Permanent deformation of hot mix asphalt under compression and tension

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ABSTRACT

In this paper, the existence of a correlation between the permanent deformations measured under different stress conditions is investigated. The results from cyclic penetration test, which is performed under compressive loading, are compared with the experimental values obtained with the indirect tensile fatigue test, which presents a dominant tensile stress field. Four different asphalt mixtures for surface and base layers were prepared and tested with both tests. The results indicate a significantly different material behavior between the two testing methods. In the case of the cyclic penetration test a first material densification is followed by deformation associated to shear effects with no change in material properties. On the other hand, during indirect tensile fatigue tests, a progressive accumulation of permanent deformation is linked to a continuous change in the mechanical properties of the material. It is observed that the development of permanent deformation under compression does not correlate with the deformation accumulation due to a tensile stress state. This suggests that the experimental results obtained with indirect tensile fatigue test cannot be used to predict the permanent deformation properties of asphalt mixture layers under the compressive state of stress induced by traffic load.

Keywords: Indirect tension, Permanent Deformation

1. INTRODUCTION

Asphalt mixtures for pavement application are designed in order to withstand traffic and temperature stresses during the entire service life. Different laboratory test methods can be used to assess the suitability of a particular asphalt mixture through the estimation of essential properties such as stiffness, fatigue resistance, resistance to low temperature cracking, and resistance to permanent deformation.

Permanent deformations represent one of the major distresses for flexible pavements especially in southern Europe and in hot weather regions. Such a phenomenon can significantly affect the driving conditions (e.g. hydroplaning and spray effects) [1] and potentially lead to cracking and pavement failure.

In order to estimate the permanent deformation properties of asphalt mixture various laboratory testing methods are available, such as wheel tracking test [2], cyclic compression tests (with or without confining pressure) [3] and cyclic penetration test [3]. A common characteristic of these tests is a dominant compressive stress state, which induces permanent deformation in the mixture. Recently research results obtained at Pavement Engineering Center at Technische Universität Braunschweig (ISBS) [4] have shown that indirect tensile fatigue test (ITT) at a standard test temperature of 20°C generates large plastic deformation for a large number of load repetitions. If only tensile stress acts in the specimen, and material viscosity is low (high temperature), the stress induced by the specific ITT test configuration will result in additional plastic deformation, which significantly increases within each loading cycle [4].

The objective of this work is to determine whether the development of permanent deformation in asphalt mixture under a compressive stress field correlates with the accumulation of permanent deformation due to tensile stresses. If such a link exists, this would give the opportunity to estimate both fatigue and permanent deformation resistance using only one test. In order to verify this hypothesis, indirect tensile fatigue test was selected and compared with cyclic penetration test. The concept of dissipated energy was used for the specific analysis [4, 5]

2. EXPERIMENTAL STUDY

2.1 Material composition

Permanent deformation tests were performed on four different mixtures. The first two mixtures were an Asphalt concrete, AC 11, and Stone Mastic Asphalt, SMA 11, for surface course. Both materials presented a Nominal Maximum Aggregate Size (NMAS) of 11mm. The reaming two mixtures were an AC 32 T S and an AC 32 T N mixtures used for base course in heavy and normal loaded road, respectively. Both base course mixtures had a NMAS=32mm. Different bitumens (plain and polymer modified) and aggregate types were selected. The mixing process was performed with a standard opposite rotation pug mill [6] (see Figure 1). Table 1 and Table 2 show the mixtures' mix design and the grain size distributions.

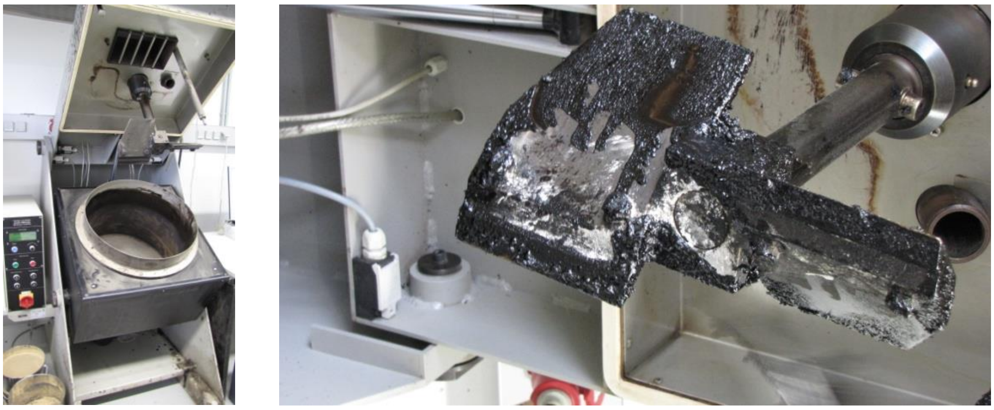

Figure 1: Opposite rotation pug mill used in this study.

Table 1: Grain size distribution of the used asphalt mixtures

Characteristic			**Unit**	**Asphalt type**			
				AC 11	**SMA 11**	**AC 32 T S**	**AC 32 T N**
Grain size distribution		≤ 0.063 mm	M.-%	7.0	8.7	6.5	5.5
	natural sand	0.063 / 0.25 mm	M.-%	2	-	5.3	8.5
		0.25 / 1 mm	M.-%	3.75	-	14.4	18.6
		1 / 2 mm	M.-%	2.5	-	7.3	4.7
	crushed sand	0.063 / 0.25 mm	M.-%	6	3.9	-	-
		0.25 / 1 mm	M.-%	11.25	7.4	-	-
		1 / 2 mm	M.-%	7.5	4.7	-	-
		2 / 5.6 mm	M.-%	27.0	11.0	12.5	12.3
		5.6 / 8 mm	M.-%	18.0	22.0	9.1	6.1
		8 / 11.2 mm	M.-%	15.0	42.0	10.6	7.1
		11.2 / 16 mm	M.-%	-	-	9.8	5.1
		16 / 22.4 mm	M.-%	-	-	9.5	6.4
		22.4 / 31.5 mm	M.-%	-	-	15	25.7
		Supplement Arbocel	M.-%	-	0.3	-	-
		Sum	M.-%	100	100	100	100
Aggregate type			-	Gabbro	Gabbro	Limestone	Diabase

Table 2: Compositions of the used asphalt mixtures

Characteristic	**Unit**	**Asphalt type**			
		AC 11	**SMA 11**	**AC 32 T S**	**AC 32 T N**
Bitumen type (penetration grade)	-	50/70	50/70	30/45	50/70
Bitumen content	M.-%	5.9	6.5	4.4	4.0
Bulk density	g/cm³	2.49	2.50	2.40	2.54
Air void content	V.-%	4.2	3.3	6.3	3.8

A Rolling Sector Compactor (or German Sector Compactor) (Figure 2) was used to prepared the asphalt slabs from which the test specimens were cored. Using the standard compaction procedure proposed by Wistuba, [7] it is possible to produce mixture with similar mechanical characteristics compared the field compaction on real asphalt pavements [8]. The compactor uses a steel roller cylindrical sector to induce a kneading action and downward force on the material in both pre-compaction and main compaction phase [7]. The pre-compaction is displacement controlled and simulates the compaction effort of paver, and main compaction is force controlled and simulates the effective compaction by roller compactor. Each phase consists of 15 roller passes.

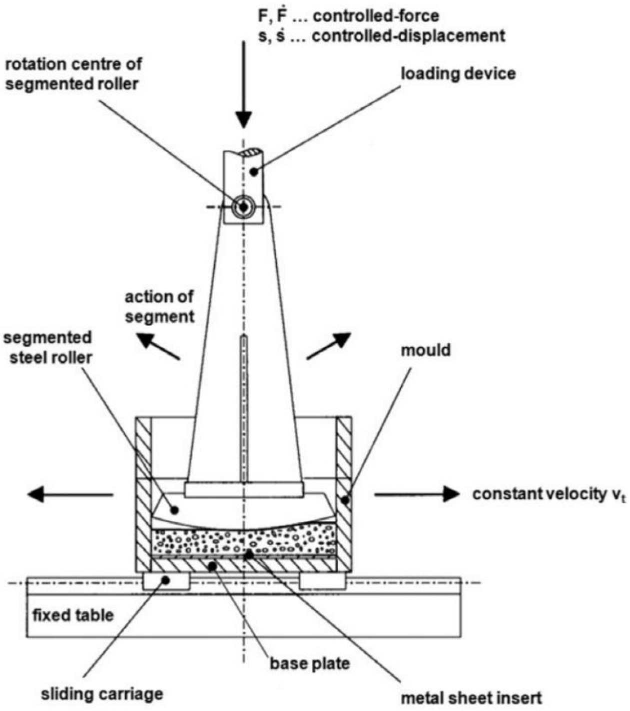

Figure 2: Rolling Sector Compactor (Wistuba, 2014)

2.2 Testing procedure

2.2.1 Cyclic penetration test

The compression test with confining pressure (so-called Triaxial Test) represents the most appropriate solution for estimating permanent deformations, since it simulates, in a more realistically manner, the main stress states arising in the pavement. Investigations conducted at ISBS [9, 10] have shown that the simple cyclic penetration test with a support ring can be also successfully used for evaluation the asphalt permanent deformation. Therefore, for comparison reasons and for simplicity, this type of test is used in this investigation.

In the cyclic penetration test a cylindrical asphalt sample (200 mm in diameter) is subjected to a compression load through a central stamp, with diameter of 80 mm [17] (Figure 3 left). Taking into consideration that its diameter is smaller than sample diameter, the asphalt material is exposed to vertical compression stress just in the restricted middle portion of the sample. In such a way the confining stresses are simulated by laterally surrounded mixture with the help of the supporting ring. The steel ring is intended to prevent any disproportionate growth of permanent deformation. The compressive stress is applied incorporating rest period in duration of 1.5s after each sinusoidal cyclic load at 5Hz (See Figure 3 right). The specified test conditions are given in Table 3.

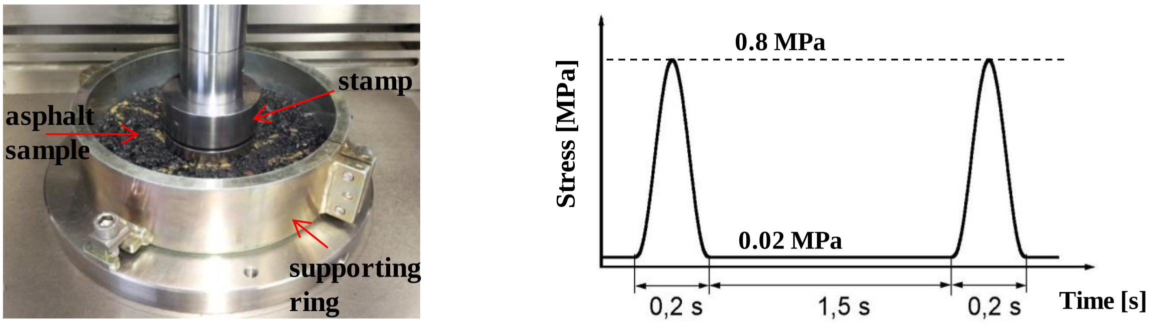

Figure 3: Cyclic penetration test with supporting ring (left) and used loading sequence (right).

Table 3: Cyclic penetration test - Test conditions

Test Temperature		50 °C
Conditioning time		150 minutes
Sample diameter		200 mm
Sample height	max. aggregate size D = 8 und D = 11mm	40 mm
	max. aggregate size D = 16 mm	60 mm
	max. aggregate size D ≥ 22 mm	80 mm
Stamp diameter		80 mm
Number of loading cycles (loading pulse + rest period)		10000
Loading duration		0.2 s (5 Hz)
Rest period duration		1.5 s
Maximum stress		0.8 MPa
Maximum stress		0.02 MPa

The deformation occurring during the test consisted of three parts (see Figure 4):

- • elastic part, which is recovered during the unloading phase,
- • viscous part, which is also partially recovered during rest period, and
- • plastic part, which is permanent and is accumulated during the entire test.

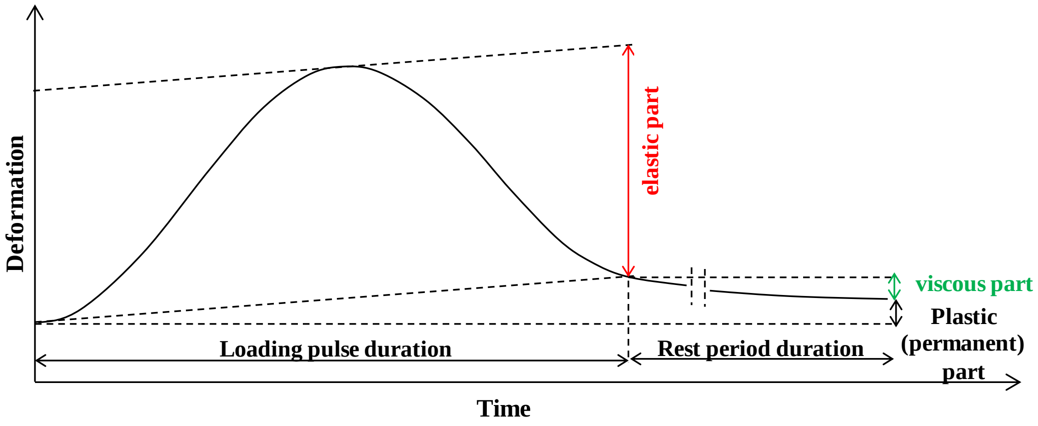

Figure 4: Deformation parts during one loading cycle (loading pulse + rest period).

During the test, the change of sample height and the resulting axial permanent deformation were recorded using two LVDTs; the permanent strain was then calculated using following equation:

$$\varepsilon_{p,i} = \frac{h_0 - h_i}{h_0} \cdot 1000 \qquad (1)$$

where:

$\varepsilon_{p,i}$: permanent strain after i loading cycle [‰],

h_0: height of the specimen at the beginning of the test (before loading) [mm],

h_i: height of the specimen after i loading repetitions [mm].

At the end of the tests (after 10000 loading cycles) the total accumulated permanent deformation is obtained.

2.2.2 Indirect tensile test

In indirect tensile test (ITT) a vertical acting sinusoidal compressive stress induces in the specimen a non-homogeneous stress state, while, in the middle portion of the specimen, a horizontal tensile stress is observed. This induced tensile horizontal stress is constantly held over the entire test duration (Figure 5 right) and it is primarily responsible for the specimen failure. The resulting horizontal deformation is captured using two transducers (LVDTs), attached at both sides of the specimen (see Figure 5, left).

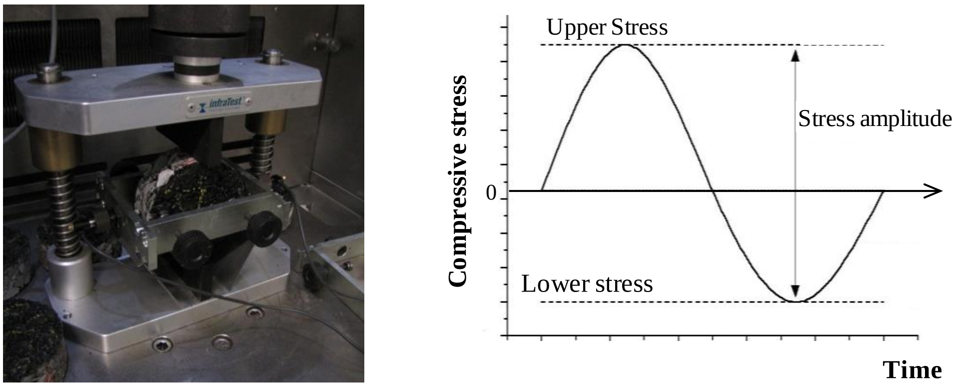

Figure 5: Indirect tensile test apparatus (left) at ISBS and loading pattern (right)

Fatigue tests were conducted at temperature of 20°C by varying the horizontal stress amplitude in three steps. For each step, three single fatigue tests were conducted. The specified test conditions are given in Table 4.

Table 4: Indirect tensile test - Test conditions

Test temperature		20 °C
Specimen diameter	max. aggregate size D ≤ 16 mm	100 mm
	max. aggregate size D < 32 mm	150 mm
	max. aggregate size D ≥ 32 mm	150 mm
Specimen height	max. aggregate size D ≤ 16 mm	40 mm
	16 < max. aggregate size D < 32 mm	60 mm
	max. aggregate size D ≥ 32 mm	90 mm
Frequency		10 Hz
Upper horizontal tensile stress		varied in 3 steps (mixture dependent) form 0.26 MPa to 0.70 MPa
Lower horizontal tensile stress		0.035 MPa

The horizontal acting tensile stress induces horizontal elastic, viscous and plastic deformation. This type of test does not include rest periods and therefore, the viscous and plastic deformation are superposed and accumulated over entire test duration. Horizontal induced stress, elastic strain and absolute value of complex modulus can be calculated as follows:

$$\sigma_H = \frac{2 \cdot F}{\pi \cdot d \cdot h} \tag{2}$$

$$\varepsilon_p = \frac{2 \cdot u \cdot (1 + 3 \cdot \mu)}{\pi \cdot d \cdot (0{,}274 + \mu)} \cdot 1000 \tag{3}$$

$$|E^*| = \frac{F \cdot (0{,}274 + \mu)}{h \cdot u} \tag{4}$$

where:

σ_H: horizontal tensile stress in the middle of the specimen [MPa],

F: vertical compressive force [N],

d: specimen diameter [mm],

h: specimen height [mm],

ε_p: horizontal elastic strain in the middle of the specimen [‰],

u: horizontal elastic deformation in the middle of the specimen [mm],

μ: Poisson`s ratio (0,298 at 20 °C) [-],

$|E^*|$: absolute value of complex modulus [MPa].

According to the German specification AL Sp-Asphalt 09 [11] the number of loading cycles at failure was evaluated using the Energy Ratio (ER) criteria proposed by Hopman et al. [12]. ER represents the ratio between the initial dissipated energy (W_0), to the dissipated energy at cycle n (W_n), multiplied by the load cycle value n:

$$ER_n = \frac{n \cdot W_0}{W_n} \tag{5}$$

where:

n:	cycle number,
W_0:	initial dissipated energy (for 100th cycle),
W_n:	dissipated energy at cycle n.

Considering that the change in phase angle during the cyclic indirect tensile test is minimal, Equation 5 can be simplified using Rowe´s approach [13] as:

$$ER_n = n \cdot |E^*|_{\mathrm{n}} \tag{6}$$

where:

n:	cycle number,
$\lvert E^* \rvert$:	absolute value of complex modulus at cycle n.

Figure 6 presents a typical example of the Energy Ratio evolution. By plotting ER versus the number of loading cycles, the fatigue life is defined as the number of loading cycles for which ER achieves the maximum. This point (number of loading cycles) represents the transition between micro and macro cracking and is specified as N_{Macro}.

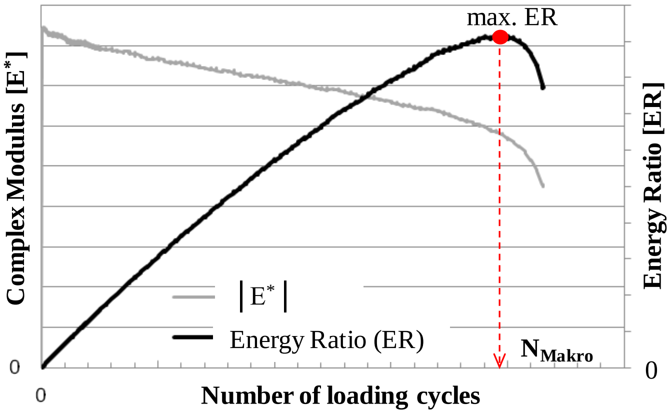

Figure 6: Typical evolution of the complex modulus |E*| and Energy Ratio (ER) over the number of loading cycles in cyclic indirect tensile fatigue test.

Finally, the resulting permanent horizontal deformation in indirect tensile test is calculated as the difference between accumulated permanent deformation at failure (at N_{Makro}) and at 100^{th} loading cycle.

3. RESULTS AND ANALYSIS

3.1 Cyclic penetration test

The cyclic penetration test and the four asphalt mixtures listed in Section 2.1 were used to evaluate the development of permanent deformation under compression loading. Figure 7 shows an example of the accumulated permanent strain evolutions over the number of loading cycles, for the base course asphalt mixture AC 32 T S.

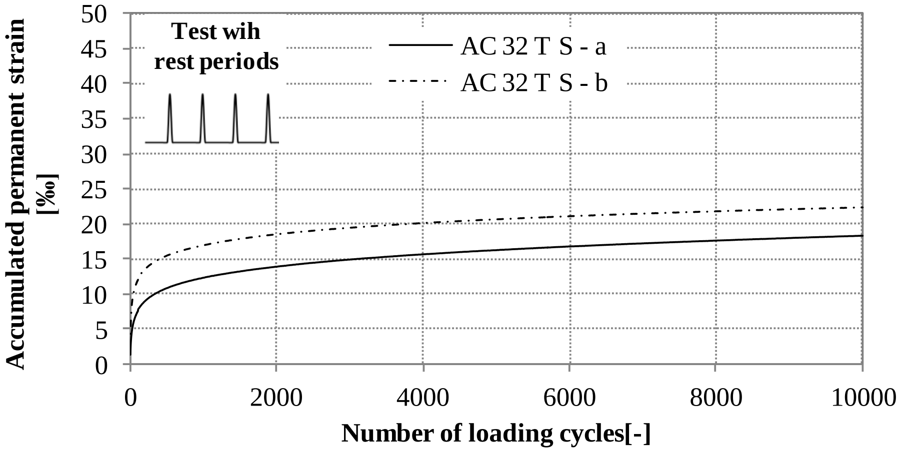

Figure 7: Cyclic penetration test: accumulated permanent strains over the number of loading cycles for asphalt mixture AC 32 T S.

Figure 8 presents the final permanent strains (after 10000 loading cycles) in the cyclic penetration tests for all the mixtures used in the present research. It can be noticed that AC 32 T S mixture exhibited lowest permanent deformation, most likely due to the harder bitumen used in the mix design and having penetration grade 30/45. As a consequence of the better aggregate skeleton and better carrying capacity, stone mastic asphalt (SMA 11) showed better results compared to AC 11 and AC 32 T N. The negative influence of round particles of sedimentary origin sand on the deformation properties at high temperatures is confirmed by the response of AC 32 T N mixture, which showed the lowest deformation resistance.

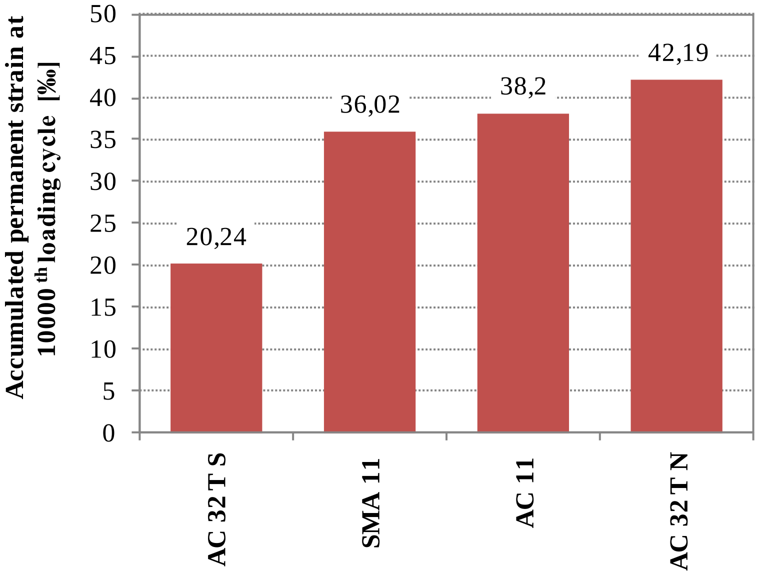

Figure 8: Accumulated permanent strain at the end of cyclic penetration test for the following mixtures: AC 32 T S, SMA 11, AC 11 and AC 32 T N.

The permanent deformation growth in pavements at high temperatures is caused by both densification and shear deformation [1 and 14]. Densification is mainly observed in the initial phase, where additional compaction due to traffic occurs. After the initial stage, the volume decrease in the wheel path is approximately equal to the volume increase in the adjacent upheaval zones. This indicates that the compaction under traffic is so far completed and further rutting is caused essentially by shear deformation, i.e., distortion without volume change.

The concept of dissipated energy was then used to evaluate the material behavior over the increased number of loading repetitions in cyclic penetration test. As reported by Di Benedetto [15] the change in mechanical properties of HMA in one cyclic test can be characterized by the change of the hysteresis loop form during cyclic loading, which directly corresponds to the change in dissipated energy. The energy dissipated within one loading cycle represents the difference between the energy provided to the material during the loading phase and the energy released during unloading. Taking into consideration that common equations for the dissipated energy calculation are just applicable for continuous tests, one cyclic penetration test was performed on asphalt mixture AC 32 T N without any rest period. The accumulated permanent strain development (A) and dissipated energy in each loading cycle (B) over the number of loading repetitions are shown in Figure 9. The initial phase of the test (first 300 cycles) is characterized by high increase of the permanent deformation and high decrease of the dissipated energy. Lower dissipated energy is associated to a dominant elastic response of the material (higher complex modulus value and lower phase angle), implying high value of volumetric hardening and material densification. After the initial phase, permanent deformation continued to increase, without any change in dissipated energy per loading cycle, or rather without any change in material properties. This is related to permanent deformation growth without volume change caused by shear deformation.

This material behavior under compression is observed in triaxial test [10] and when using wheel tracking device [14] as well, and it may be also expected in penetration test with rest periods.

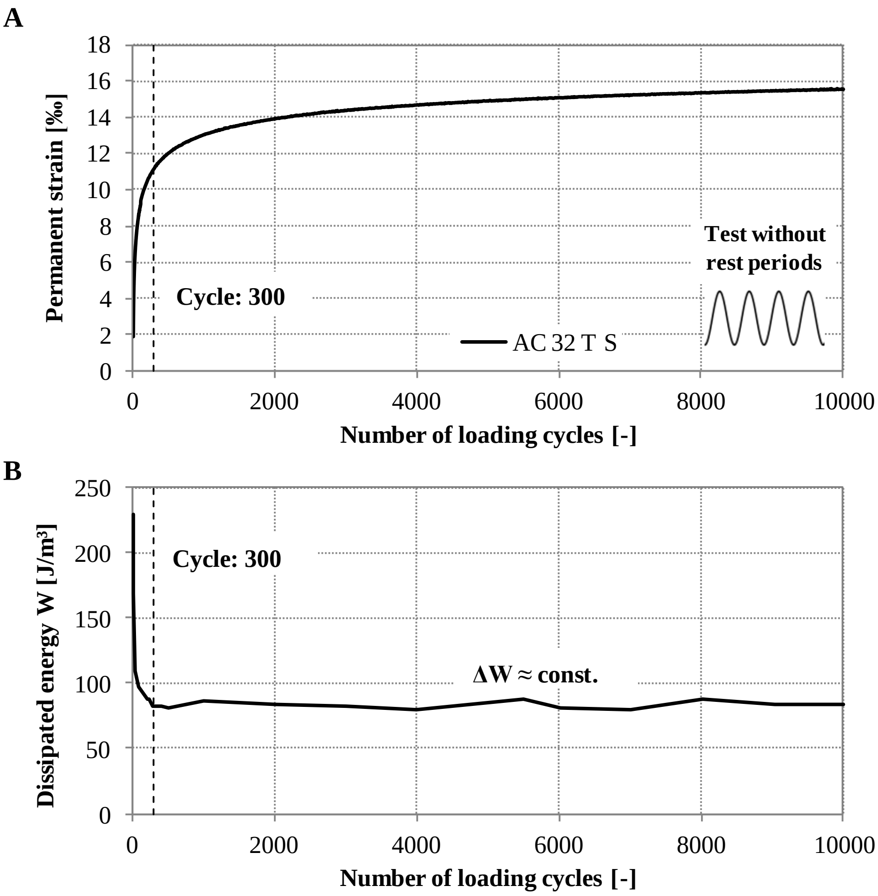

Figure 9: Cyclic penetration test without rest period: accumulated permanent strain and dissipated energy in each loading cycle for asphalt mixture AC 32 T S.

3.2 Indirect tensile test

Permanent deformation development under tension was evaluated using indirect tensile fatigue test at 20°C [11]. An example of the complex modulus, energy ratio, dissipated energy, phase angle and accumulated permanent strain evolutions in one fatigue test, conducted on asphalt mixture AC 32 T S is shown in Figure 10.

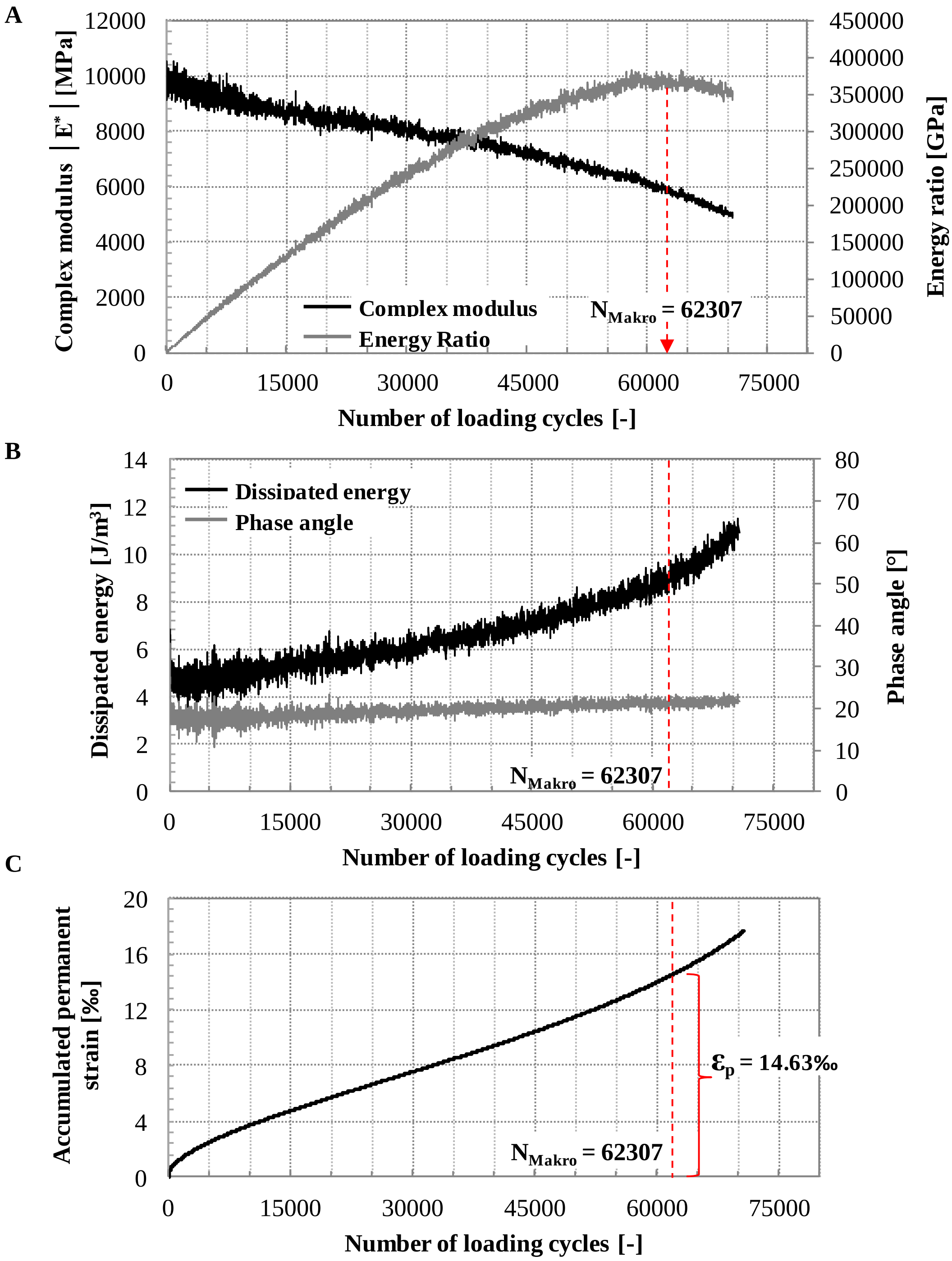

Figure 10: Evolution of the absolute value of complex modulus ,energy ratio, dissipated energy, phase angle and accumulated permanent strain over the number of loading cycles in indirect tensile test at 20°C and at upper stress level of 0.35MPa.

The formulation of Rowe [13] can be used to determine the number of loading cycles at failure when relatively small increase of the phase angle during the test (18% at N_{Makro}) are considered. As a consequence of the material deterioration, the dissipated energy increases from the very beginning of the test. This increase is relatively low compared to the other fatigue tests [4], implying that failure is partially associated with permanent deformation accumulation. Based on high test temperature and material viscosity, the horizontal permanent deformation is generated within increased number of loading repetitions (see Figure 10 C).

Fatigue tests at three different stress levels were conducted for each asphalt mixture and permanent strains were calculated. It was expected that with increasing fatigue life the accumulated permanent strain also increases as a consequence of the longer loading duration and material viscosity. The relationship between number of loading cycles at failure (N_{Makro}) and the accumulated permanent strain for all tested asphalt mixtures is presented in Figure 11. Although moderate linear relationships are achieved it is quite well possible to distinguish different materials by their susceptibility to permanent deformation. In order to compare these results with those form cyclic penetration test, the accumulated permanent strains at N_{Makro} = 10000 (Figure 11, dashed horizontal line) were calculated based on simple linear regression [16]. Figure 12 shows the results. Mixtures AC 32 T S and AC 32 T N show distinct lower values compared to the mixtures for surface course. It is assumed that grain size distribution has a high influence on the permanent deformation induced in the area of the specimen under tension. Gap grading asphalt mixture with high content of course aggregate (SMA 11) showed in this test the worst results. Most probably the specific designed grain size distribution if SMA is favorable for compressive stresses (because of the high particle interlock), but not for tensile stresses.

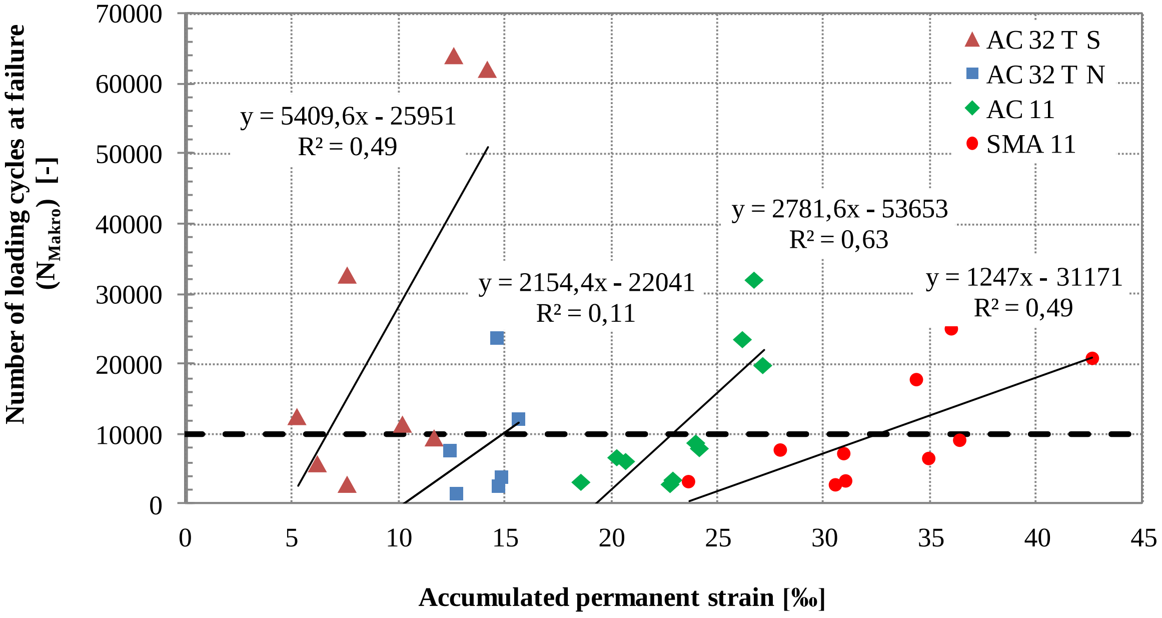

Figure 11: Indirect tensile test: accumulated permanent strain in relationship with the number of loading cycles at failure (N_{Makro}) for AC 32 T S, AC 32 T N, AC 11 and SMA 11.

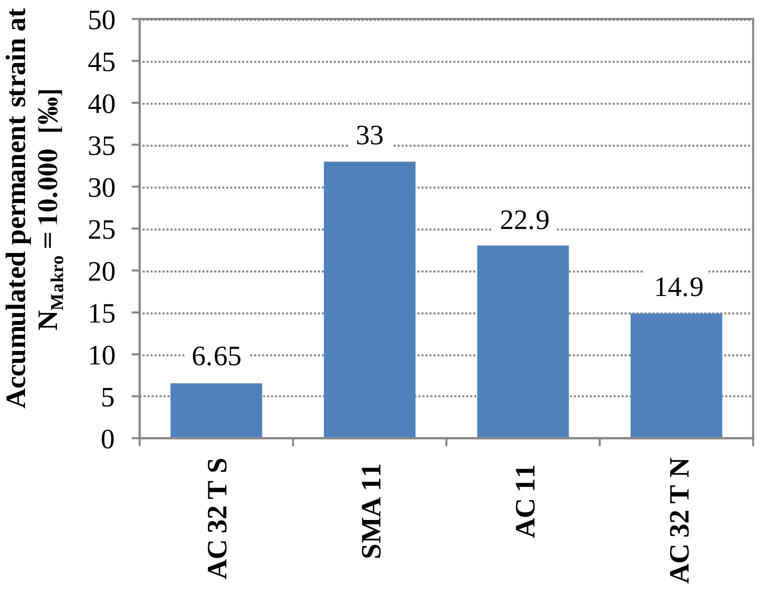

Figure 12: Indirect tensile test: computed accumulated permanent strains at N_{Makro} = 10000 cycles for AC 32 T S, SMA 11, AC 11 and AC 32 T N.

3.3 Results comparison

Based on the dissipated energy approach, a quite different material behavior was observed in both tests. In cyclic penetration test after the initial densification phase, no change of mechanical properties was found, even though permanent deformation constantly increased. On the other hand, in indirect tensile test, the dissipated energy was increasing with increased permanent deformation, indicating a change in mechanical properties over the entire test.

In order to qualitatively compare the results from both of tests, the accumulated permanent strains (at the end of test - after 10000 cycles for penetration test and at N_{Makro} = 10000 for indirect tensile test) were put in correlation with the accumulated strain of AC 32 T S mixture (where the accumulated strain of AC 32 T S was set to 1) (see Table 5 and Figure 13). It can be seen that the indirect tensile test results in different mixture ranking with respect to permanent deformation resistance when compared to the cyclic penetration test.

Table 5: Accumulated permanent strains in cyclic penetration test and indirect tensile test for all tested mixtures and relative correlation to AC 32 T S mixture

Asphalt type	**Cyclic penetration test**		**Indirect tensile test**	
	Accumulated permanent strain at the end of the test [‰]	Relative strain to AC 32 T S [-]	Accumulated permanent strain at N_{Makro} = 10000 cycle [‰]	Relative strain to AC 32 T S [-]
AC 32 T S	20.24	**1.0**	6.65	**1.0**
SMA 11	36.02	**1.78**	33.0	**4.96**
AC 11 D	38.20	**1.89**	22.9	**3.44**
AC 32 T N	42.19	**2.08**	14.9	**2.24**

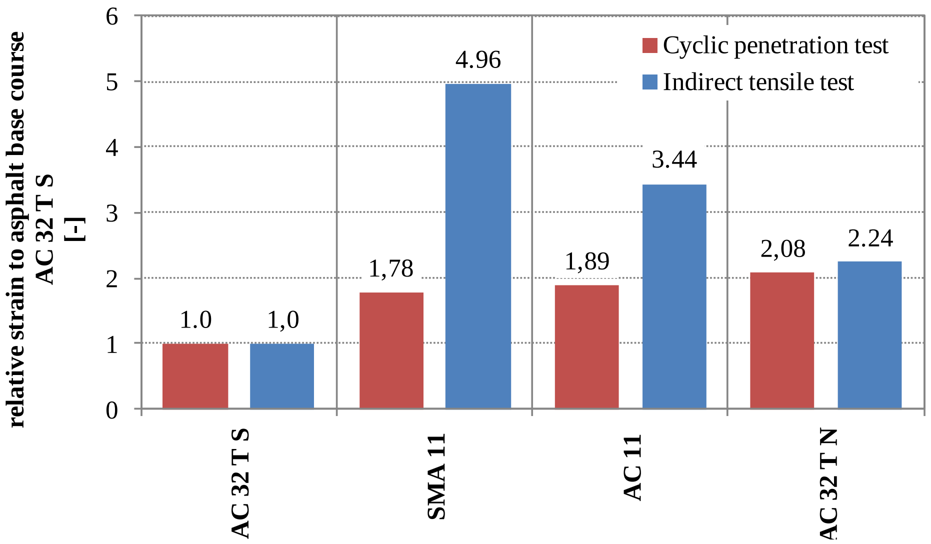

Figure 13: Comparison of the test results; relative correlation to AC 32 T S mixture in cyclic penetration test and indirect tensile test from the strain values given in Table 5.

4. CONCLUSIONS

In this paper an experimental study was performed to determine whether the permanent deformation development and accumulation in the indirect tensile fatigue test correlate with those from common used compression tests.

For that purpose the cyclic penetration test with supporting ring was employed and its results were compared with results from indirect tensile test. Permanent deformation tests were performed on four asphalt mixtures, while analysis of material behavior was based on the dissipated energy concept.

It has been shown that material behavior observed in both test is quite different. The cyclic compression test is characterized by initial densification phase, where dominant elastic properties are observed. After the initial phase, permanent deformation continued to increase, without any change in material properties. This indicates that the densification under load is so far completed and further deformation increase is caused essentially by shear deformation. In indirect tensile test the dissipated energy increased with increased permanent deformation, indicating change in mechanical properties over the test duration.

Based on this research it can be confirmed that the permanent deformation development under compression does not correlate with the permanent deformation accumulation under tensile stress state. Indirect tensile test results in different mixture ranking with respect to permanent deformation resistance compared to the cyclic penetration test. Therefore, this type of test cannot be used for evaluation of both fatigue resistance and permanent deformation resistance (under compression) at the same time.

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