt pavement wearing ourse (4.0 cm)	Asphalt pavement binder course (4.0 cm)	Asphalt pavement base course (10.0 cm)
10	SMA 11 S	AC 16 AS	AC 32 PS
11	SMA 11 $S_{(PMB)}$	AC 16 $AS_{(PMB)}$	AC 32 PS
12	SMA 11 $S_{(PMB)}$	AC 16 AS	AC 32 PS
13	AC 11VS	AC 16 AS^1	AC 32 PS
14	AC 11VS	AC 16 AS^2	AC 32 PS
15	AC 11VS	AC 16 AS^3	AC 32 PS
16	AC 11VS	AC 16 AS^4	AC 32 PS
17	AC 11VS	AC 16 AS^5	AC 32 PS
18	AC 11VS	AC 16 AS^6	AC 32 PS
19	AC 11VS	AC 16 AS	AC 32 PS
26	AC 11VS	AC 16 AS	AC 32 PS^6
27	AC 11VS	AC 16 AS	AC 32 PS^7

Note: ^{1} – 50% granite + 50% granite (11/16), dolomite (5//8), dolomite 50%, granite 50% (8/11); ^{2} – 50% granite + 50% granite (8/11, 11/16), crushed gravel (fine particles); ^{3} – 50% dolomite + 50% dolomite (8/11, 11/16), crushed gravel (fine particles); ^{4} – 50% granite + 50% sand; ^{5} – 100% crushed granite; ^{6} – 100% gravel; ^{7} – 50% dolomite + 50% gravel.

of the occurrence of cracks was started in the very beginning of road operation (19 October 2007). To perform the research and to assess the results obtained, the structures with the layers of different asphalt materials were selected (Table 1). The main aspect in selecting the site for the test sections and their research was that this road is used by the heavy vehicles traveling to and from the two queries (*Silikatas and Pagirių Nesta*). For the analysis and assessment of research results, the data of researches was chosen which were carried out in a spring period based on the experimental research plan presented in Fig. 1.

The whole traffic flow, passing along the test road, was calculated and classified from the very beginning of road construction. Based on the current data of heavy traffic volume (the total and of separate classes) and the average ESA_{100} of one vehicle representing a certain heavy vehicle class, the number of passed ESA_{100} was calculated in a certain time period. The test section is passed by 60000–70000 $ESAL_{100}$ on average every year, the total number of $ESAL_{100}$ from the opening of the test section to June 2012 was 310 000 (Fig. 2).

Measurements of the bearing capacity using the Benkelman beam were performed in the rut and between the ruts of both traffic lanes (the loaded and un-loaded). When assessing measurement results, a larger attention was paid to the results obtained in the rut of the loaded traffic lane (Fig. 3) due to a heavier acting load.

In summary, the bearing capacity measurements and the determined static moduli of elasticity in the rut of asphalt pavement of the loaded traffic lane showed that in 5 years of operation the lowest weakening was represented by the structure No. 10, the wearing course of which is laid from SMA 11 S, binder course – AC 16 AS, base course – AC 32 PS, also by the structure No. 11 (wearing course – SMA 11 S with PMB, binder course – AC 16 AS with PMB and base course – AC 32 PS) and the structure No. 16 (wearing course – AC 11 VS, binder course – AC 16 AS^4 and base course – AC 32 PS).

Measurements of the depth of ruts in asphalt pavement of the test section were carried out by a mobile road research laboratory RST-28 in both traffic lanes (loaded and un-loaded). The average depth of the right and left ruts, and of the maximum clearance was calculated and presented. Measurements showed that the depth of the right and left ruts, and of the maximum clearance in the loaded traffic lane was higher than that in un-loaded lane. Scientific research has determined that the largest rut depth is formed in the loaded traffic lane in the trajectory zone of the right wheel of moving vehicle (Fig. 4).

In course of research the least rutted pavement structures were determined after 5 years of road operation: No. 12 (rut depth – 3.6 mm, asphalt pavement layers are made of: SMA 11 S with PMB, AC 16 AS, AC 32 PS); No. 11 (rut depth – 3.7 mm, asphalt pavement layers are made of: SMA 11 S with PMB, AC 16 AS with PMB, AC 32 PS). The highest rutting was represented by the following pavement structures: No. 27 (rut depth – 6.5 mm, asphalt pavement layers are made of: AC 11 VS, AC 16 AS, AC 32 PS^7); No. 15 (rut depth – 5.3 mm, asphalt pavement layers are made of: AC 11 VS, AC 16 AS^3, AC 32 PS).

Having analysed the asphalt layers deformation data obtained from the cores that were taken in the mostly rutted pavement structures (No. 27 and No. 19) and in the least rutted pavement structures (No. 11 and No. 12), it could be stated that in the period of 5 years of road operation plastic deformations were formed in the wearing course of pavement.

Initiation of defects in both traffic lanes of pavement structures of the test section was monitored from the very beginning of experimental road operation. And only one transverse crack was recorded in 2010 in the pavement structure No. 27. No more defects were detected after 5 years of road operation.

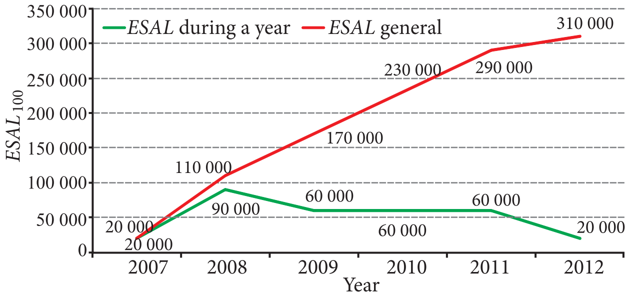

Fig. 2. Change in $ESAL_{100}$ during the experiment

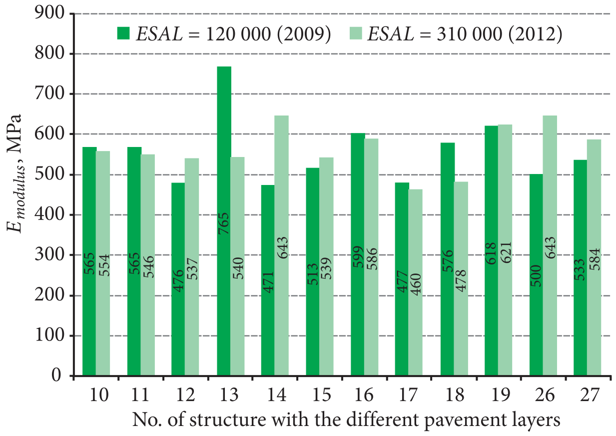

Fig. 3. Change in the static modulus of elasticity in the rut of the loaded traffic lane

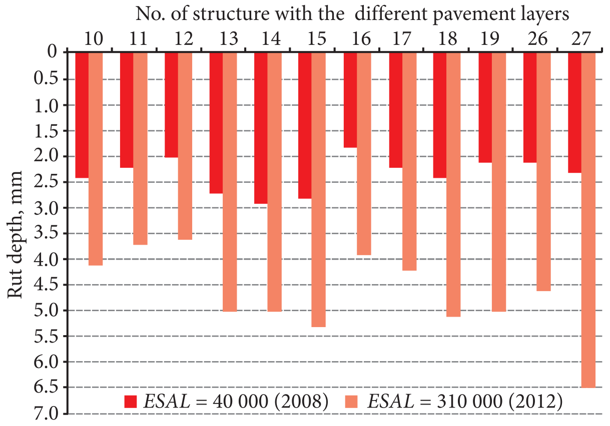

Fig. 4. Change in the depth of the right rut of the loaded traffic lane

5. Economic evaluation of asphalt pavement layers of different composition

The costs of constructing 1 km long asphalt pavement of the test section (Fig. 5) were calculated for the pavement structures No. 10–19, No. 26 and No. 27, the structural layers of which were laid from different materials. Cost estimations were made with the help of the computer software SISTELA, based on March 2012 market prices.

The above figure shows that the most expensive is the construction of asphalt pavements of the structures No. 11 (1377.4 thousand LTL (400.4 thousand Euro)); SMA 11 S with PMB, AC16 AS with PMB, AC 32 PS) and No. 12 (1347.1 thousand LTL; SMA 11 S with PMB, PMB, AC 16 AS, AC 32 PS), the cheapest – No. 18 (1224.4 thousand LTL (355.9 thousand Euro)); AC 11 VS, AC 16 AS^6,

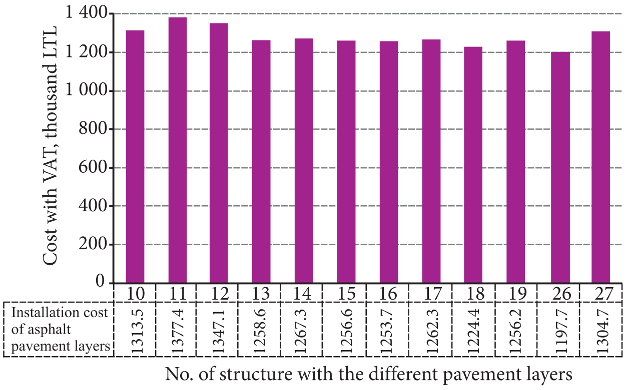

Fig. 5. Distribution of construction costs (1 Euro = 3.44 LTL) of all three asphalt pavement layers according to the materials used

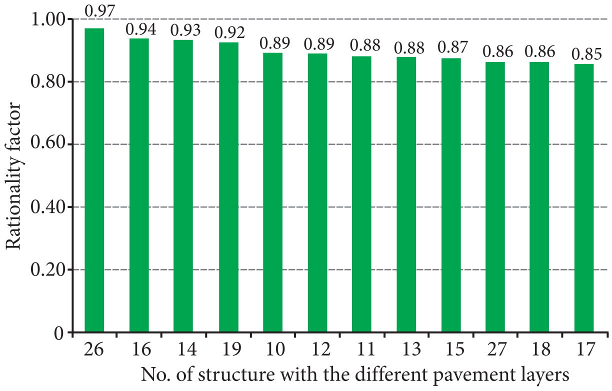

Fig. 6. Efficiency coefficient of structures with asphalt pavement from different mixtures

AC 32 PS) and No. 26 (1197.7 thousand LTL (348.2 thousand Euro)); AC 11 VS, AC 16 AS, AC 32 PS^6).

When selecting the most rational asphalt pavement the Simple Additive Weighing Method (SAW) was used. The following significance criteria were assumed: modulus of elasticity of the structure (significance coefficient – 0.35), rut depth (significance coefficient – 0.15) and the cost of constructing 1 km of asphalt pavement layers (significance coefficient – 0.5). The calculated efficiency coefficients of the structures are given in Fig. 6.

Having made calculations by the SAW methodology the distribution of structures with asphalt pavement layers of different mixtures was determined based on the efficiency coefficient which describes pavement quality. The top four pavement structures could be distinguished with the efficiency coefficient ≥ 0.90: the structure No. 26 (A = 0.97); the structure No. 16 (A = 0.94); the structure No. 14 (A = 0.93); the structure No. 19 (A = 0.92).

6. General conclusions

1. Having analysed the volume and composition of heavy traffic of the test section in 710 m length and 27 different experimental pavement structures, it was determined that the largest destructive impact on asphalt pavement structure is caused by a two-axle truck tractor with three-axle semitrailer and heavy-weight vehicles with three axles and four axles. The share of vehicles of the above-mentioned classes in the total flow of heavy traffic is 18.5%, 32.0% and 5.0%, respectively.

2. Having analysed and assessed the data of bearing capacity and the rut depth in a period of 5 year operation of twelve asphalt pavement structures selected for the research, it could be stated that the mentioned indices have no correlation. The bearing capacity of all asphalt pavement structures (≥ 460 MPa) is sufficient and have no impact on the initiation of ruts after 5 years of road operation and the passage of 310 000 equivalent standard 100 kN axle loads. In case if the baring capacity of asphalt pavement structure is sufficient, the occurrence of ruts is directly dependent on the properties of asphalt wearing course. After 5 years of road operation the highest bearing capacity were determined:

- No. 14 (E = 643 MPa; where asphalt wearing course is from AC 11 VS with the 100% of granite aggregates, asphalt binder course is from AC 16 AS with the 50% of the fraction 8/11 and 11/16 of granite rubble and 50% of fraction 0/8 of crushed gravel aggregate mixture, asphalt base course is from AC 32 PS with the 100% of dolomite aggregates).

Asphalt pavement structures of the lowest bearing capacity are as follows:

- No. 17 (E = 460 MPa; where asphalt wearing course is from AC 11 VS with the 100% of granite aggregates, asphalt binder course is from AC 16 AS with the 100% of the crushed granite aggregate mixture, asphalt base course is from AC 32 PS with the 100% of dolomite aggregates).

3. Analysis and assessment of the tendencies of rut depth in asphalt pavement structures showed that the depth of the right rut is larger than that of the left rut, therefore the depth of the right rut was assumed as a criterion for the assessment of pavement structures. After 5 years of road operation the least rut depth (after the passage of 310 000 equivalent standard 100 kN axle loads) was determined in the following asphalt pavement structure:

- No. 12: the largest rut depth – 3.6 mm (where asphalt wearing course is from SMA 11 S with the 100% of granite aggregates, asphalt binder course is from AC 16 AS with the 100% of granite aggregate mixture, asphalt base course is from AC 32 PS with the 100% of dolomite aggregates).

The largest rut depth was determined in the following asphalt pavement structure:

- No. 27: the largest rut depth – 6.5 mm (where asphalt wearing and binder courses is accordingly from AC 11 VS and AC 16 AS with the 100% of granite aggregate mixture, asphalt base course is from AC 32 PS with the 50% of dolomite and 50% crushed gravel aggregates).

4. Depending on the relationship between the bearing capacity, rut depth and construction cost of each pavement structure and on the significance level of each value determined during economic evaluation of tested twelve

structures, it was found out that the most rational asphalt pavement structure is No. 26 (where asphalt wearing and binder courses is accordingly from AC 11 VS and AC 16 AS with the 100% of granite aggregate mixture, asphalt base course is from AC 32 PS with the 100% crushed gravel aggregates), and the least rational pavement structure is No. 17 (where asphalt wearing course is from AC 11 VS with the 100% of granite aggregates, asphalt binder course is from AC 16 AS with the 100% of the crushed granite aggregate mixture, asphalt base course is from AC 32 PS with the 100% of dolomite aggregates).

5. Data of the above mentioned research is applicable and had already been applied in practice for designing asphalt pavement structures at weight–in–motion posts based on the permissible deflection and max permissible rut depth methods of pavement structure.

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