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RUTTING MECHANISMS AND ADVANCED LABORATORY TESTING OF ASPHALT MIXTURES RESISTANCE AGAINST PERMANENT DEFORMARION

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Abstract. *Permanent deformation in asphalt layers which manifestation on pavement surface is named rutting represents one of the most significant distresses of asphalt pavements. Depending on the level, it can be a huge inconvenience for traffic safety, driving comfort, and overall pavement life-cycle. Rutting may be classified into three basic types: one-dimensional or vertical compaction, lateral flow or plastic movement, and mechanical deformation. As an addition to Superpave® mixture volumetric design three, so called, simple performance tests (SPT) were recommended. Each of these tests in conduced in uniaxial or triaxial compression of cylindrical specimens. They cover the determination of dynamic modulus, repeated load permanent deformation test (flow number), and static load permanent deformation test (flow time). These tests provide relatively good insight in on-site mixture performance. An application of these tests provides a potential link between mixture design and structural analysis that was an underlying goal of substantial amount of earlier flexible pavement researches.*

Key words: *asphalt mixtures, rutting, permanent deformation, fundamental characteristics, dynamic modulus, repeated load, flow number, static load, flow time.*

1. INTRODUCTION

Permanent deformation in asphalt layers is one of the most significant types of asphalt pavements deterioration, and, depending on the level, it can be a considerable obstacle for traffic safety, driving comfort, and overall life-cycle of pavement structure. Permanent deformation of asphalt layer is caused by a combination of densification (volume change) and shear deformation (no volume change) from the repetitive application of traffic loads. Shear deformation of properly constructed (compacted) pavements – caused primarily by large shear stresses in the upper portions of asphalt layer(s) – is dominant. [1]

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The Distress Identification Manual for the Long-Term Pavement Performance Project defines rut as "a longitudinal surface depression in the wheel path [that] may have associated transverse displacement". [2] Some amount of rutting occurs in merely all flexible pavements. [1]

Experience from the implementation process during past years showed that volumetric design procedure without testing of mechanical characteristics is not adequate for acceptable mixture performance assurance. Unlike the Marshall mixture design method, testing of mechanical characteristics for controlling of mixture performance after completing the volumetric design procedure is not covered by Superpave® volumetric mixture design procedure. [3] Related to this, three "simple performance tests" (SPT) have been adopted.

2. Types of Rutting

Rutting is categorized into three types and defined by the cause and layers in which rutting occurs, and it can be characterized by two components of the original (initial) pavement profile change which are direct consequences of permanent deformation: uplift and downward deformation (Figure 1). [4]

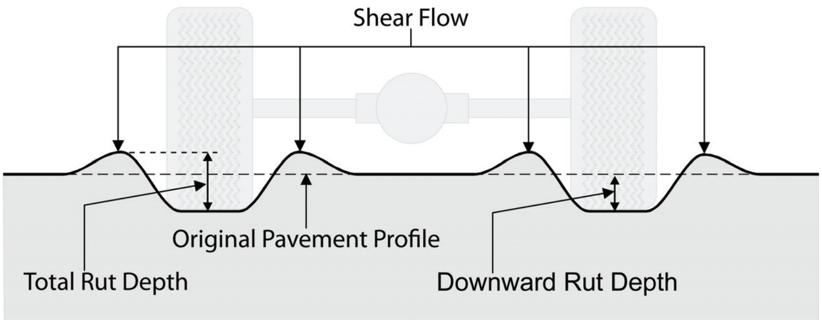

Fig. 1. Characterization of downward and total rutting [4], [5]

2.1. One-dimensional densification or vertical compression

A rut depth caused by material densification is a depression near the centre of the wheel path without an accompanying hump on either side of the depression. Generally, the densification of material is caused by excessive air voids or inadequate compaction after placement of asphalt material, thereby allowing the material or underlying layers to compact when subjected to traffic loads This type of rut depth usually results in a low-to-moderately-severe level of rutting. [4]

2.2. Lateral flow or plastic movement

Such longitudinal or lateral distortion of asphalt mixtures is caused by the localized shear failure resulting from overstressing the mixture with high tire pressure. [4]

A rut depth caused by the lateral flow of material is a depression near the centre of the wheel path with humps on either side of the depression. This type of rut depth usually results in a moderate-to-highly-severe level of rutting. Lateral flow or displacement of materials will occur in those mixtures with inadequate shear strength or an insufficient amount of total voids in the asphalt layer. Voids of an asphalt mixture in the range of 2 – 2,5 % or less after construction can be susceptible to lateral flow because the low voids allow the asphalt to act as a lubricant rather than a binder during hot weather. Overdensification of the HMA layer by heavy wheel loads can also result in bleeding or flushing on the pavement surface. This type of rutting is most difficult to predict. [4]

For visco-elastic materials, such as asphalt mixtures, the time of load affects the amount of deformation that occurs in the material, so distortions will be less on highways with higher speeds than on highways with lower speeds, given the same truckloads. Also this deformation at the constant load conditions will be higher at higher temperatures.

Most of the permanent deformation models developed to date, except the WesTruck models, use one-dimensional compression tests. Rutting caused by lateral flow is difficult to accurately predict with repeated load triaxial testing equipment, especially when the asphalt mixture is highly anisotropic, i.e. properties vary with direction. [4]

2.3. Mechanical deformation

The third type of rutting is consolidation, densification, and/or lateral movement of the unbound materials below the asphalt surface. This type of rutting has been referred to as "mechanical deformation". Mechanical deformation is a result of subsistence in the base, subbase, and/or subgrade and is usually accompanied by a longitudinal cracking pattern at the pavement's surface when the asphalt mixture is too stiff (i.e., high elastic modulus). These longitudinal cracks generally occur in the centre and along the outside edges of the ruts. [4]

3. Factors Affecting Rutting of Asphalt Mixtures

The permanent deformation of mixtures of bitumen and aggregate is a complex phenomenon where the overall performance is dependent on the properties of the aggregate, bitumen, contact of aggregate and bitumen, etc. These properties (as well as their relative influence) change through time to the end of their service life, i.e. till the failure due to excessive permanent deformation or cracking. The performance of the asphalt mixtures depends on the load frequency and temperature, and also, there is a strong dependency in terms of the voids content. By ageing, their flow ability decreases, that may play an important role in permanent deformation development. Various factors affecting the permanent deformation as well as effects of their changes are given in Table 1.

Table 1. Factors affecting rutting of asphalt mixtures [4], [6]

Factor		Change in Factor	Effect of Change in Factor on Rutting Resistance
Aggregate	Surface texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size	Increase 1)
Binder	Stiffness 2)	Increase	Increase
Mixture	Binder content	Increase	Decrease
	Air void content 3)	Increase	Decrease
	Voids in mineral aggregate 4)	Increase	Decrease
	Method of compaction	— 5)	— 5)
Test of Field Conditions	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease if mixture is water sensitive

1) Assuming constant layer thickness.
2) Refers to stiffness at temperature at which rutting propensity is being determined. Modifiers may be utilized to increase stiffness at critical temperatures, thereby reducing rutting potential.
3) When air void contents are less than about 3 %, the rutting potential of mixtures increases.
4) It is argued that very low (i.e., less than 10 %) voids in mineral aggregate should be avoided.
5) The method of compaction, whether laboratory or field, may influence the structure of the system and therefore the propensity for rutting.

4. DYNAMIC MODULUS (E *)

For linear visco-elastic materials such as asphalt mixtures, a complex number that gives stress-to-strain relationship under continuously applied sinusoidal loading in the frequency domain, represents complex dynamic modulus (E*). Complex modulus is defined as relationship of sinusoidal stress (at any given time, t, and angular load frequency, ω), $\sigma = \sigma_0 \sin(\omega\ t)$, and sinusoidal dilatation, $\varepsilon = \varepsilon_0 \sin(\omega\ t - \varphi)$, at the same time and frequency, that results in a steady-state response (Figure 2) [3]:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0\, e^{i\,\omega t}}{\varepsilon_0\, e^{i(\omega t - \phi)}} = \frac{\sigma_0 \sin(\omega\, t)}{\varepsilon_0 \sin(\omega\, t - \phi)} \tag{1}$$

where:
σ_0 – peak (maximum) stress,
ε_0 – peak (maximum) strain,
φ – phase angle, [°],
ω – angular velocity,
t – time, [s].

Mathematically, the dynamic modulus is defined as an absolute value of complex modulus, or:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

while the phase angle is defined as:

$$\phi = \frac{t_i}{t_p} 360 \tag{3}$$

where:
t_i – time lag between peak stress and peak strain, [s],
t_p – time lag between two cycles of stress, e.g. strain (period), [s],
i – imaginary number.
Expressed by real and imaginary part:

$$E^* = E' + i\,E'' = |E^*|\cos\phi + i\,|E^*|\sin\phi \tag{4}$$

E' as a complex modulus component is usually called elasticity or storage modulus, while E'' is called loss or viscosity modulus. The phase angle, φ, is the angle by which ε_0 lags behind σ_0. It is an indicator of viscous characteristics of the material being evaluated.
For a purely elastic material, $\varphi = 0°$, it can be seen that the complex modulus (E^*) is equal to the absolute value, i.e. to the dynamic modulus. For purely viscous material, $\varphi = 90°$. Testing of asphalt mixtures dynamic modulus is performed by using a pattern of uniaxial applied sinusoidal stress as it is shown in Figure 2.

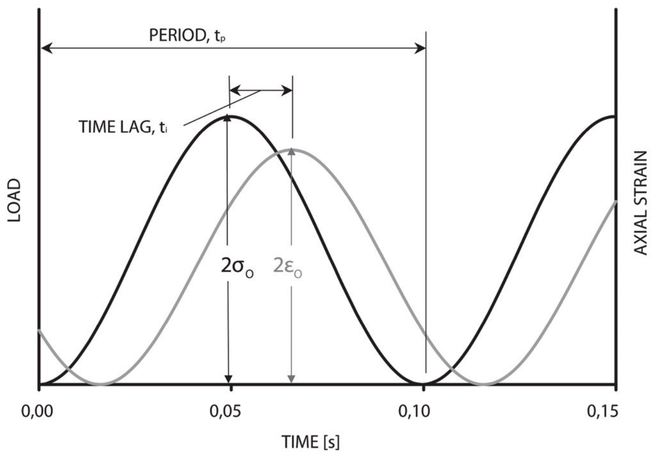

Fig. 2. Typical appearance of stress-strain diagram during a dynamic modulus testing [7]

5. Repeated Load Permanent Deformation Test - Flow Number (F_N)

One of the approaches in determination of asphalt materials permanent deformation resistance characteristics is the application of repeated load with several thousand repetitions and observation of cumulative deformation as a function of load repetition number (cycles). During the about 3 h testing, sinusoidal pulse 0,1 s loading is alternately applied with 0,9 s relaxation (relaxation time). The result of such approach is approximately 10 000 loading cycles applied on a specimen. [8], [9] Figure 3 shows repeated load pattern that is used in this test.

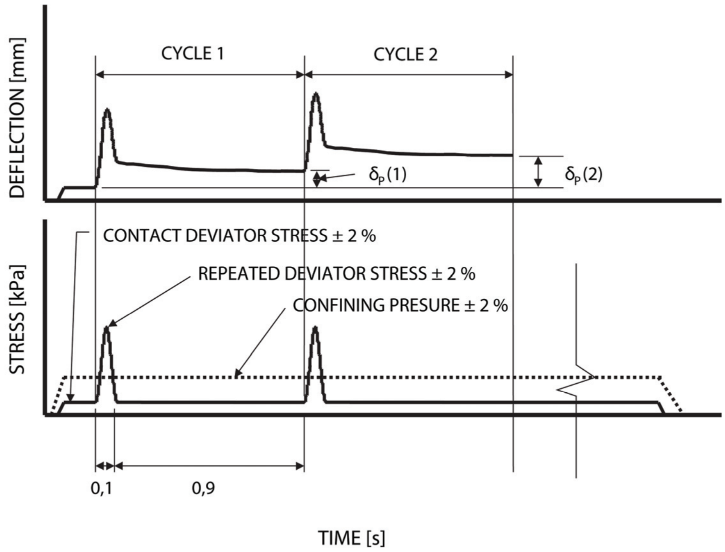

Fig. 3. Load pattern and obtained results about deflection during the repeated load permanent deformation test (F_n) [7]

Cumulative permanent strain, ε_p, in terms of cycle number N could be characterized by using power law

$$\varepsilon_p = a\, N^b \tag{5}$$

where a and b are regression constants that depend on material and testing conditions, and which respectively represent intercept with ordinate, and tangent slope due to transformation log ε = log a + b log N. It should be noticed that parameters a and b are obtained from the linear (secondary) part of cumulative plastic strain curve as a function of load repetitions cycle number which is drawn in log-log scale. In this, initial primary passing response and final tertiary instability are omitted. Parameter a represents permanent strain when $N = 1$, and b, the rate of permanent strain increase as a function of number of loading cycles, log N. For the characterization plastic strain increase during one load repetition, ε_{np}, an alternative mathematical model could be used:

$$\frac{d\varepsilon_p}{dN} = \varepsilon_{pn} = \frac{d(a\, N^b)}{dN} \tag{6}$$

or

$$\varepsilon_{pn} = a\, b\, N^{b-1} \tag{7}$$

Generally, it is assumed that the recoverable strain, ε_r is independent from the number of load repetitions, N, so the plastic-to-elastic strain ratio could be expressed as:

$$\frac{\varepsilon_{pn}}{\varepsilon_r} = \left(\frac{a\,b}{\varepsilon_r}\right) N^{b-1} \tag{8}$$

Replacing $\mu = \left(\frac{a\,b}{\varepsilon_r}\right)$ and $\alpha = 1 - b$, yields:

$$\frac{\varepsilon_{pn}}{\varepsilon_r} = \mu\, N^{-\alpha} \tag{9}$$

where:
ε_{pn} – plastic strain rate due to N-the load application,
μ – plastic to elastic strain ratio when $N = 1$,
α – permanent deformation decrease rate with increase of load repetitions number.

6. Static Loading Permanent Deformation Test - Flow Time (F_T)

Figure 4 shows static loading pattern which is used in static loading permanent deformation test. Similar to the repeated loading test, here can be seen that the creep compliance curve can be divided into three basic stages: primary, secondary, and tertiary flow. For constant loading stress conditions, during the primary stage, flow strain rate and creep compliance rate decrease with time, they are approximately constant during the secondary stage, and are increasing during the tertiary stage flow. In low stress conditions, asphalt concrete experiences primary flow mostly, i.e., flow rate slowly decreases to zero as the total strain asymptotically aims to limit value. This also suggests that in low stress flow rate in secondary stage can also reach zero. On higher stress levels, constant secondary flow rate will depend on applied load.

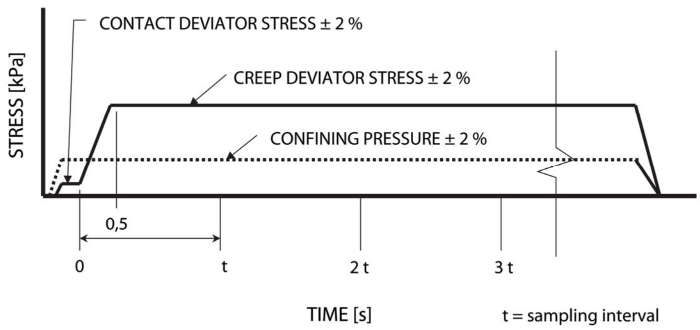

Fig. 4. Static loading pattern in static loading permanent deformation test (F_t) [7]

Considerable creep compliance rate during the tertiary stage flow, generally, occurs in constant volume. Therefore, flow time, F_t, is defined as a time at the beginning of shear deformation in constant volume. Flow time could also be noticed as the point of minimum at creep compliance in terms of loading time diagram.

7. EUROPEAN APPROACH BASED ON DETERMINATION STIFFNESS AND CYCLIC COMPRESSION TEST

In the European countries that harmonized their specifications to European standards (EN), two tests methods are adopted for determination fundamental mixture characteristics that could predict permanent deformation performance. These tests include determination of stiffness and cyclic compression test, according to EN 13108-26:2004 [12] and EN 13108-25:2005 [13], and respectively. Unlike the wheel-tracking test also included in EN standards as an empirically based one, there is a huge variety in test methods and conditions in which these tests are conducted.

Regarding determination of mixture stiffness, *S*, there are seven proposed test methods including two point bending tests on either trapezoidal (2PB-TR) or prismatic specimens (2PB-PR), three and four point bending tests on prismatic specimens (3PB-PR and 4PB-PR), direct tension-compression on cylindrical specimens (DTC-CY), test applying direct tension to cylindrical (DT-CY) or to prismatic specimens (DT-PR), and test applying indirect tension to cylindrical specimens (IT-CY). [12], [14]

The resistance to permanent deformation is determined in triaxial cyclic compression test, test method B. The mixture resistance is expressed in terms of creep rate per load cycle, f_c. Here, a cylindrical test specimen, maintained at elevated conditioning temperature of 15 ºC, is placed between two plan parallel loading plates. The specimen is subjected to confining pressure of 150 kPa for surface and 50 kPa for binder and base courses, on which a cyclic axial pressure of 300 kPa for surface and 200 kPa for binder and base courses is superposed. Test is conducted at 50 ºC for surface and at 40 ºC for binder and base courses, and loading pulse pattern is either 3 Hz haversine or 1s/1s block. [13], [14]

Figure 5 shows the servo-hydraulic testing device for both dynamic compression and tension tests which hydrostatic servo cylinder allows tests at frequencies of up to 60 Hz and maximum vertical load of 50 kN. The device is also suitable for testing of resistance to fatigue according to EN 13108-24:2004+A1:2007 [15]. Such high loading frequencies are needed to simulate high speed traffic loading. As mentioned test require the wide temperature range at which the tests are carried out, the device is also equipped with environmental chamber that allows specimen conditioning in a range of between – 25 and 80 ºC which satisfies even the most demanding researches.

By following the principle of time-temperature superposition, master curves for asphalt mixtures can be developed as shown in Figure 6. The two curves presented are developed for two asphalt concrete mixtures for base layers for heavy traffic load with maximum aggregate size of 22,4 mm, and are in accordance to German national specifications. The mixtures have a significantly different air void content and their characteristics are shown in Table 2. A different air void content predominantly influenced mixtures dynamic modulus values at the higher frequencies of load.

Table 2. Basic characteristics of the mixtures for which the master curves in Figure 6 are developed

Mixture designation	AC 22 T S — A	AC 22 T S — B
Aggregate type	Limestone	Diabas
Filler content by mass	6,8 %	5,4 %
Air void content	5,0 %	10,3 %
Bitumen content by mass	4,1 %	3,7 %

Fig. 5. Servo-hydraulic dynamical testing device for determination of stiffness, cyclic compression test, and fatigue resistance according to EN 13108-26:2004 [12], EN 13108-25:2005 [13], and EN 13108-24:2004+A1:2007 [15].

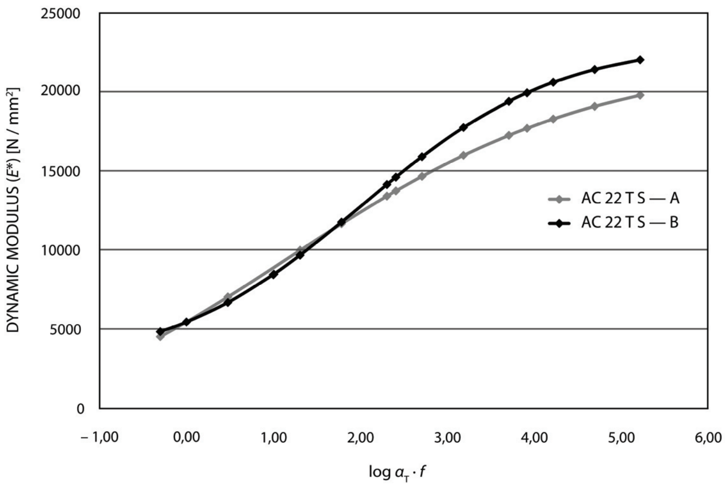

Fig. 6. Dynamic modulus master curves for two asphalt concrete mixtures for base layers with different air void content.

8. CONCLUSION

Permanent deformation in asphalt layers which manifestation on pavement surface is named rutting represents one of the most significant distresses of asphalt pavements. Depending on the level, it can be a huge inconvenience for traffic safety, driving comfort, and overall pavement life-cycle. [10]

Depending on the cause and the layer permanent deformation predominantly occurs, rutting may be classified into three basic types: one-dimensional or vertical compaction, lateral flow or plastic movement, and mechanical deformation.

Mixture permanent deformation susceptibility is equally dependent on component materials and their relative content as on test i.e. performance conditions.

As an addition to Superpave® mixture volumetric design three, so called, simple performance tests (SPT) were recommended. The objective of test is acquiring a better insight asphalt mixtures performance. They cover the determination of dynamic modulus, repeated load permanent deformation test (flow number), and static load permanent deformation test (flow time). Each of these tests in conduced in uniaxial or triaxial compression of gyratory compacted cylindrical specimens. Dynamic modulus is also main material input in mechanistic-empirical pavement design. [11] By the empirical wheel-tracking test, European standards fundamental approach is based on determination of stiffness and cyclic compression test which also involve the testing at wide range of frequencies and temperatures. European standards (EN) also introduce several different test methods including both bending and tension-compression tests An application of these tests provides a potential link between mixture design and structural analysis that was an underlying goal of substantial amount of earlier flexible pavement researches.

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MEHANIZMI NASTAJANJA KOLOTRAGA I NAPREDNA LABORATORIJSKA ISPITIVANJA OTPORNOSTI ASFALTNIH MEŠAVINA NA TRAJNU DEFORMACIJU

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Trajna deformacija asfaltnih slojeva, čija se manifestacija na površini kolovoza naziva kolotrazima, predstavlja jedno od najznačajnijih oštećenja asfaltnih kolovoznih konstrukcija. Zavisno od nivoa, ona može predstavljati veliku smetnja za bezbednost saobraćaja, udobnost vožnje, i sveukupan životni vek kolovozne konstrukcije. Kolotrazi se mogu klasifikovati u tri osnovna tipa: jednodimenzionalno vertikalno zbijanje, bočno tečenje i plastična deformacija, i mehanička deformacija. Kao dodatak uz Superpave® volumetrijsko projektovanje mešavina, preporučena su tri, takozvana jednostavna opita ponašanja (SPT). Svaki od ova tri opita se sprovodi pri jednoaksijalnoj ili triaksijalnoj kompresiji cilindričnih probnih tela. Opiti obuhvataju određivanje dinamičkog modula, opit trajne deformacije sa ponavljanim opterećenjem (broj tečenja), i opit trajne deformacije sa statičkim opterećenjem (vreme tečenja). Ovi opiti omogućavaju relativno dobar uvid u ponašanje mešavine na terenu, a njihova primena daje potencijalnu vezu između projektovanja mešavine i strukturne analize što je bio cilj u osnovi značajnog broja ranijih istraživanja fleksibilnih kolovoznih konstrukcija.

Ključne reči: *asfaltna smeša, nastajanje kolotraga, trajna deformacija, fundamentalne karatkteristike, dinamički modul, ponavljano opterećenje, broj tečenja, statičko opterećenje, vreme tečenja.*