Reuse of Linz-Donawitz (LD) Slag in Asphalt Mixtures for Pavement Application

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ABSTRACT. Standard asphalt mixtures for road infrastructures consist of natural aggregate and bitumen. A number of research efforts have successfully investigated the possibility of replacing the conventional aggregate skeleton with industrial by-products such as slag originating from steel production process. However, little is known on the effect of steel slag on the mixtures functional performance and properties such as resistance to low temperature cracking and to permanent deformation, stiffness and fatigue.

This paper presents a comprehensive and extensive investigation on the fundamental performance properties of different types of asphalt mixtures prepared with 100% LD slag aggregate. A conventional asphalt mixture containing natural Gabbro aggregate was also prepared for comparison purposes, while sophisticated testing methods and procedures were used to evaluate the key performance parameters for the set of asphalt mixtures investigated.

Low temperature cracking represents a serious distress for asphalt pavements built in cold regions. This phenomenon is induced either by single low temperature event or multiple freeze thaw cycles and it is associated to further damage due to traffic loading. In this study, low temperature cracking was addressed through Thermal Stress Restrained Specimen Tests.

Penetration Tests and Cyclic Compression Tests were used to evaluate the response of asphalt binder and asphalt mixture to permanent deformation due repeated loading, respectively. The Cyclic Indirect Tensile Test was selected for investigating both stiffness properties and fatigue resistance. For this purpose the complex stiffness modulus was measured to quantify material stiffness under different temperature and loading conditions providing information on the visco-elasto-plastic material behavior. Fatigue tests were used to determine the progressive and localized material damage caused by cyclic loading.

In addition, skid resistance properties were analyzed with the Wehner/Schulze Polishing machine and by calculating the Polished Stone Value.

The experimental results and the analysis conducted in the present investigation indicate that asphalt mixtures prepared with LD slag are suitable for asphalt pavement construction and that in most cases they perform better than conventional asphalt mixtures prepared with Gabbro aggregate.

KEYWORDS: LD Slag, Low Temperature Cracking, Permanent Deformation, Fatigue.

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1 Background and scope

1.1 Use of slag in asphalt mixtures

The production process of steel results in a significant amount of slag by-product: approximately 1 ton of slag per 3 tons of stainless steel [1]. For Europe every year nearly 12 million tons of steel slag is produced. The European Union has among its targets an efficient use of natural resources; within this framework, the asphalt industry needs to recycle industrial wastes such as steel slags.

In Germany, the use of slags in asphalt mixtures has a long tradition. A number of research efforts were performed by the German Research Association on blast furnace and steel slags, so that the material characteristics of slags are well known [2]. At international level, research activities centered their effort on addressing the chemical and physical properties of slags used in asphalt mixtures. Wu et al. evaluated the possibility of using steel slag as aggregate in stone mastic asphalt (SMA) mixtures; mechanochemistry and physical changes of the steel slag were investigated through X-Ray Diffraction (XRD) analysis, Scanning Electron Microscopy (SEM), Thermogravimetry Analysis (TGA) and mercury porosimeter tests [3]. Based on the experimental results, they concluded that steel slags can be used as aggregate since they represent an alternative, cost effective and environmentally friendly aggregate source [4]. The use of steel slag in asphalt mixture was also addressed by Hassan and Khabiri [5] and Norman et al. [6] based on Marshall and stability tests according to European Standard EN 12697-34 [7]. Kara et al. used steel slag to prepare asphalt pavement mixtures for base, binder and wearing courses [8], [9]; according to the authors, the physical properties of steel slag satisfied the standards requirements for asphalt mixture production. Regarding skid resistance of asphalt mixture containing steel slag, Asi stated that mixtures containing 30% slag have the highest skid number compared to Superpave, SMA, and Marshall mixtures [10]. In addition, a positive effect of steel slag on rutting resistance and fatigue performance was identified [11].

One of the most critical possible drawbacks associated to the use of steel slag is volume expansion caused by hydration of lime or magnesia components. Hence, high levels of free lime or magnesia may cause cracking of asphalt pavement. The simplest solution to limit this deleterious effect is obtained by aging slags or by accelerating the hydration reaction with water. Alternatively, slag washing can be used, so that minimal volume expansion occurs [12].

1.2 Objective

The objective of the present research is to determine how the use of LD slag in asphalt mixtures affects the functional performance of pavement construction, and specifically, in comparison to conventional mixture prepared with natural aggregate such as Gabbro. The results of this study and the recommendation for construction process are discussed in this paper.

2 Research approach

The research approach used in this study is based on an extensive experimental program which includes different test methods to assess the mechanical response and the performance of the asphalt mixture composite prepared with different aggregates: steel slag and natural Gabbro. The following properties were evaluated on a set of 8 asphalt mixture variants used in the different structural layers which an asphalt pavement is made of: surface, binder and base layers [13]:

- Resistance to permanent deformation;
- Stiffness;
- Fatigue resistance,
- Resistance to low temperature cracking;
- Skid resistance of the surface layer.

3 Materials

A total of 8 asphalt mixtures were prepared in the asphalt pavement laboratory. Four different types of mixtures, each with natural Gabbro aggregate and LD slag, were designed using a standard 50/70 asphalt binder and a SBS modified binder with 45/80-65 penetration grade according to European Standard EN 1426 [14] and ring and ball temperature according to European Standard prEN 1427 [15]:

- MA 11 S (surface layer, mastics asphalt, high filler content),
- SMA 11 S (surface layer, stone-mastic-asphalt, low filler content),
- AC 16 B S (binder layer, asphalt concrete with a maximum aggregate size of 16 mm),
- AC 22 T S (base layer, asphalt concrete with a maximum aggregate size of 22 mm).

Table 1 provides a summary of the asphalt mixtures used.

Table 1: Asphalt mixtures

Asphalt mixture, layer	Asphalt binder type	Gabbro*	LD-Slag
Mastic asphalt, surface layer	MA 11 S, SBS 45/80-65	M1	M2
Rolled asphalt, surface layer	SMA 11 S, 50/70	S1	S2
Rolled asphalt, binder layer	AC 16 B S, SBS 45/80-65	B1	B2
Rolled asphalt, base layer	AC 22 T S, 50/70	T1	T2

*Reference aggregate

Asphalt mixtures were chosen to ensure that all layers of an asphalt pavement structure (surface layer, binder layer and base layer) are taken into account. Furthermore, conventional asphalt mixtures with different filler content were used. The corresponding mix design was chosen in accordance with the German Technical Standard: TL Asphalt -StB 07, [16].

4 Test methods

In order to address the performance characteristics, durability and skid resistance of asphalt with LD slag and with conventional (natural) Gabbro aggregate, asphalt specimens were produced and then tested according to the methods described hereafter. The results obtained from asphalt mixtures prepared with LD slag were then compared to the experimental data measured on asphalt mixtures containing natural Gabbro aggregate. Results and discussion are presented in section 5.

4.1 Resistance to permanent deformation

Deformation resistance was addressed by

- Cyclic Compression Test in accordance with European Standard EN 12697-25 [17] and German Standard TP Asphalt -StB , Part 25 B1 [18] respectively, (rolled asphalt SMA 11 S, AC 16 B S and AC 22 T S) and
- Penetration Test in accordance with European Standard EN 12697-25 [17] and German Standard TP Asphalt -StB, Part 25 A1 [19] respectively, (mastic asphalt MA 11 S).

In Cyclic Compression Test (Figure 3, left) a cylindrical specimen is subjected to repeated pulsed compressive load for 0.2s, followed by a 1.5s rest period at a test temperature of 50°C. During the test irreversible deformations along the loading direction are recorded for each load cycle. The specimen is positioned centrally under the loading frame to ensure most homogeneous load distribution.

The load curve is characterized by the lower stress level σ_u and the upper stress level σ_o (Figure 1). σ_u ensures contact between specimen and load stamp. The test starts with the application of the first load cycle. A constant upper stress of $\sigma_o = 0.35$ MPa was chosen for testing.

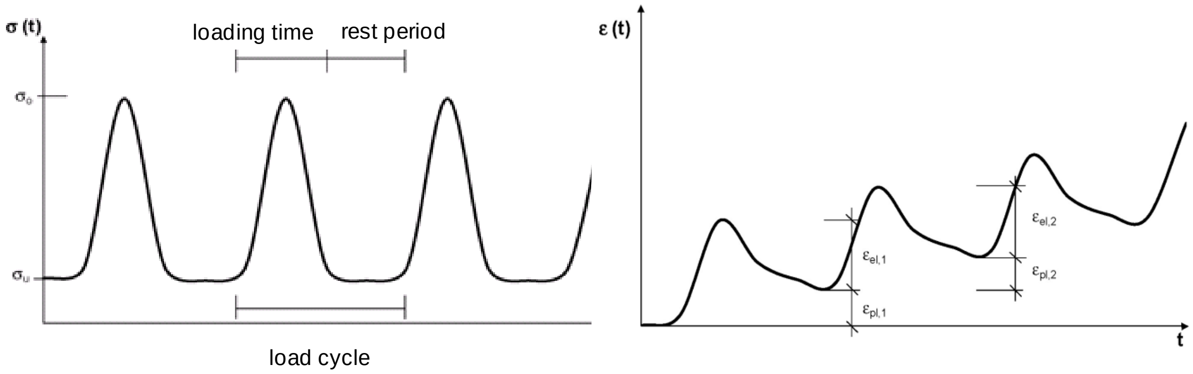

Figure 1. Loading conditions and resulting strains elastic (ε_{rl}) and plastic (ε_{pl}) in the Cyclic Compression Test.

Test ends as soon as 10,000 cycles are reached or when a deformation of 40‰ is exceeded. The basis of evaluation is the creep curve, which shows the evolution of the irreversible permanent deformations in the specimen (Figure 2).

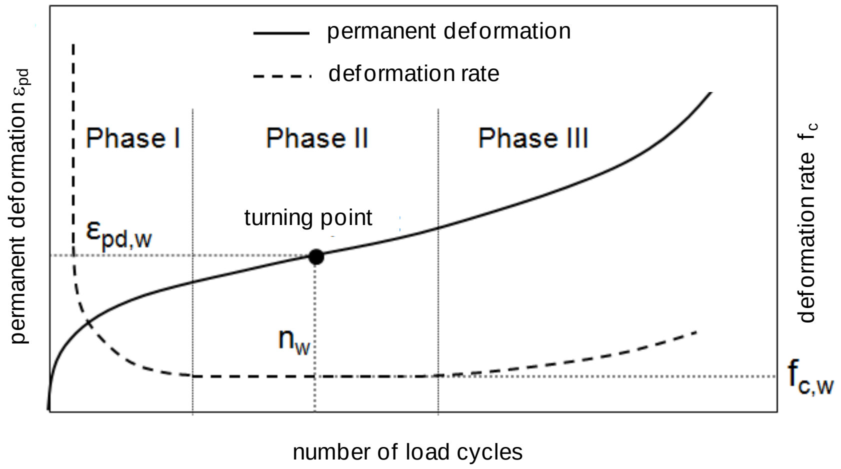

Figure 2. Creep curve as a result of Cyclic Compression Test.

For the evaluation of deformation resistance, phase II of the creep curve is of particular importance; within Figure 2 the following parameters are used for characterization:

- Number of load cycles at the turning point n_w [-],
- Strain at the turning point ε_w [‰],
- Strain rate at the turning point ε_w* [‰ * 10^{-4} / n].

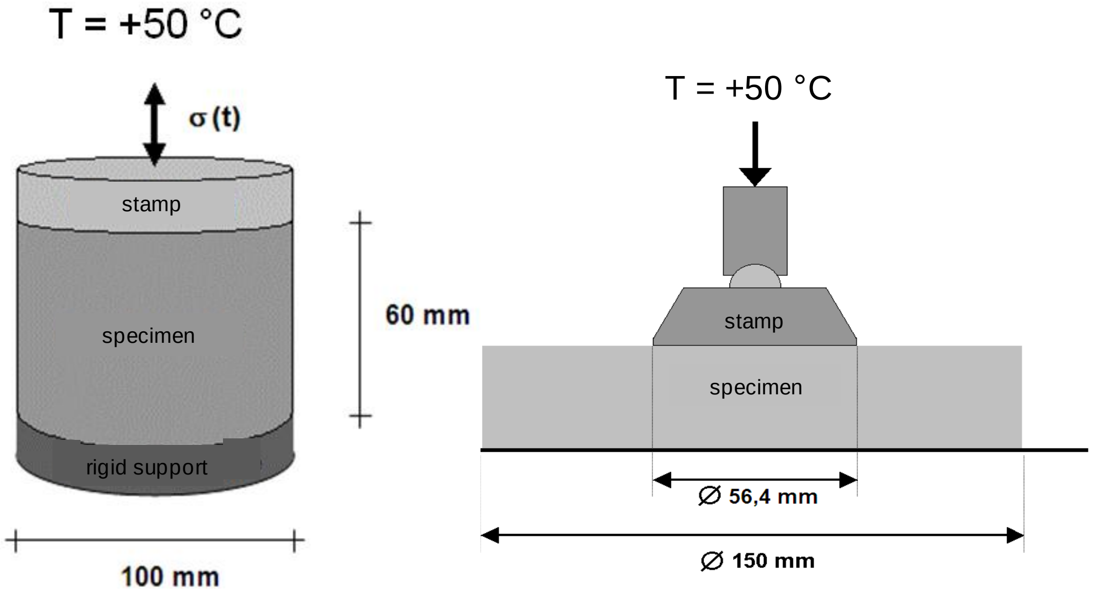

Figure 3. Cyclic Compression test principle (right), Penetration test principle (left).

In the Penetration test (Figure 3, right) the dynamic penetration (ET_{dyn}) is determined. The specimen is subject to a sinusoidal load for 0.2s followed by a rest period of 1.5s. The test ends when 2,500 load cycles (= load pulse + rest period) are reached. Penetration depth at end of test is documented. The test temperature was set to 50°C.

4.2 Stiffness and fatigue resistance

Stiffness and fatigue resistance (cracking resistance to repeated loading) is addressed by Cyclic Indirect Tensile Test according to the European Standard EN 12697-24 [20], and to German Standard AL Sp-Asphalt 09 respectively [21]. A sinusoidal load is applied to a cylindrical asphalt specimen via two diametrically opposite load transfer rails. To stabilize the position of the asphalt specimen in the loading frame, a seating load equivalent to a stress of σ_u = 0.035 MPa is applied, while the maximum stress σ_o is chosen based on elastic horizontal strain ε_{el} between 50 and 100 µm/m. Tests were carried out in a temperature-frequency sweep mode as shown in Table 2. Resulting parameter is stiffness modulus in function of frequency, represented by isotherm plot and by master curve plot.

Table 2. Experimental parameters for the determination of stiffness based on Cyclic Indirect Tensile Test according to EN 12697-24 and Al Sp-Asphalt 09.

Parameters	**Values/Response**
Test Temperature [°C]	+20; +10; 0; -10
Loading frequency [Hz]	0.1, 1, 5 und 10
Results	Stiffness modulus $\lvert E \rvert$ in [MPa] and Master-Curve

Fatigue performance is obtained based on a continuous cyclic loading procedure in the non-linear domain. Stress is varied in a way that initial strains are in a range of 0.05 to 0.30‰ and the number of load cycles until macro cracking (drop in stiffness modulus by 50%) is in the range of 10.000 to 1.000.000 load cycles. on Cyclic Indirect Tensile Test were carried out under the conditions specified in Table 3. Resulting parameters are the number of load cycles until macro cracking, and the material-specific fatigue function.

Table 3. Experimental parameters for the determination of fatigue performance by Cyclic Indirect Tensile Test according to EN 12697-24 and Al Sp-Asphalt 09.

Parameters	**Values/Response**
Test Temperature [°C]	+20
Loading frequency [Hz]	10
Results	• Number of load cycles until macro crack • Fatigue function $N_{Makro} = C_1 \cdot \varepsilon_{el,anf}^{C_2}$ with material specific parameters C_1 und C_2

4.3 Resistance to low temperature cracking

In order to determine the resistance to low temperature cracking, prismatic asphalt specimens were subjected to Thermal Stress Restrained Specimen Tests in accordance with European Standard EN 12697-46 [22] and German Standard "Technische Prüfvorschrift Verhalten von Asphalten bei tiefen Temperaturen" respectively [23].

Prior to the test, prismatic specimen having dimensions 40x40x160 mm³ were glued to steel adapters. After a minimum of 48h glue curing, specimens are installed in the test device, see Figure 4.

During Thermal Stress Restrained Specimen Test, the length of the specimen is held constant through a set of linear variable displacement transformer (LVDT), while its temperature is decreased from an initial value of T = + 20°C with a constant cooling rate of ΔT = -10°C/h. A close-loop control system keeps the specimen at constant length. Due to the prohibited thermal shrinkage, the specimen is subjected to an increasing (cryogenic) tensile stress. The test ends at a minimum test temperature of T = - 40°C or at failure, when the cryogenic stress exceeds the tensile strength of the asphalt mixture, respectively.

The test returns a temperature-dependent function of cryogenic stress $\sigma_{cry}(T)$ [MPa], a failure stress σ_F [MPa] and a failure temperature T_F [°C].

Figure 4. Test device used for conducting Thermal Stress Restrained Specimen Test.

4.4 Skid resistance

The skid resistance of the surface layer of an asphalt pavement is addressed by measuring the friction coefficient according to German Standard TP Gestein-StB, Part 5.4.2 [24]. For this purpose a Wehner / Schulze machine (Figure 4) is used to polish the specimen surface, and thus friction.

One side of the disk-shaped asphalt specimen is first polished so that the aggregate surfaces are partially exposed. The surface is then treated by sandblasting, so that the residual binder and mortar are completely removed. The specimen is initially subjected to polishing followed by a measurement of the friction coefficient in the test device (Figure 5). In the polishing process, the simulation of traffic exposure occurs through three operating slip rubber rollers which polish the specimen surface for 1 hour at 500 rounds per minute. In addition, the polishing effect is intensified by the continuous injection of a water-quartz powder mixture to the specimen surface to ensure an effective and accelerated simulation of the traffic action. The friction coefficient measurement is realized by 3 circumferential rotating (100 km/h) measuring rubber bodies that are lowered onto the specimen wet surface and are thereby braked. As a result, the friction force needed to stop the measurement rubber body is recorded. The friction coefficient is calculated from the friction force in relation to the vertical force of the measuring rubber body at 60 km/h.

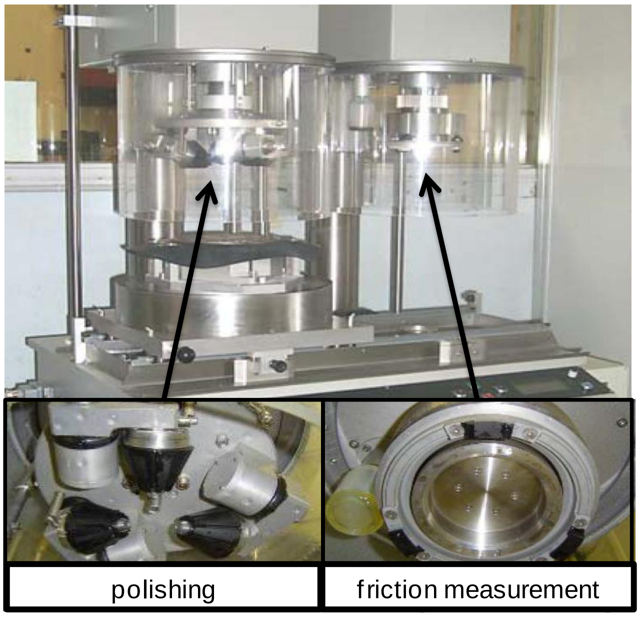

Figure 5. Wehner/Schulze machine to address the skid resistance by determining the friction coefficient.

5 Results and discussion

5.1 Resistance to permanent deformation

Penetration depths observed for mastic asphalt (MA 11 S with LD slag and with natural Gabbro aggregate) are shown in Figure 6, (left). After 2,500 load cycles MA 11 S with LD slag showed much lower penetration depth compared to the MA with natural Gabbro aggregate.

The use of LD slag in mastic asphalt leads to an advantageous deformation resistance compared to mastic asphalt with natural Gabbro aggregate.

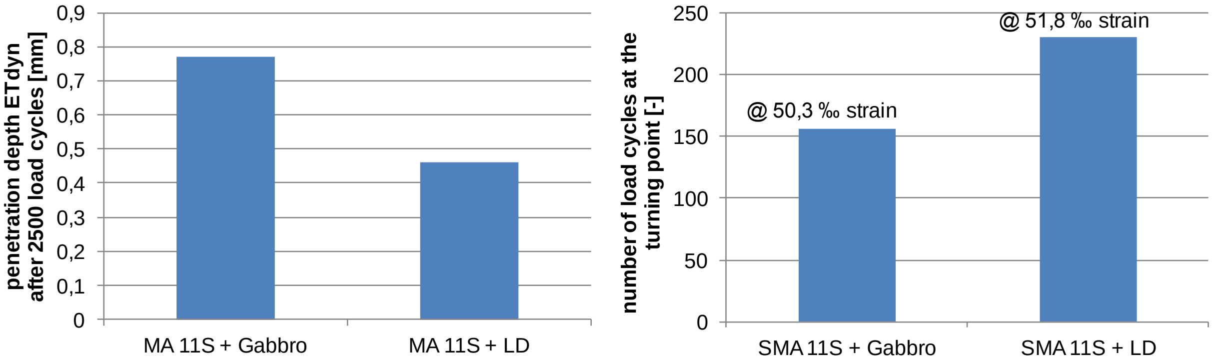

Figure 6. Deformation resistance of mastic asphalt MA 11 S with LD slag and natural Gabbro aggregate (left); deformation resistance of stone mastic asphalt SMA 11 S with LD slag and natural Gabbro aggregate (right).

Deformation resistance of stone mastic asphalt SMA 11 S (Figure 6, right) shows the same tendency as for the mastic asphalt variants. The number of tolerable load cycles until the turning point of the SMA with LD slag is significantly higher than for the SMA 11 S with natural aggregate Gabbro. The resulting strains are comparable in magnitude. Hence, a trend similar to those observed for MA is shown by the SMA when using LD-slag.

The deformation resistance in terms of number of load cycles at the turning point for the asphalt mixture for binder and base courses (AC 16 B S and AC 22 T S with LD slag and with natural Gabbro aggregate, respectively) is shown in Figure 7. The results indicate an opposite trend compared to the asphalt mixtures for surface layer (MA and SMA). The number of tolerable load cycles until the turning point is much lower for mixtures prepared with LD slag; the resulting strains are comparable in magnitude.

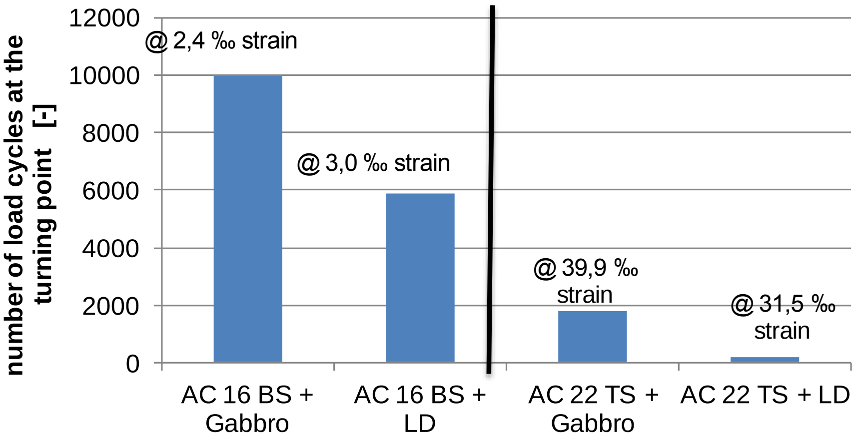

Figure 7. Deformation resistance of asphalt binder AC 16 B S with LD slag and natural Gabbro aggregate (left); deformation resistance of asphalt base course AC 22 T S with LD slag and natural Gabbro aggregate (right).

Concerning the disadvantageous deformation behavior of the asphalt binder and asphalt base mixtures prepared with LD slag it has to be noted that similar mix design (same gradation and bitumen content) was used for mixtures containing natural and recycled aggregates. Consequently, LD slag mixtures showed higher air voids contents (up to 3.0 vol.-%). This is probably due to a higher asphalt binder demand of LD slag associated to their porous structure. High air voids contents negatively affect stiffness and resistance to permanent deformation.

5.2 Stiffness and fatigue resistance

The stiffness of the asphalt surface mixtures (mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S, each with LD slag and natural Gabbro aggregate) is shown in Figure 8 in terms of modulus *E* (complex modulus) in function of temperature. The resulting stiffness is for all asphalt surface mixtures at a comparable level, regardless of whether LD slag or natural Gabbro aggregate was used.

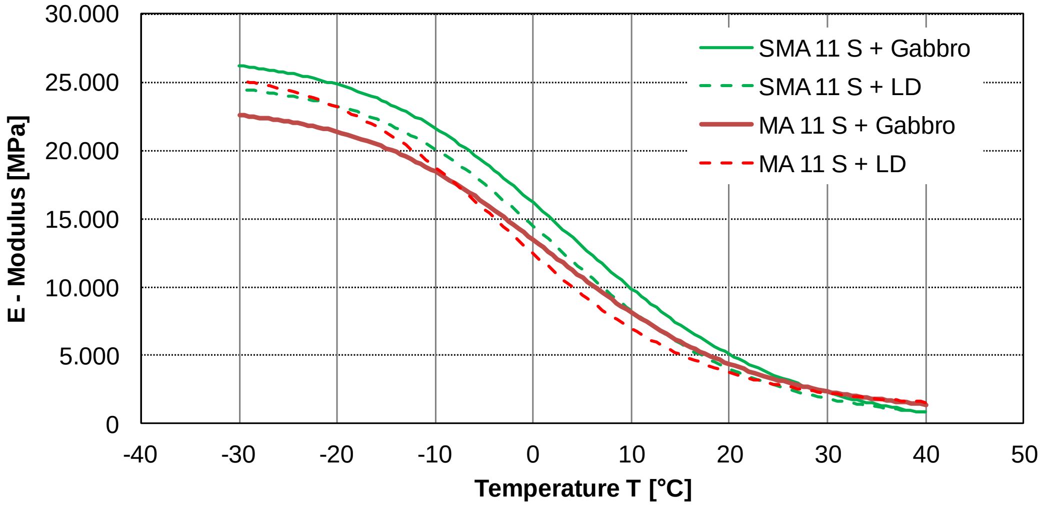

Figure 8. Stiffness of mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S: *E*-Modulus [MPa] in function of temperature, observed on asphalt mixtures with LD slag (dashed lines) and with natural Gabbro aggregate (full lines).

The stiffness of the asphalt binder and asphalt base course mixtures (AC 16 B S and AC 22 T S, each with LD slag and natural Gabbro aggregate) are shown in Figure 9. Also in this case, the *E*-modulus is comparable, both when using LD slag and natural Gabbro aggregate.

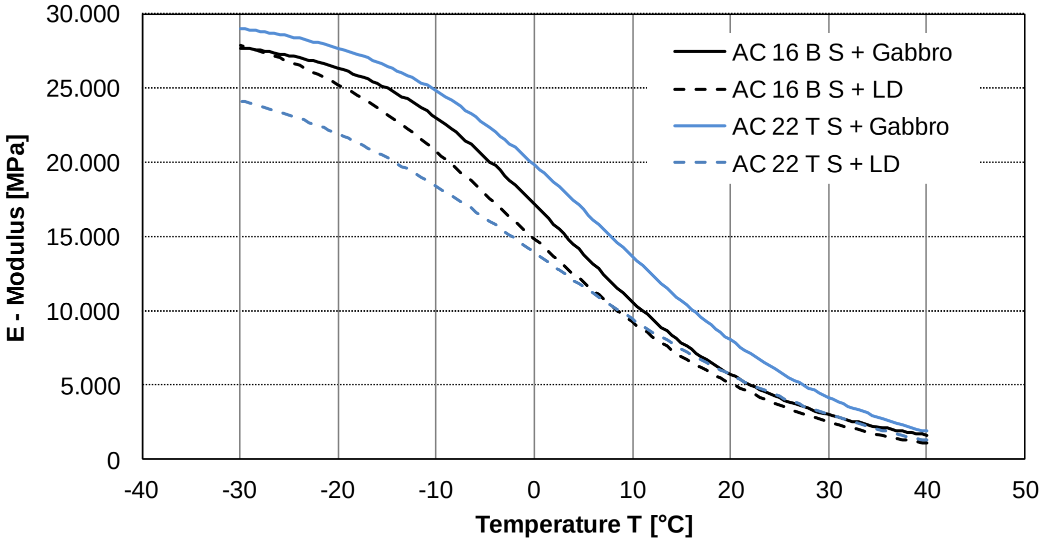

Figure 9. Stiffness of asphalt binder AC 16 B S and asphalt base course AC 22 T S: *E*-Modulus [MPa] in function of temperature, observed on asphalt mixtures with LD slag (dashed lines) and with natural Gabbro aggregate (full lines).

Overall, a minimal decrease in stiffness can be observed for mixture prepared with LD slag. Nevertheless, this is negligible and does not significantly affect the performance of asphalt pavement under traffic loading.

Fatigue resistance of the asphalt surface mixtures (mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S, each with LD slag and natural Gabbro aggregate) are shown as Wöhler curves in Figure 10. Similar fatigue resistance is shown for mixtures prepared from natural and recycled aggregates (LD slag).

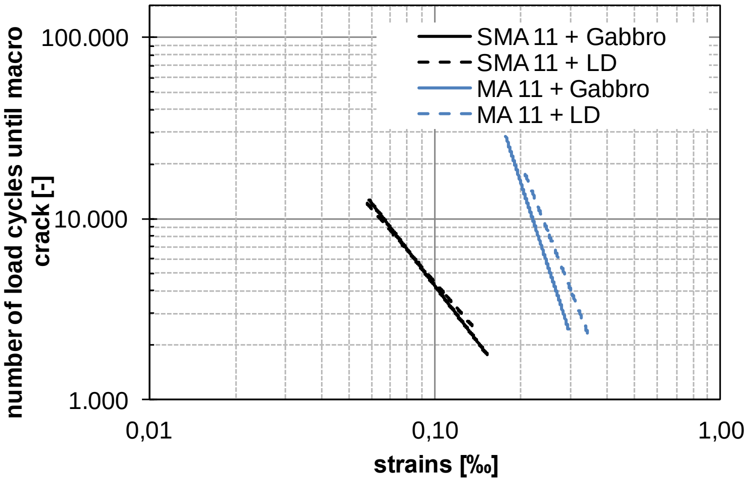

Figure 10. Fatigue resistance of mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S: Wöhler curves observed for asphalt variants with LD slag (dashed lines) and with natural Gabbro aggregate (full lines).

Fatigue resistance of the asphalt binder and asphalt base course variants (AC 16 B S and AC 22 T S, each with LD slag and natural Gabbro aggregate) are shown as Wöhler curves in Figure 11.

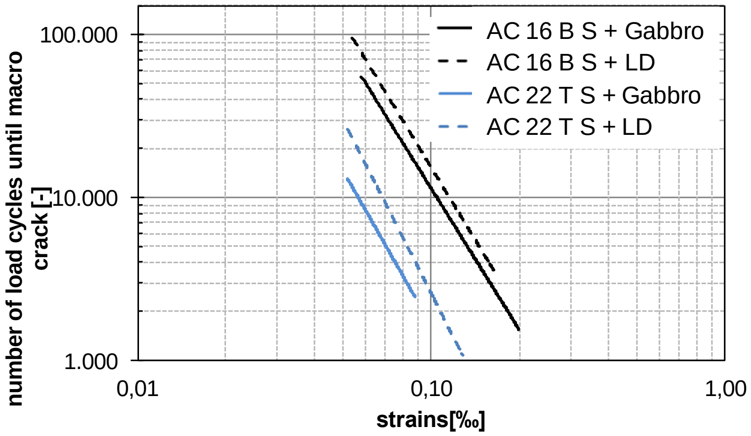

Figure 11. Fatigue resistance of asphalt binder AC 16 B S and asphalt base course AC 22 T S: Wöhler curves observed for asphalt variants with LD slag (dashed lines) and with natural Gabbro aggregate (full lines).

The Wöhler curves of asphalt binder and asphalt base mixtures with LD slag are shifted upwards in an almost parallel manner with respect to those of the mixtures containing natural aggregate. Thus, for the same elastic strain, mixtures with LD slag can sustain a higher number of load cycles before a macro crack (material failure) appears. Therefore, the experimental results indicate that the use of LD slag in asphalt binder and asphalt base course mixtures leads to a higher fatigue resistance in comparison to mixture designed with natural Gabbro aggregate.

5.3 Resistance to low temperature cracking

The resistance to low temperature cracking of the asphalt surface mixtures (MA 11 S and SMA 11 S, each with LD slag and natural Gabbro aggregate) were determined based on

Thermal Stress Restrained Specimen Tests. Figure 12 shows the cryogenic failure stresses (maximum stress until failure) while Figure 13 presents the corresponding temperatures at failure.

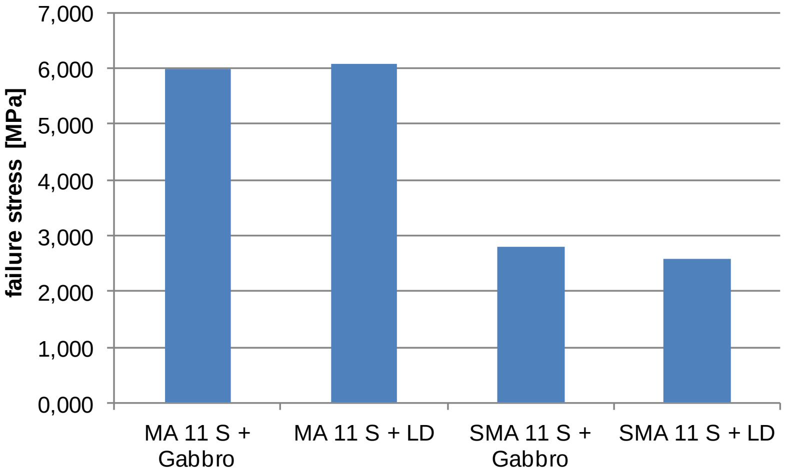

Figure 12. Resistance to low temperature cracking of mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S: failure stress [MPa] observed for asphalt mixtures with LD slag and with natural Gabbro aggregate.

The parameters describing the resistance to low temperature cracking are comparable for all asphalt surface mixtures prepared with LD slag or natural aggregate. The failure stresses observed are at a high (good) level. This level is typical for commonly used asphalt pavement surface layers in Europe. The failure temperatures are below T = -20°C (marked in Figure 13), and thus on a non-critical level for thermal cracking.

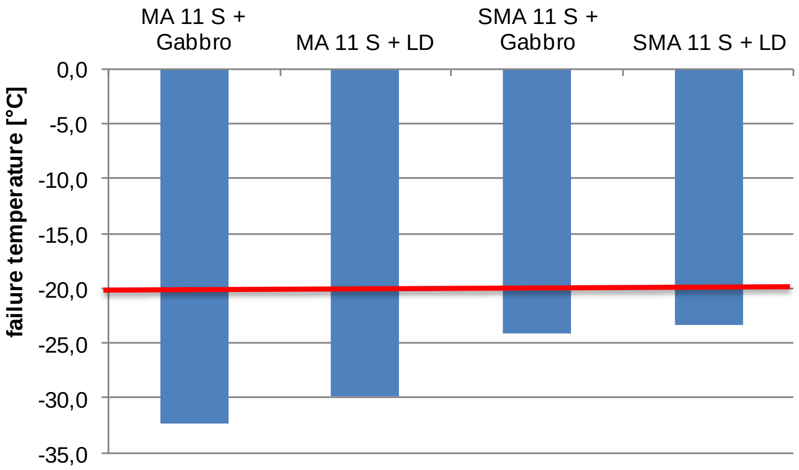

Figure 13. Resistance to thermal cracking of mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S: failure temperature [°C] observed for asphalt mixtures with LD slag and with natural Gabbro aggregate.

The resistance to thermal cracking of the asphalt binder and asphalt base course mixtures (AC 16 B S and AC 22 T S, each with LD slag and natural Gabbro aggregate) is shown in Figure 14 and Figure 15.

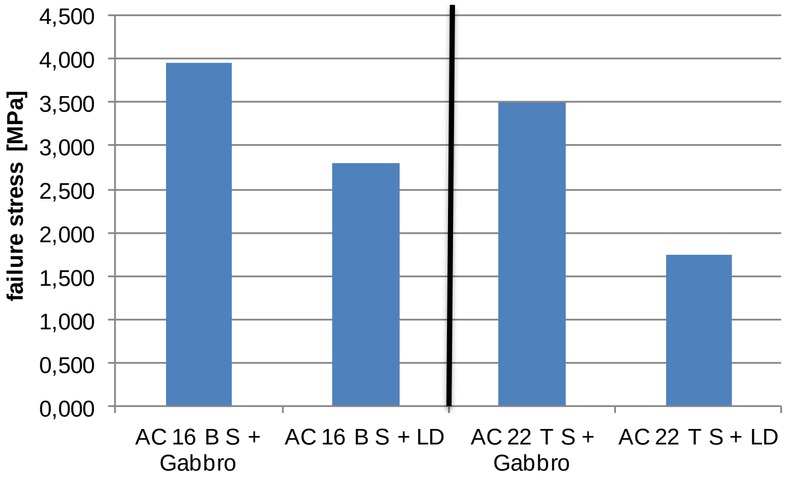

Figure 14. Resistance to low temperature cracking of asphalt binder AC 16 B S and asphalt base course AC 22 T S: failure stress [MPa] observed for asphalt mixtures with LD slag and with natural Gabbro aggregate.

The parameters describing the resistance to thermal cracking indicate that the low-temperature behavior of mixtures with LD slag tends to provide relatively poor performance compared to the mixture with natural Gabbro aggregate. The failure stresses are lower and the failure temperatures are higher. However, the level is evaluated as "adequate" for European weather conditions.

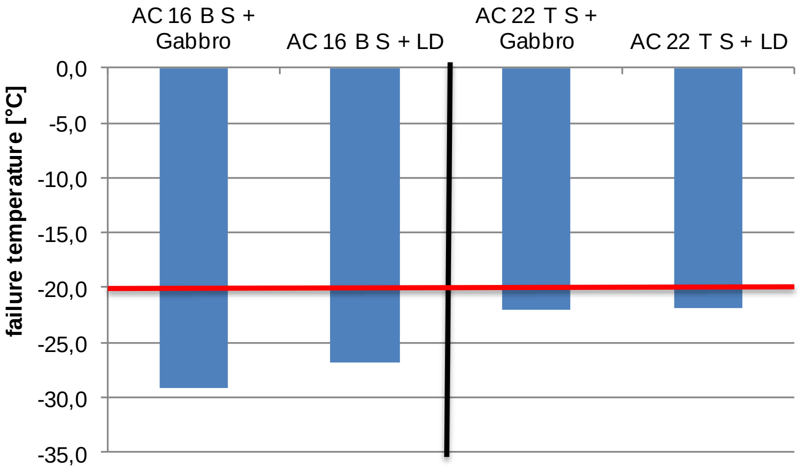

Figure 15. Resistance to thermal cracking of asphalt binder AC 16 B S and asphalt base course AC 22 T S: failure temperature [°C] observed for asphalt mixtures with LD slag and with natural Gabbro aggregate.

5.4 Skid resistance

Skid resistance of the asphalt surface mixtures (mastic asphalt MA 11 S and stone mastic asphalt SMA 11 S, each with LD slag and natural Gabbro aggregate) was addressed by measuring friction coefficients after 90,000 and 180,000 polishing cycles shown in Figure 16.

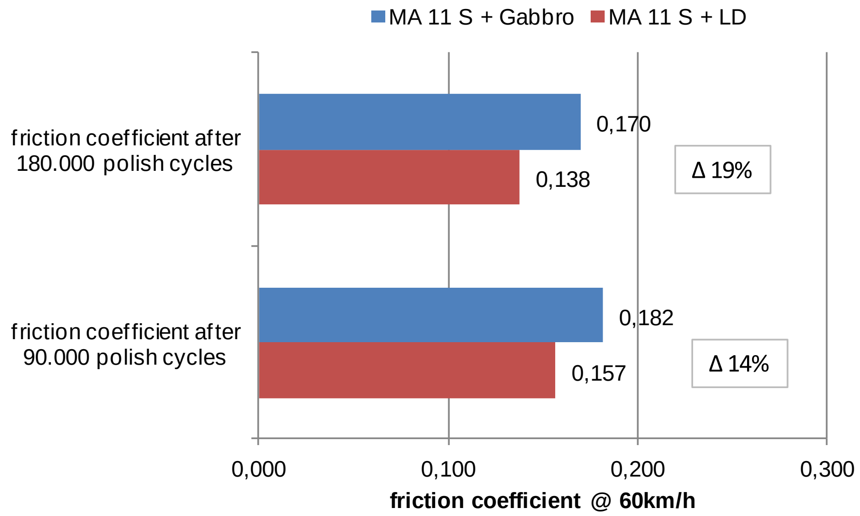

Figure 16. Skid resistance of a surface layer from mastics asphalt MA 11 with LD slag compared to that with natural Gabbro aggregate.

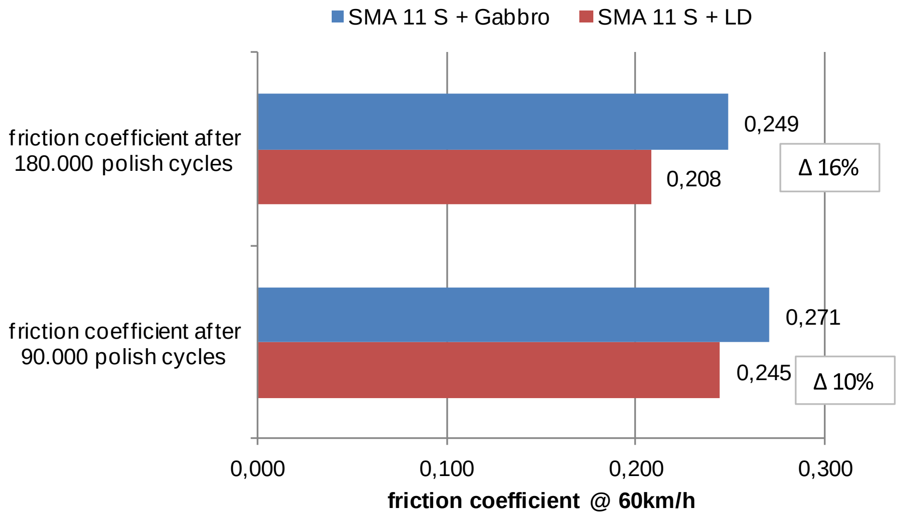

Figure 17. Skid resistance of a surface layer from stone mastic asphalt SMA 11 S with LD slag compared to that with natural Gabbro aggregate.

It is observed that the resulting friction coefficients of the mixtures with LD slag after 90,000 and 180,000 polishing cycles are about 15 to 20% lower than the friction coefficients of the mixtures with natural Gabbro aggregate in the case of MA mixtures and about 10 to 16% lower for SMA mixtures. Thus, the skid resistance of mixtures with LD slag is slightly lower compared to mixtures prepared with natural aggregate. Nevertheless, the friction coefficients are at a very high level which can be assumed as satisfactory for safety purposes.

6 Summary and conclusions

In this paper the fundamental performance properties of different types of asphalt mixtures prepared with 100% LD slag and natural aggregate were investigated. Resistance to permanent deformation, stiffness, fatigue, low temperature cracking, as well as skid resistance of the surface layer mixtures were evaluated based on a comprehensive set of experimental methods. The following conclusions can be drawn:

- The use of LD slag in mastic asphalt leads to an advantageous deformation resistance compared to mastic asphalt with natural Gabbro aggregate. In contrast asphalt binder and asphalt base course mixtures with LD slag showed a lower deformation resistance compared to the mixtures with natural Gabbro aggregate. This can be explained by the volumetric asphalt mixture composition. Due to a higher binder need of LD slag, the mixtures with LD slag showed slightly higher air voids contents resulting in a disadvantageous resistance to deformation.
- The stiffnesses of the asphalt surface, asphalt binder and asphalt base mixtures are at a comparable level, regardless of whether LD slag or natural Gabbro aggregate was used.
- Fatigue resistances for the asphalt surface mixtures are at a comparable level, regardless of whether LD slag or natural Gabbro aggregate was used. The use of LD slag in asphalt binder and asphalt base course leads to a higher fatigue resistance in comparison to mixtures with natural Gabbro aggregate.
- The level of resistance to thermal cracking are comparable for all asphalt mixtures, regardless of whether LD slag or natural aggregate Gabbro was used. The level is evaluated as "adequate" for European weather conditions.
- The skid resistance of variants with LD slag tends to be smaller compared to the variant with natural Gabbro aggregate. However, the friction coefficients are generally at a very high level of skid resistance, which can generally be evaluated as uncritical.

Overall, the experimental results and the analysis conducted in the present investigation indicate that asphalt mixtures prepared with LD slag are suitable for asphalt pavement construction and that in most cases they perform as good as or even better than conventional asphalt mixtures prepared with natural aggregate.

References

[1] D.M. Proctor, K.A. Fehling, E.C. Shay: Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags, Environ. Sci. Technol., 34 (2000), pp. 1576–1582.

[2] Motz, H., Geiseler, J.: Products of steel slags an opportunity to save natural resources, Waste Manage., 21 (2001), pp. 285–293.

[3] Wu, S., Xue, J., Ye, Q., Chen,Y.: Utilization of steel slag as aggregates for stone mastic asphalt (SMA) mixtures, *Build. Environ.*, 42 (7) (2007), pp. 2580–2585.

[4] Xue, Y., Wu, S., Hou, H., Zha, J.: Experimental investigation of basic oxygen furnace slag used as aggregate in asphalt mixture, J. Hazard. Mater., 138 (16) (2006), pp. 261–268.

[5] Hassan, Z., Khabiri, M.: Preventive maintenance of flexible pavement and mechanical properties of steel slag in asphalt J. Environ. Eng. Landscape Manage., 15 (3) (2007), pp. 188b–192b.

[6] Norman, A., Joseph, C., Papagiannakis, T., Theriault, E.G., Bergan, A.T.: Use of Steel Slag in Asphaltic Concrete, 1147 ASTM Special Technical Publication (1992) pp. 3–18.

[7] European Committee for Standardization (CEN): European Standard EN 12697-34. Bituminous mixtures. Test methods for hot mix asphalt. Marshall test, (2012), Brussels.

[8] Kara, M., Gunay, E., Kavakli, B., Tayfur, S., Eren, K., Karadag, G.: The use of steel slag in asphaltic mixture, Key Eng. Mater., 264–268 (III) (2004), pp. 2493–2496.

[9] Kandhal, P. S., Hoffman, G. L.: Evaluation of steel slag fine aggregate in hot-mix asphalt mixtures,Transportation. Research. Record 1583, (1997), pp. 28–36.

[10] Asi, I.M.: Evaluating skid resistance of different asphalt concrete mixes, Build. Environ., 42 (2007), pp. 325–329.

[11] Asi, I.M., Qasrawi, H.Y., Shalabi, F.I.: Use of steel slag aggregate in asphalt concrete mixes, Can. J. Civil Eng., 34 (8) (2007), pp. 902–911.

[12] Kneller, W. A., Gupta, J., Borkowski, M. L., Dollimore, D.: Determination of original free lime content of weathered iron and steel slags by thermogravimetric analysis, Transportation Research Record 1434, National Research Council, Washington, DC, (1994).

[13] MS-4: The Asphalt Handbook, Asphalt Institute, College Park Medison, (1989), Vol. 4.

[14] European Committee for Standardization (CEN): European Standard EN 1426. Bitumen and bituminous binders - Determination of needle penetration, (2013), Brussels.

[15] European Committee for Standardization (CEN): European Standard prEN 1427. Bitumen and bituminous binders - Determination of the softening point - Ring and Ball method, (2013), Brussels.

[16] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Technische Lieferbedingungen für Asphaltmischgut für den Bau von Verkehrsflächenbefestigungen (TL Asphalt-StB 07), (2007). Forschungsgesellschaft für Straßen- und Verkehrswesen, Köln.

[17] European Committee for Standardization (CEN): Bituminous mixtures - Test methods for hot mix asphalt - Part 25: Cyclic compression test, (2005), Brussels.

[18] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Technische Prüfvorschriften für Asphalt im Straßenbau, Teil 25 B 1: Einaxialer Druckschwellversuch – Bestimmung des Verformungswiderstands von Walzasphalt bei Wärme (TP Asphalt-StB, Teil 25 B 1), (2010). Forschungsgesellschaft für Straßen- und Verkehrswesen, Köln.

[19] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Technische Prüfvorschriften für Asphalt im Straßenbau, Teil 25 A 1: Dynamischer Stempeleindringversuch an Gussasphalt (TP Asphalt-StB, Teil 25 A 1), (2010). Forschungsgesellschaft für Straßen- und Verkehrswesen, Köln.

[20] European Committee for Standardization (CEN): Bituminous mixtures - Test methods for hot mix asphalt - Part 24: Resistance to fatigue, (2012), Brussels.

[21] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Arbeitsanleitung zur Bestimmung des Steifigkeits- und Ermüdungsverhaltens von Asphalten mit dem Spaltzug-Schwellversuch als Eingangsgröße in die Dimensionierung von Asphaltbefestigungen (AL-SP – ASPHALT 09), (2009). Forschungsgesellschaft für Straßen- und Verkehrswesen, Köln.

[22] European Committee for Standardization (CEN): Bituminous mixtures - Test methods for hot mix asphalt - Part 46: Low temperature cracking and properties by uniaxial tension tests, (2012), Brussels.

[23] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Technische Prüfvorschrift Verhalten von Asphalten bei tiefen Temperaturen. (1994).

[24] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Technische Prüfvorschriften für Gesteinskörnungen im Straßenbau, Teil. 5.4.2: Bestimmung des Polierwertes mit den Verfahren nach Wehner/Schulze (TP Gestein-StB, Teil 5.4.2), (2010). Forschungsgesellschaft für Straßen- und Verkehrswesen, Köln.