Experimental Investigation on the use of Linz-Donawitz steel slag in asphalt mixture

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Padua, Italy, December 14, 2017

Experimental Investigation on the use of Linz-Donawitz and EAF steel slags in asphalt mixture

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Outline

Two-case study

- Linz-Donawitz slag
  (Germany and Austria)

- Electric Arc Furnace Steel Slag – EAFSS
  (South Korea and Germany)

What is LD-Slag

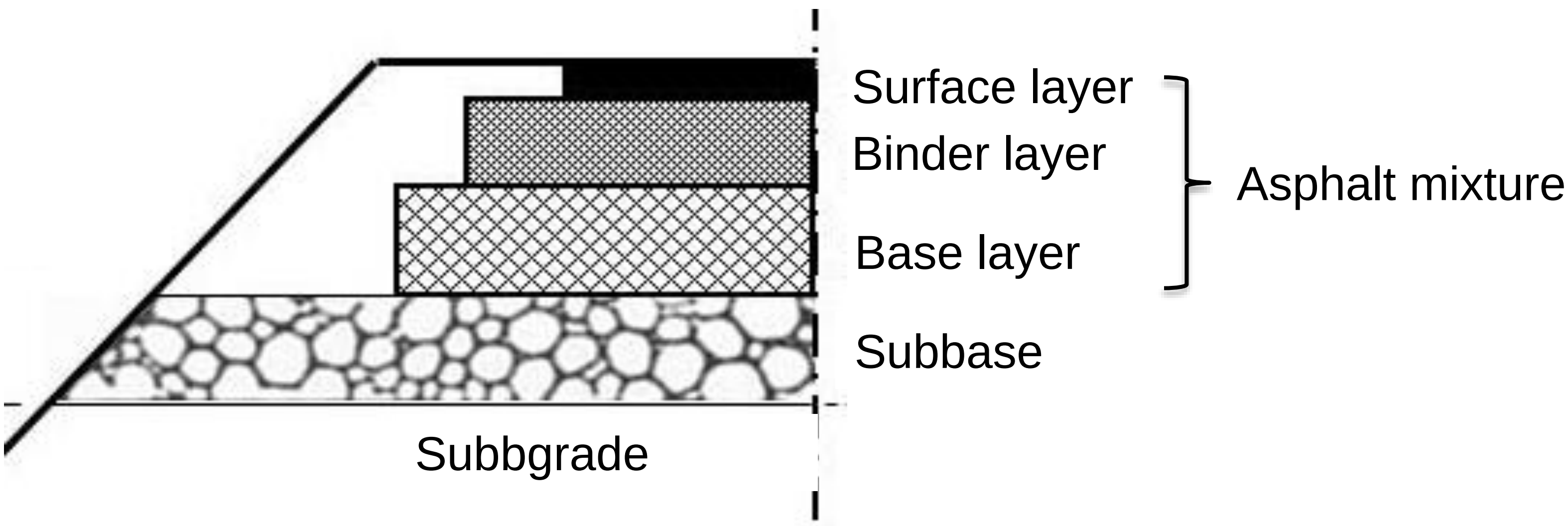
- Byproduct of steel production (LD process) as pig iron is processed into crude steel
- Slag is derived from the crude steel and separately processed
- Main components: iron oxide, calcium oxide and silicon dioxide

In Europe, ~12M tons of steel slag are produced per year

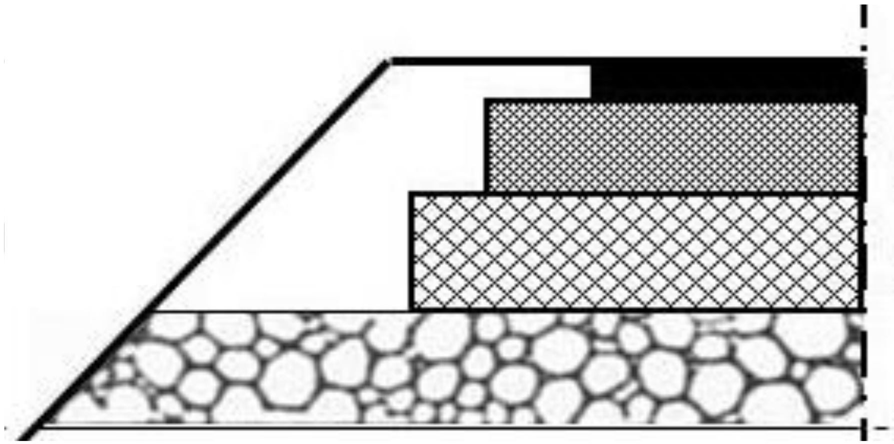
Objective and Research Approach

How does the use of LD slag in asphalt mixtures affects the functional performance of asphalt pavement compared to asphalt mixtures prepared with natural aggregate Gabbro?

Asphalt pavement – layered system



Objective and Research Approach



Surface layer
Binder layer
Base layer

Asphalt mixture


Laboratory prepared asphalt mixture with
LD slag and natural aggregate Gabbro:

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

Objective and Research Approach

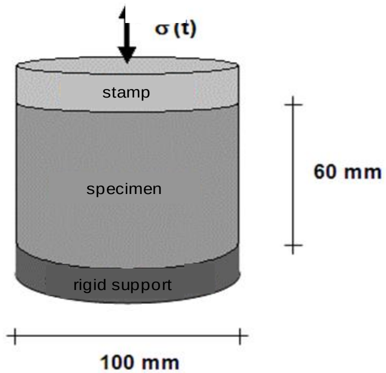
Asphalt properties evaluated:

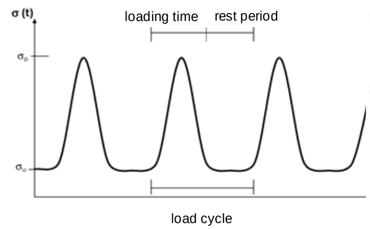
- Resistance to permanent deformation
- Stiffness
- Fatigue
- Resistance to low temperature cracking
- Skid resistance of surface layer

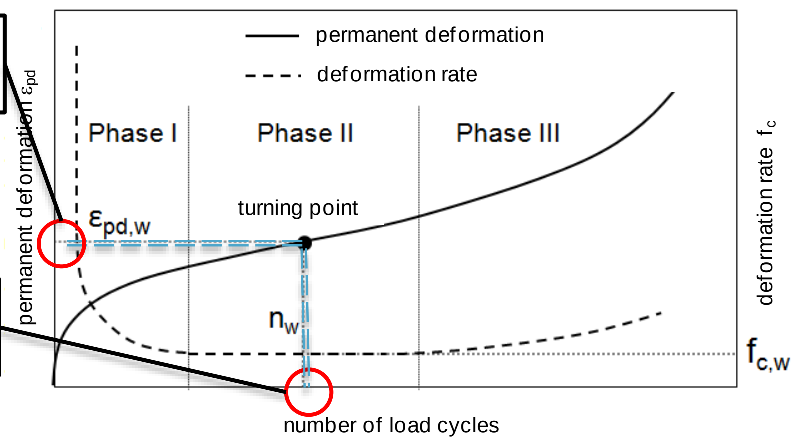
Test Methods - Resistance to permanent deformation

Cyclic Test
[EN 12697-25, Pt. A1]

T = +50 °C





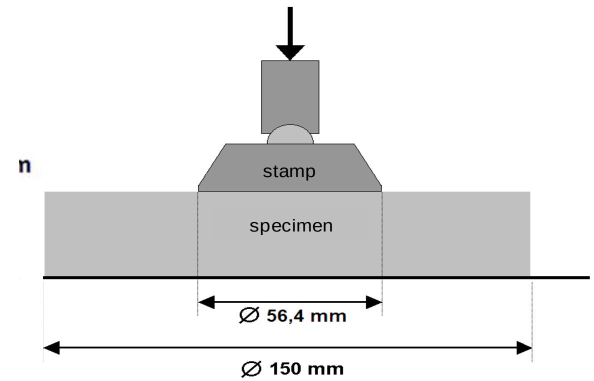


Strain @ turning point [‰]

No. of load cycles @ turning point [-]

German standard
FGSV TP Asphalt -StB, Part 25 A1
(2010)

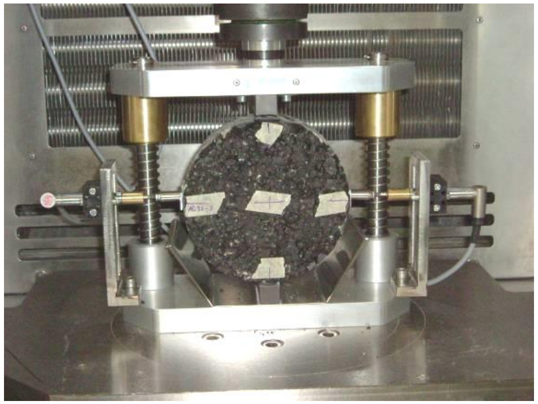
T = +50 °C

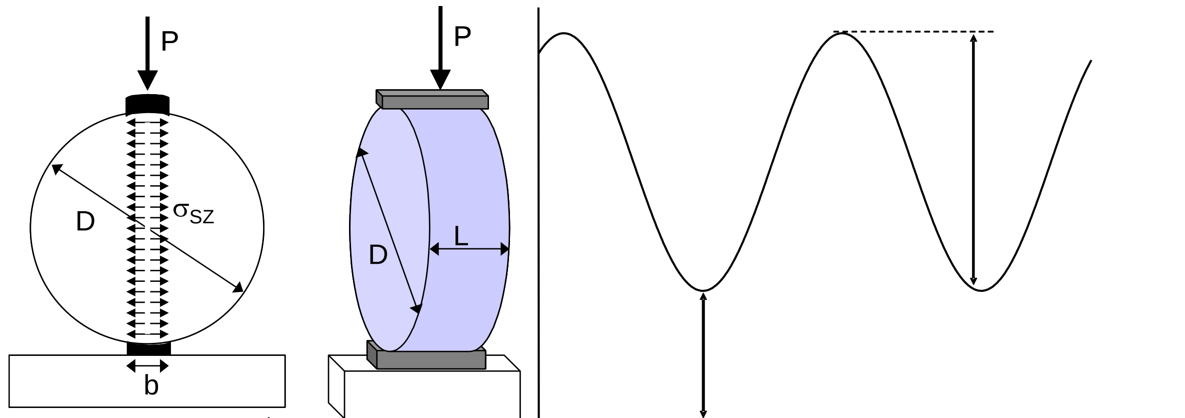


Accumulated displacement ET_{dyn} after 2500 load cycles [mm]

Test Methods - Stiffness and Fatigue

Cyclic Indirect Tensile Test [EN 12697-24]





Stiffness

$$E = f(T)$$

Fatigue

$$N_{macro} = C_1 \cdot \varepsilon^{C_2}$$

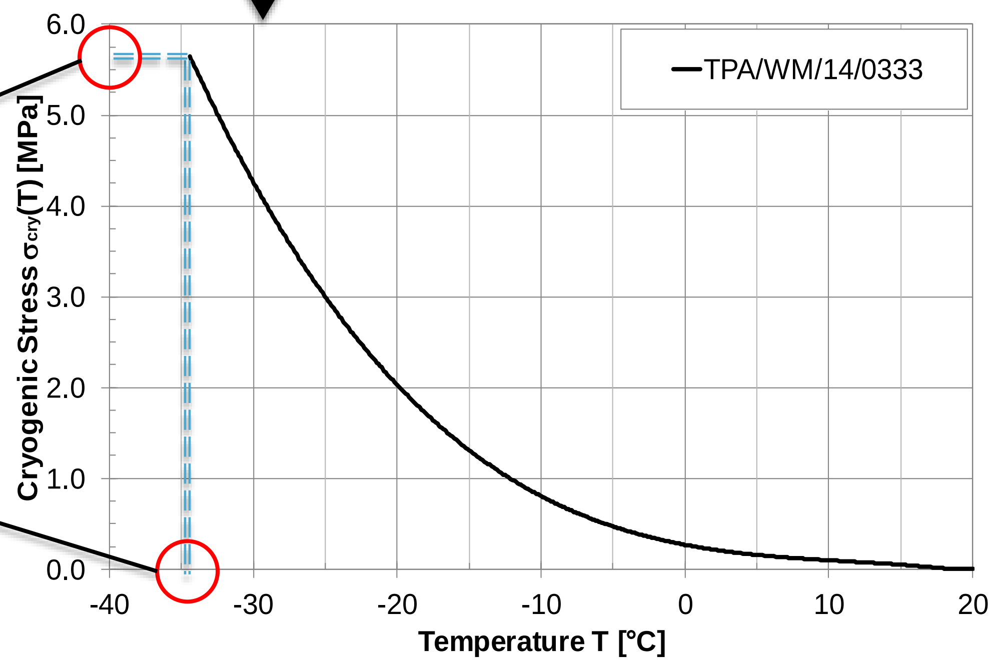
Test Methods – Resistance to low temperature cracking

Thermal Stress Restrained Specimen Test [EN 12697-46]

1. Start @ T = 20 °C
2. Cooling Rate ΔT = -10 °C/h
3. Thermal shrinkage is prevented

Failure stress σ_F [MPa]

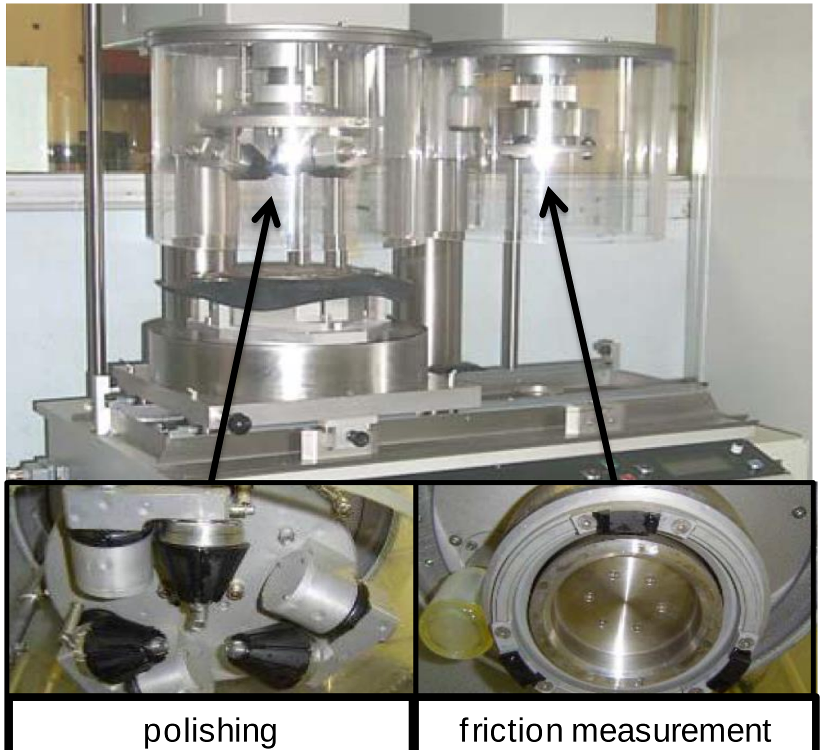
Failure temp. T_F [°C]



Test Methods – Skid Resistance

Skid resistance of surface layer [German Standard TP Gestein-StB, Pt 5.4.2]

Wehner/Schulze machine



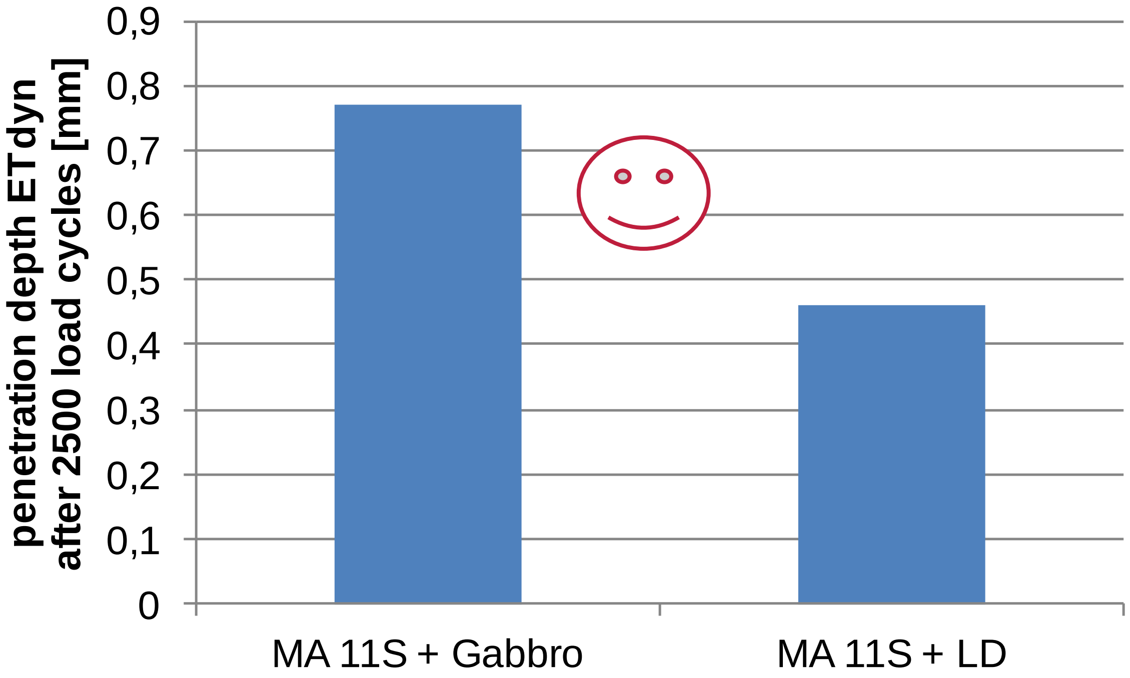
Simulate the exposure to traffic
1 hour / 500 rpm
Injection of water-quartz powder mix

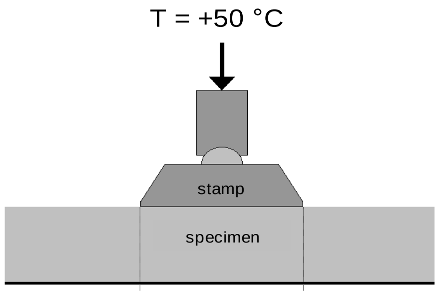
Rotating rubber bodies (100 km/h)
lowered onto specimen surface
thereby braked → friction coefficient

Results - Resistance to permanent deformation

disadvantageous | comparable (good) level | advantageous

Surface layer: mastic asphalt (MA)



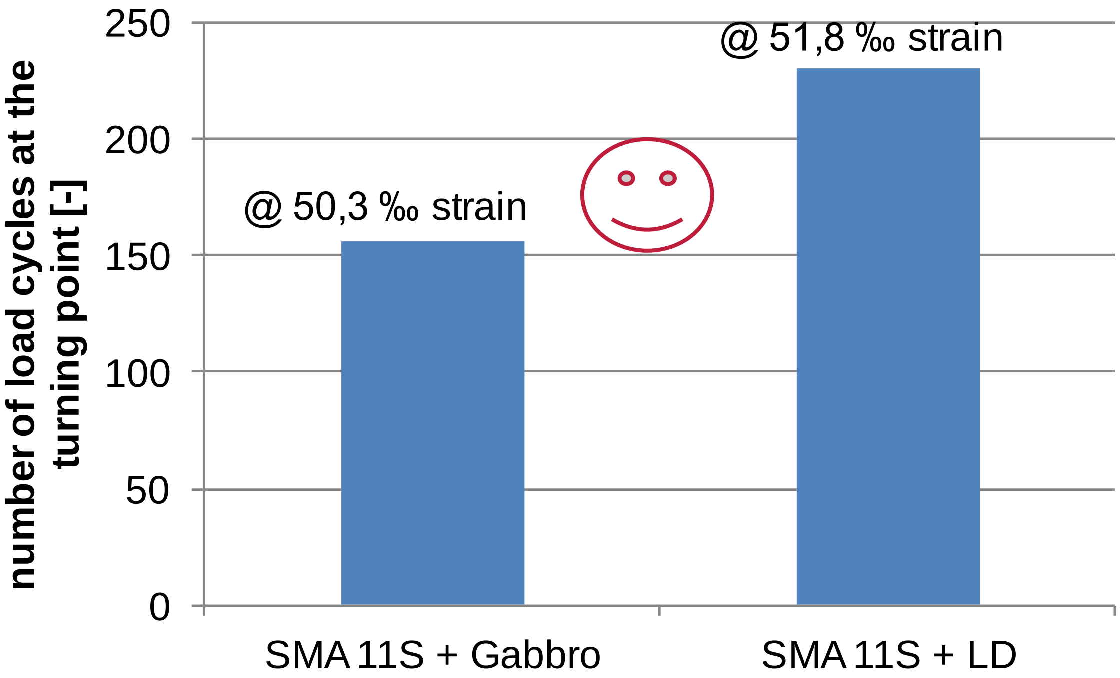


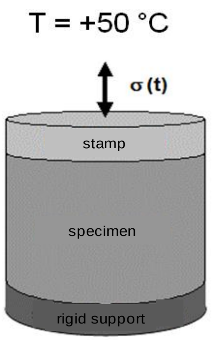
Slag mixture has a much lower penetration depth compared to MA with natural Gabbro

The use of LD slag in mastic asphalt (MA) leads to improved deformation resistance compared to mastic asphalt with natural Gabbro aggregate

Results - Resistance to permanent deformation

Surface layer: stone mastic asphalt (SMA)



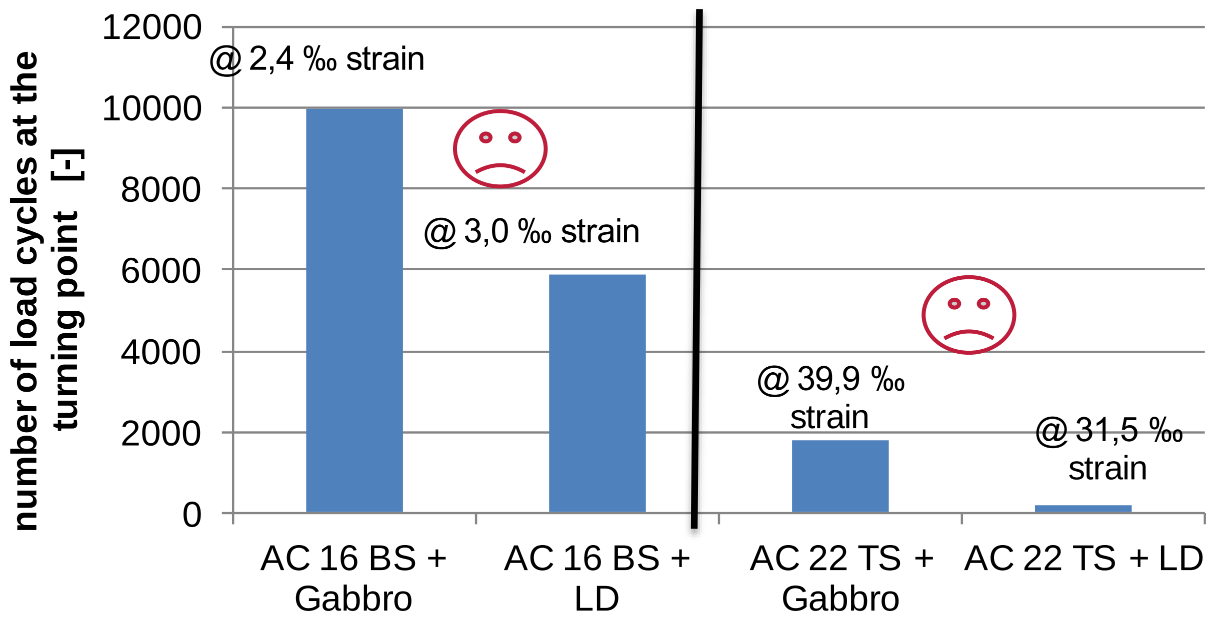


- Slag lead to higher number of load cycles compared to SMA with natural Gabbro

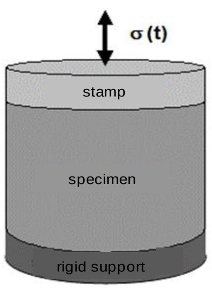
➡ Using LD slag in stone mastic asphalt (SMA) leads to an advantageous deformation resistance compared to stone mastic asphalt with natural Gabbro aggregate (same trend for MA)

Results - Resistance to permanent deformation

Binder & Base layers: AC 16 BS & AC 22 TS



T = +50 °C

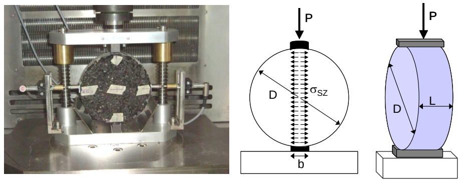


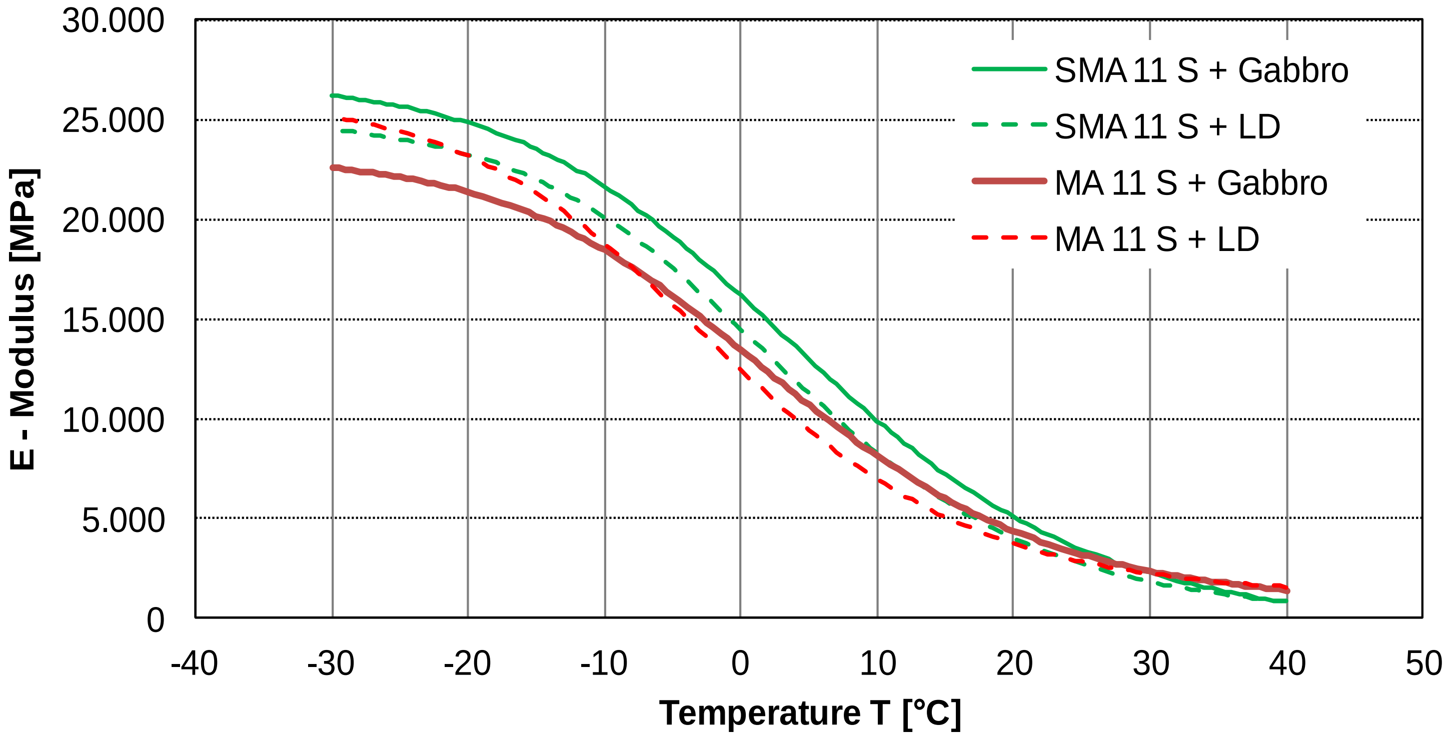
- number of load cycles @ turning point much lower for LD slag mixtures
- Strains comparable in magnitude

LD slag mixtures show higher air voids content (up to 3.0 vol.-%)
This may negatively affect the resistance to permanent deformation

Results - Stiffness

Surface layers: mastic asphalt (MA) & stone mastic asphalt (SMA)

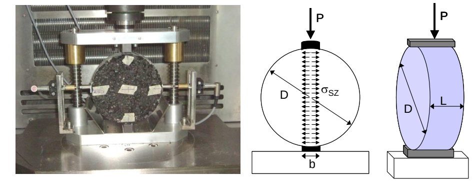


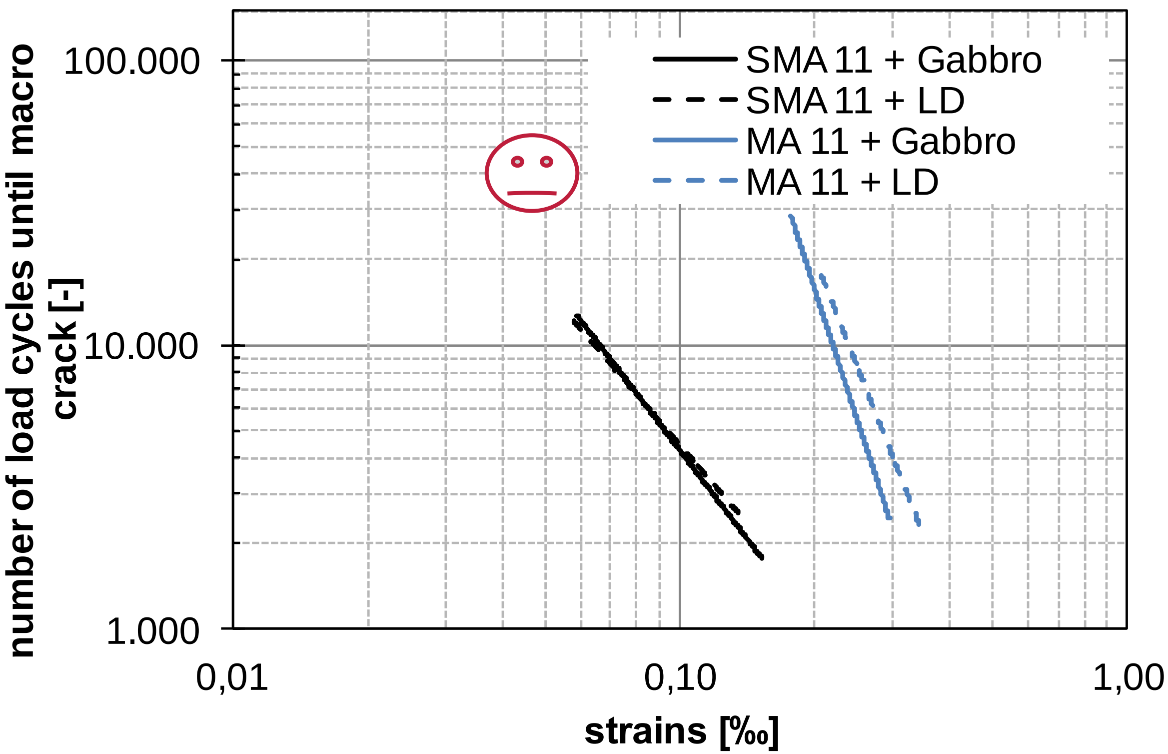


Resulting stiffness is for all asphalt surface mixtures at a comparable level, regardless of whether LD slag or natural Gabbro aggregate was used

Results - Fatigue

Surface layers: mastic asphalt (MA) & stone mastic asphalt (SMA)

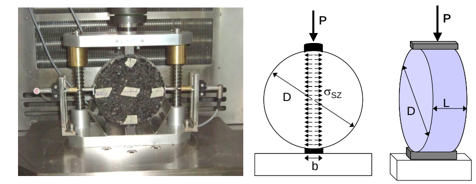


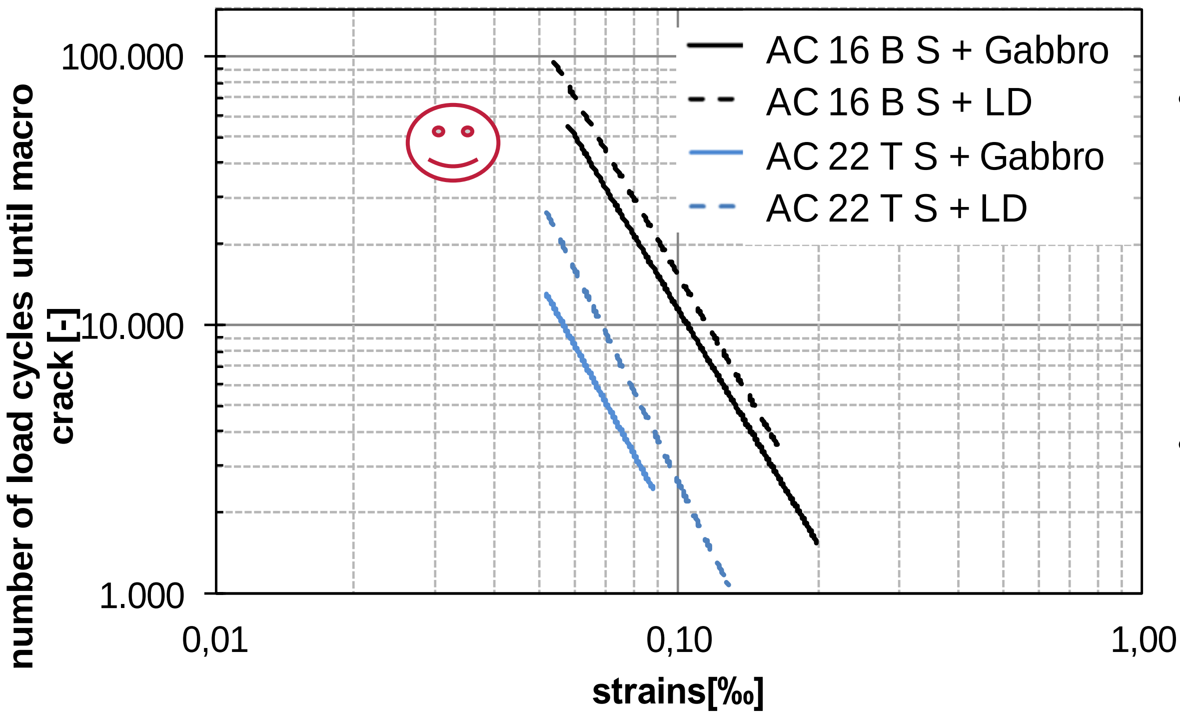


Similar fatigue resistance for mixtures with natural aggregate Gabbro and LD slag

Results - Fatigue

Binder- & base layers: AC 16 BS & AC 22 TS





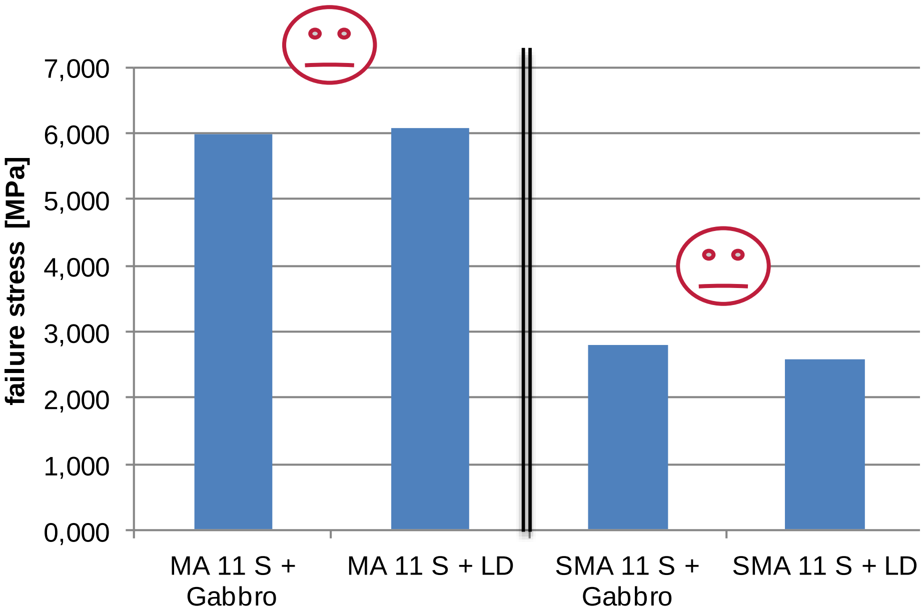
- Fatigue curves of asphalt binder and asphalt base mixtures with LD slag are shifted upwards

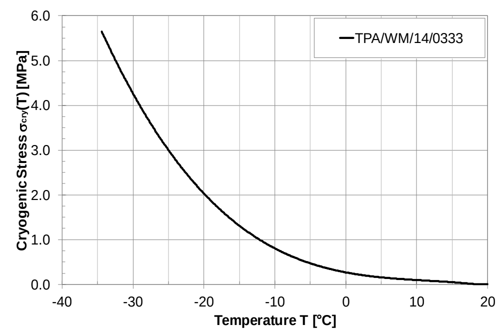
- For the same strain, mixtures with LD slag can sustain a higher number of load cycles before macro cracking

Use of LD slag in asphalt binder and asphalt base course mixtures leads to a higher fatigue resistance in comparison to mixture with natural Gabbro

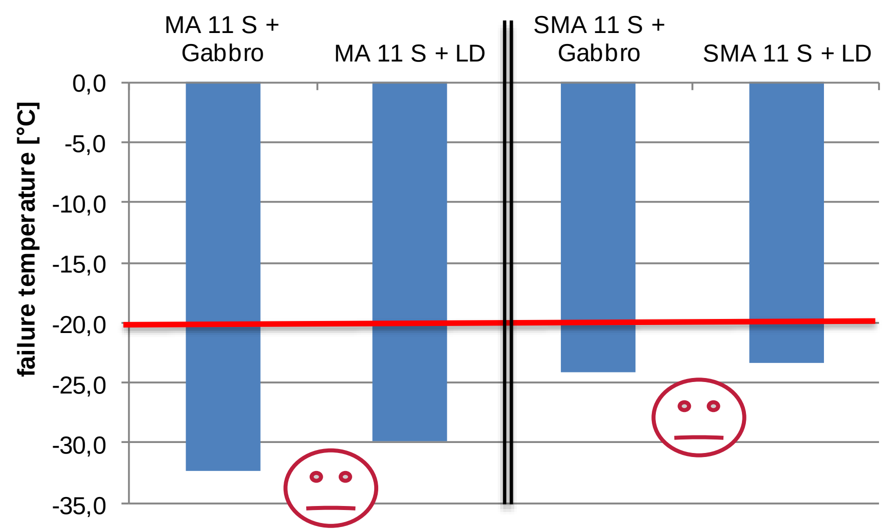
Results - Resistance to low temperature cracking

Surface layers: mastic asphalt (MA) & stone mastic asphalt (SMA)

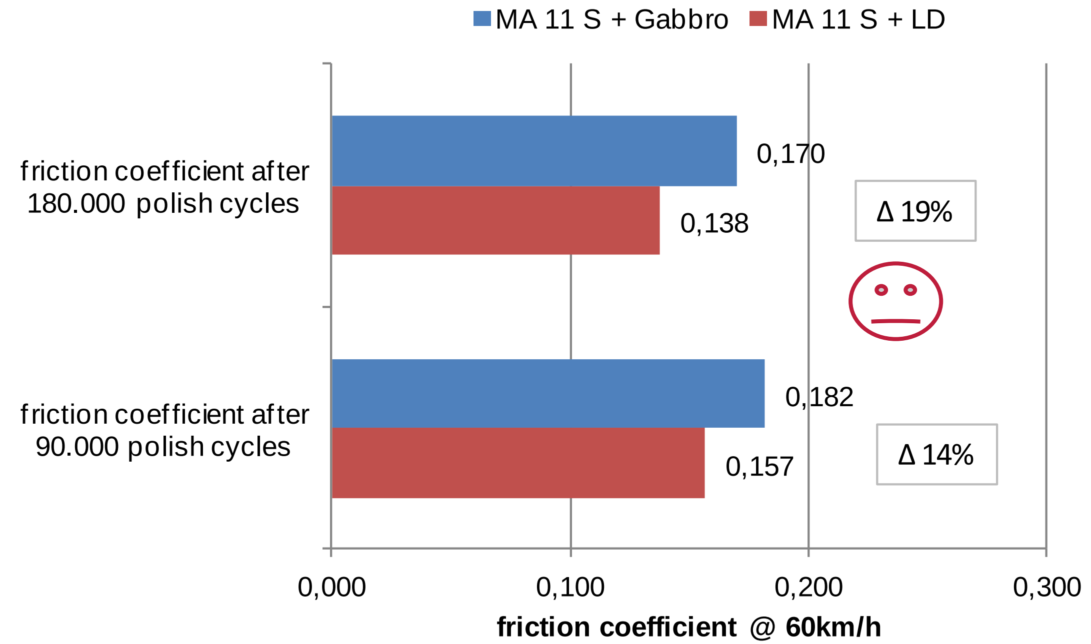


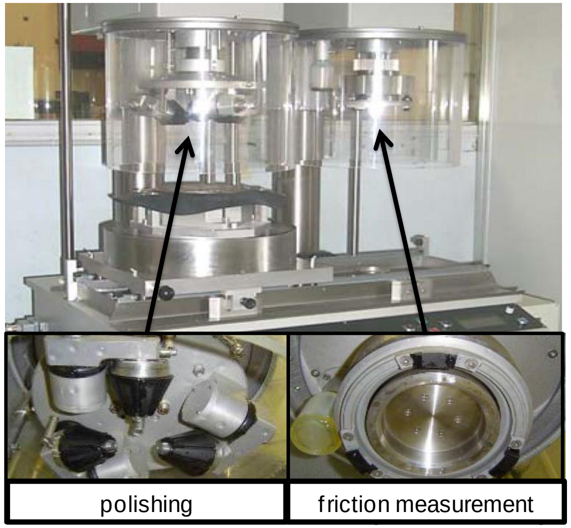


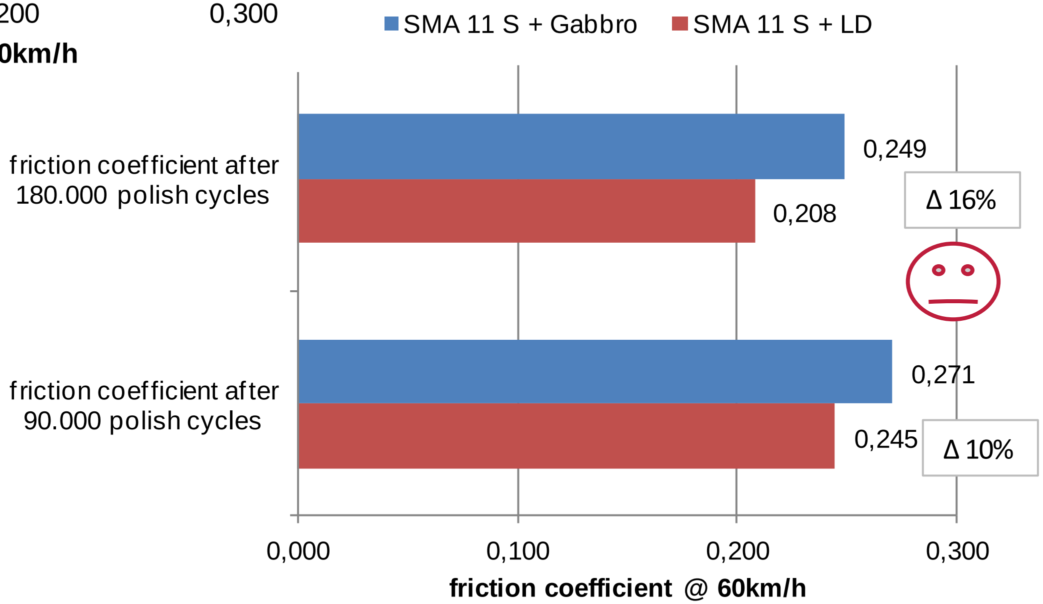
- Comparable resistance to low temperature cracking
- Similar failure stress
- Slightly higher cracking temperature



Results - Skid Resistance of surface layer







- Friction coefficients of the mixtures with LD about 15% to 20% lower compared to Gabbro

Summary and conclusions – LD Slags

How does the use of LD slag in asphalt mixtures affects the functional performance of asphalt pavement compared to asphalt mixtures prepared with natural aggregate Gabbro?

 disadvantageous  comparable (good) level  advantageous

Resistance to permanent deformation  surface

 binder, base → voids!

Stiffness 

Fatigue 

Summary and conclusions – LD Slags

disadvantageous | comparable (good) level | advantageous

Resistance to low temperature cracking (comparable (good) level)

Skid resistance of surface layer (comparable (good) level)

1. asphalt mixtures with LD slag are suitable for asphalt pavement construction
2. performance as good as or in some cases better than conventional asphalt mixtures prepared with natural Gabbro aggregate

Outline

Two-case study

- Linz-Donawitz slag
  (Germany and Austria)

- Electric Arc Furnace Steel Slag – EAFSS
  (South Korea and Germany)

Objective and Research Approach

Experimentally investigate the effect of adding different amounts of Reclaimed Asphalt Pavement (RAP) and Electric Arc Steel Furnace Slag (EAFSS) on the creep and fracture response of asphalt mixtures at low temperature.

Based on:

- Bending Beam Rheometer (BBR) tests
- Semi-Circular Bending (SCB) tests

Quick look at Permanent Deformation and Skid Resistance

Objective and Research Approach

Materials

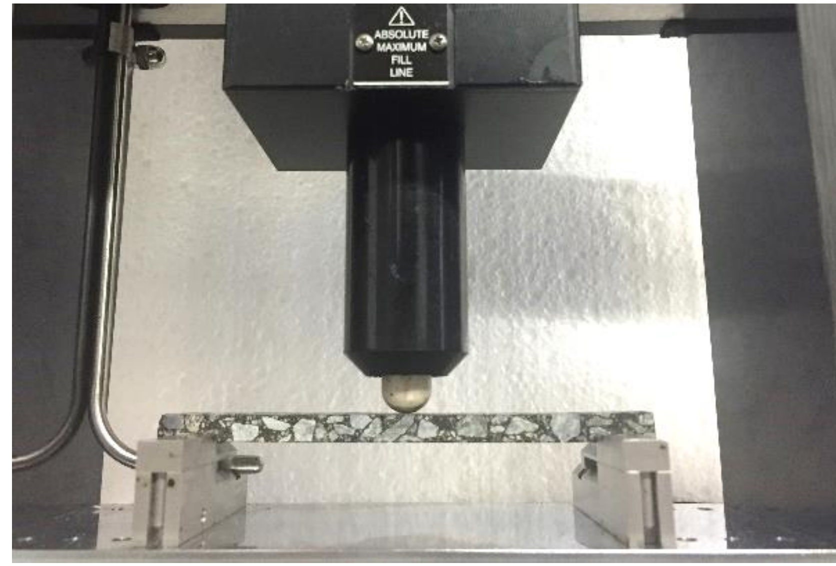
Asphalt mixtures

Mix ID	Asphalt Binder	RAP (%)	Steel Slag (%)	P_b (%)	*VMA* (%)	*VFA* (%)	Air Voids (%)
A	PG 58-28	0	0	5.1	15.69	72.4	7
B	PG 58-28	25	0	5.4	17.12	73.9	7
C	PG 58-28	25	75	5.7	17.20	77.3	7
D	PG 58-28	0	100	6.0	15.58	79.1	7
E	PG 58-34	0	0	5.0	15.65	72.2	7
F	PG 58-34	25	0	5.3	17.22	73.6	7
G	PG 58-34	25	75	5.7	17.16	77.1	7
H	PG 58-34	0	100	6.0	15.89	79.2	7

* NMAS: Nominal Maximum Aggregate Size (mm), P_b: Asphalt binder content (%), VMA: Voids between mineral aggregate (%), VFA: Voids filled with asphalt (%)

Test Methods

BBR creep testing



BBR Device

- Relaxation modulus, *E(t)*

$$t = \int_0^t E(\tau) \cdot D(t-\tau)\,d\tau = \int_0^t E(t-\tau) \cdot D(\tau)\,d\tau$$

- Thermal stress

$$\sigma(\xi) = \int_{-\infty}^{\xi} \frac{d\varepsilon(\xi')}{d\xi'} \cdot E(\xi - \xi')\,d\xi' = \int_{-\infty}^{t} \frac{d(\alpha \Delta T)}{dt'} \cdot E(\xi(t) - \xi'(t))\,dt'$$

$\xi = t / a_T$ reduced time

α coefficient of thermal contraction of asphalt mixture

Test Methods

SCB fracture testing

- Semi-circular shape with diameter of 150mm, thickness of 30mm and straight vertical central notch of 15mm
- The sample is placed on a frame consisting of two fixed rollers and having a span of 120mm.

The fracture energy, G_f:

$$G_f = \frac{W_f}{A_{lig}}$$

W_f work of fracture
A_{lig} area of ligament

SCB Test

Test Methods

SCB testing

The fracture toughness (critical stress intensity factor), K_{Ic} :

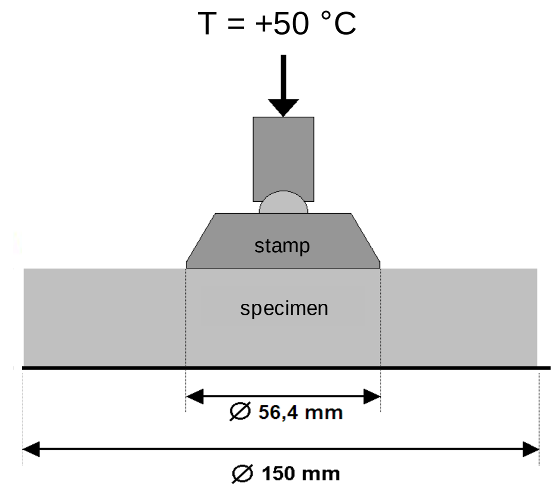
$$K_{Ic} = [P_c / (2 \cdot r \cdot t)] \cdot \sqrt{\pi \cdot a} \cdot \left[Y_{I(S_0/r)} + (\Delta s_0 / r) \cdot B \right]$$

where,

P_c	peak load
r	radius
t	thickness
Y_I	normalized stress intensity factor
a	notch length
Δs_0	geometry parameter
B	parameter depending on a and r

Test Methods

Resistance to permanent deformation



- German standard FGSV TP Asphalt -StB, Part 25 A1 (2010).

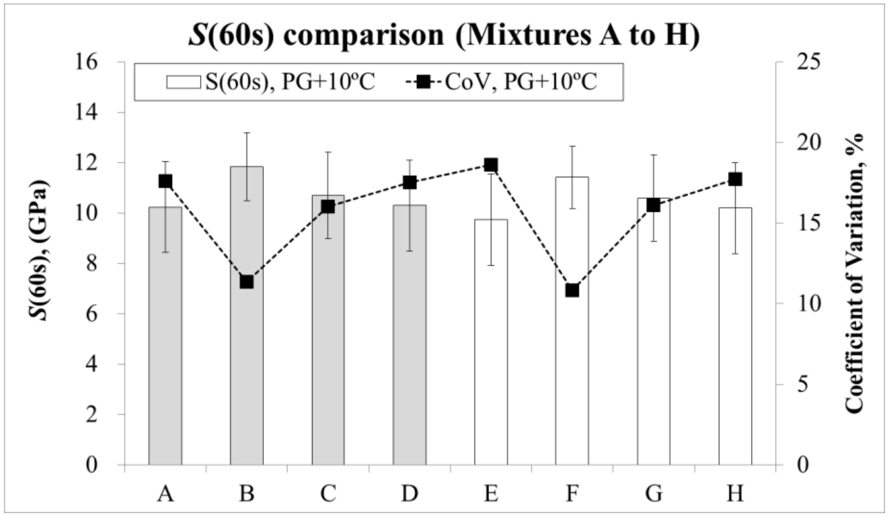
Skid resistance

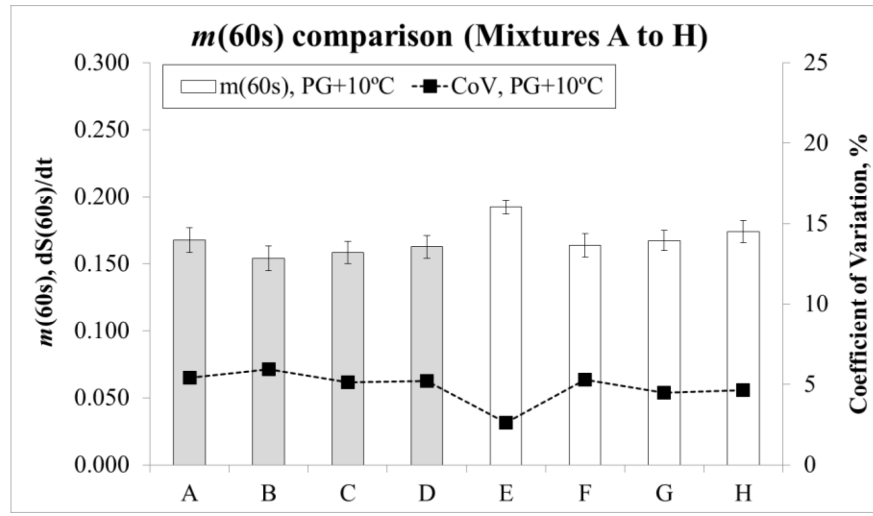
- German Standard TP Gestein-StB, Part 5.4.2 (2010).

Wehner/Schulze machine

Results and Analysis

Creep Tests Results

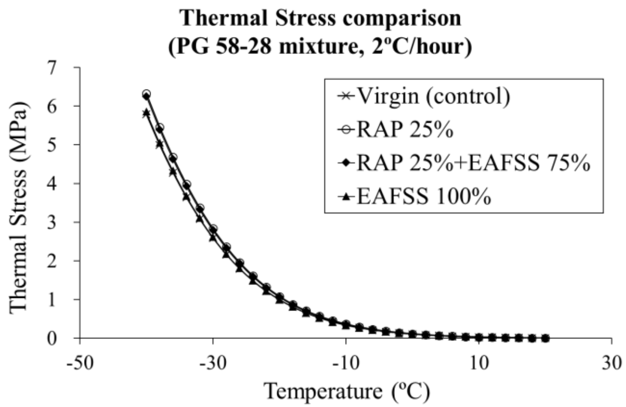


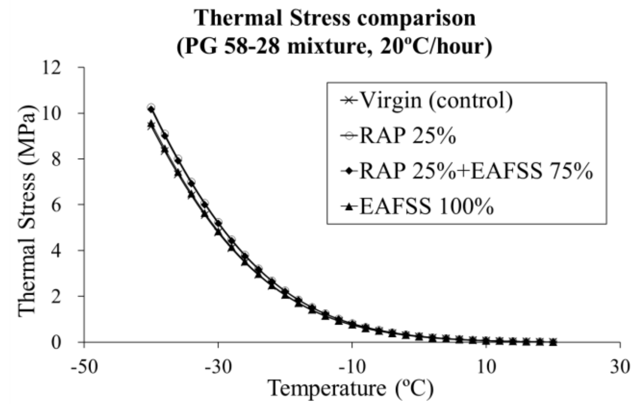


Creep stiffness (left) and *m*-value (right) mixture results at 60s (lowPG+10ºC)

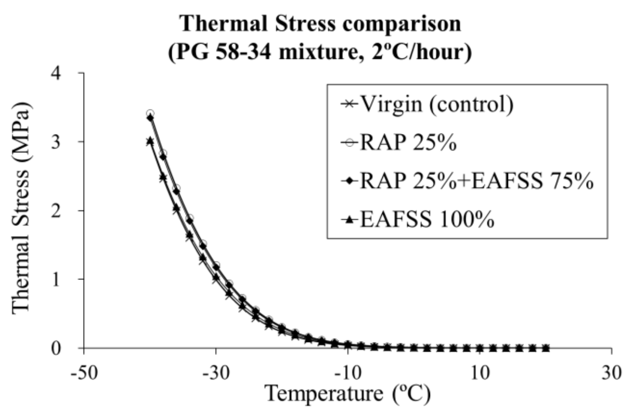
Results and Analysis

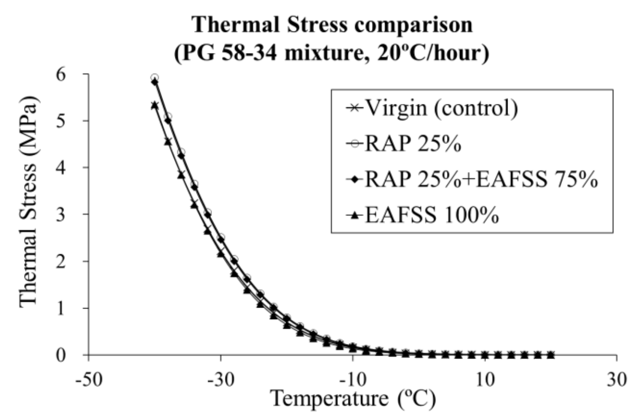
Thermal stress and critical cracking temperature results





PG 58-28 mixture





PG 58-34 mixture

σ(*T*) comparison (2ºC/h and 20ºC/h cooling rate)

Results and Analysis

Thermal stress and critical cracking temperature results

Critical cracking temperature, T_{CR}, comparison (PG 58-28 mixture)

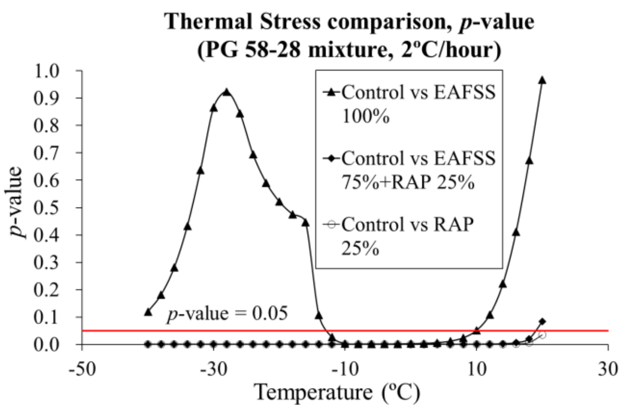
Binder	T_{CR}, 2ºC/hour cooling rate				T_{CR}, 20ºC/hour cooling rate			
	Control	E100%	E75%+R25%	R25%	Control	E100%	E75%+R25%	R25%
PG58-28	-25.91	-25.95	-25.88	-25.85	-23.06	-23.07	-22.88	-22.82
PG58-34	-29.32	-28.95	-28.79	-28.74	-26.58	-26.91	-26.32	-26.25

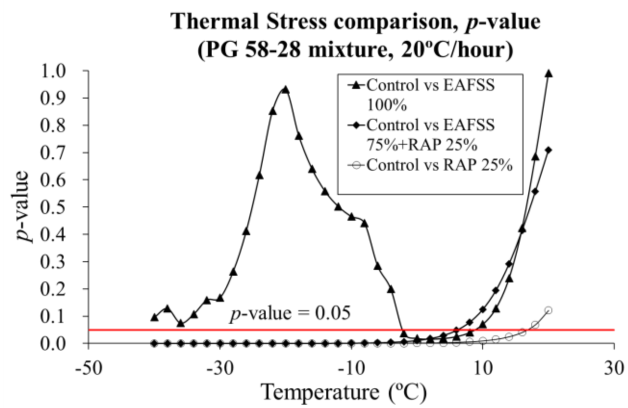
* E: EAFSS, R: RAP

- For 75% EAFSS+25% RAP, and 25% RAP, higher $\sigma(T)$ and T_{CR} were found compared to mixtures designed with virgin material for both binder.
- When the aggregate skeleton was entirely (100%) replaced with EAFSS, a very close response to that of mixtures prepared with conventional aggregates was observed, both in terms of thermal stress and critical cracking temperature.

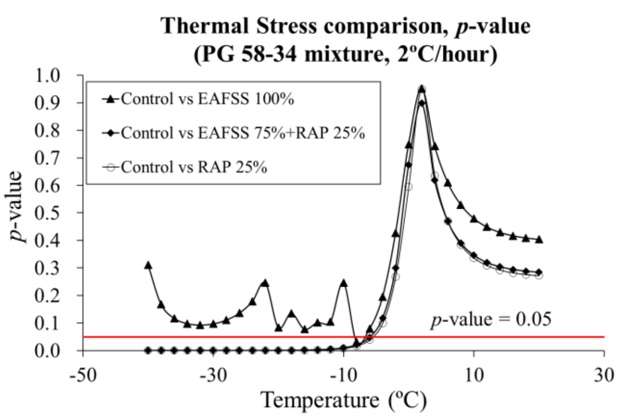
Results and Analysis

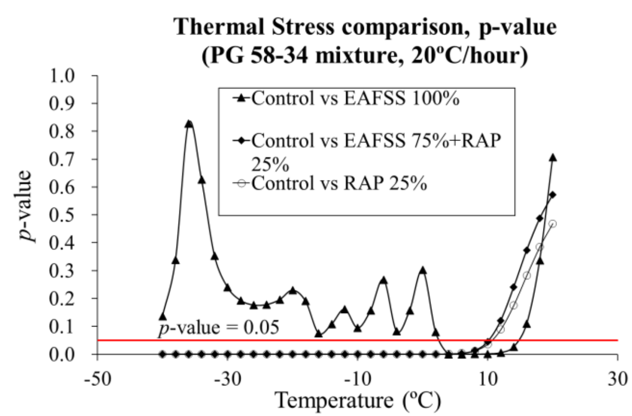
Thermal stress and critical cracking temperature results





PG 58-28 mixture





PG 58-34 mixture

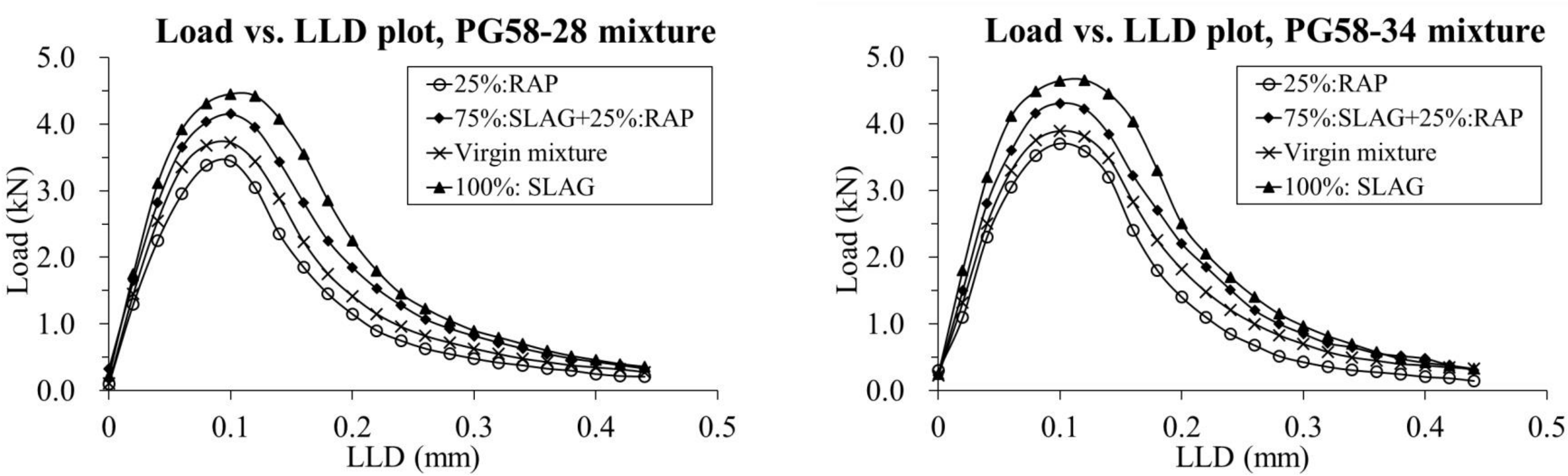
Statistical comparison of $\sigma(T)$

Results and Analysis

Fracture energy and fracture toughness

SCB test results

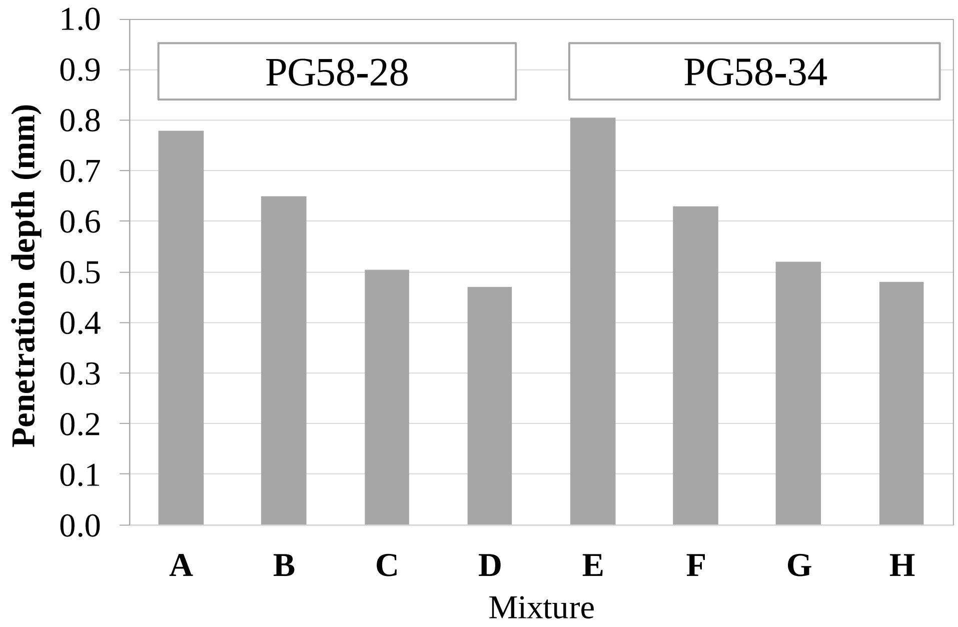
Mixture	Fracture energy: G_F (J/m^2)				Fracture toughness: K_{Ic} (MPa*m$^{0.5}$)			
	Control	E100%	E75%+R25%	R25%	Control	E100%	E75%+R25%	R25%
58-28 mixture	0.446	0.599	0.510	0.381	1.106	1.324	1.222	1.026
58-34 mixture	0.495	0.641	0.567	0.420	1.157	1.383	1.279	1.100



Load vs. LLD curves for PG58-28 and PG58-34 mixtures

Results and Analysis

Resistance to permanent deformation



TP Asphalt -StB, Part 25 A1 (2010)

- A decrease in permeant deformation is achieved for mixtures containing both RAP and EAFSS.

Results and Analysis

Skid resistance

- The results were addressed by measuring the friction coefficients after 90,000 and 180,000 polishing cycles.

- An overall decrease was found for larger contents of EAFSS: from a value of 0.245 and 0.221 at 90,000 and 180,000 cycles in the case of virgin material to 0.198 and 0.172 for mixture prepared with 100% slags.

Summary and conclusions – EAFSS

- The effect of the combined use of RAP and EAFSS on the low temperature creep and fracture performances of asphalt mixture was experimentally investigated based on BBR mixture creep SCB fracture test. Eight asphalt mixtures with two different asphalt binder were prepared and tested.
- In addition, a preliminary investigation on permanent deformation and skid resistance was performed.

Summary and conclusions – EAFSS

- BBR results indicate that mixture prepared with 100% EAFSS aggregate have similar low temperature response to that of conventional mixtures.
- Mixtures containing a combination of EAFSS (75%) and RAP (25%) shows higher thermal stresses and critical cracking temperature.
- Better fracture performances were found for EAFSS 100% and EAFSS 75%+RAP 25% mixtures.
- Better resistance to permanent deformation and lower friction coefficient are exhibited by mixture prepared with EAFSS.

Acknoledgements

Laboratory Team

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Korea Expressway Corporation

RILEM CMB 2018

Technische Universität Braunschweig

ISBS Institut für Straßenwesen TU Braunschweig

rilem

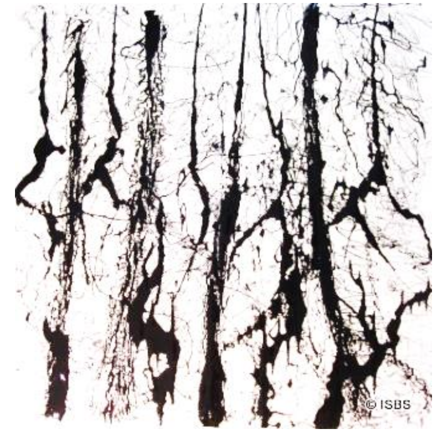
RILEM 252-CMB-SYMPOSIUM
BRAUNSCHWEIG, GERMANY
SEPTEMBER 17 – 18, 2018
CHEMO MECHANICAL CHARACTERIZATION OF BITUMINOUS MATERIALS

Important Dates

Nov. 27th, 2017	Submission of paper open
Apr. 10th, 2018	Submission of paper due
Jun. 1st, 2018	Notification of papers acceptance
Sept. 17-18th, 2018	RILEM 252-CMB Symposium
Sept. 19-20th, 2018	RILEM Cluster F-TCs Annual Meeting

Topics

- Bitumen aging mechanisms and characterization
- Chemo-mechanical coupling
- Low, intermediate and high temperature behavior
- Microstructure and micro-mechanics
- Thermal properties
- Recycling and rejuvenation
- Nanotechnology for bituminous materials
- Multiphase analysis of binders



Thank you!