Multi-scale analysis of warm-mix asphalt with electric arc furnace steel slag

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Emiliano Pasquini – Short CV

- (2005) Master Thesis dissertation: "*Performance characterization of grids for road pavements reinforcement* ", Polytechnic University of Marche (Ancona, Italy)
- (2009) Ph.D. dissertation: "*Advanced characterization of innovative environmentally friendly bituminous mixtures*", Polytechnic University of Marche (Ancona, Italy)
- (2009/15) Research Associate (Polytechnic University of Marche, University of Padua)
- (from 2015) Assistant Professor at University of Padua (Padua, Italy)
- (from 2017) National (Italian) Scientific Qualification to function as Associate Professor
- lecturer at the National Advanced School of Public Works (ENSTP), Yaoundé, Cameroun
- member of the Scientific Committee of International Conferences
- reviewer for 19 International Journals
- more than 40 publications in International Journals and Conferences (2 awards)

Research Gate profile: http://www.researchgate.net/profile/Emiliano_Pasquini
ResearcherID profile: http://www.researcherid.com/rid/G-4423-2014
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GoogleScholar profile: https://scholar.google.it/citations?user=RUu37lcAAAAJ&hl=it

Outline

I. Introduction
II. Research Objective and Approach
III. Experimental Plan
IV. Materials
V. Methodologies and Results
VI. Conclusions
VII. Further Studies

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Introduction

Steel slag in asphalt mixtures

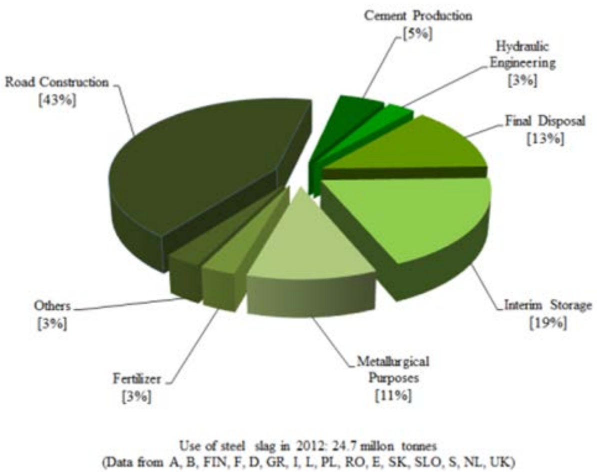
- Selected **UniPD** publications (about 30 papers since 1990)

i. M. Pasetto, N. Baldo (2010) Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags
ii. M. Pasetto, N. Baldo (2011) Mix design and Performance Analysis of Asphalt Concretes with Electric Arc Furnace Slag
iii. M. Pasetto, N. Baldo (2012) Fatigue Behavior Characterization of Bituminous Mixtures made with Reclaimed Asphalt Pavement and Steel Slag
iv. M. Pasetto, N. Baldo (2012) Performance comparative analysis of stone mastic asphalts with electric arc furnace steel slag: a laboratory evaluation
v. M. Pasetto, N. Baldo (2012) Fatigue Performance of Asphalt Concretes with RAP aggregates and Steel Slags
vi. M. Pasetto, N. Baldo (2012) Fatigue Characterization of Asphalt Rubber Mixtures with Steel Slags
vii. M. Pasetto, N. Baldo (2013) Fatigue performance of asphalt concretes made with steel slags and modified bituminous binders
viii. M. Pasetto, N. Baldo (2014) Resistance to Permanent Deformation of Base Courses Asphalt Concretes made with RAP aggregate and Steel Slag
ix. M. Pasetto, N. Baldo (2014) Fatigue performance and stiffness properties of Stone Mastic Asphalts with steel slag and coal ash
x. M. Pasetto, N. Baldo (2014) Rutting resistance of Stone Mastic Asphalts with steel slag and coal ash

Introduction

Steel slag in asphalt mixtures

- Steel slag is a high quality crushed product, with a black-color stone appearance, characterized by high strength and rough texture
- Steel slags are able to provide increased structural performances (stiffness and rutting resistance) and skid resistance allowing both saving natural resources and re-using industrial waste



http://www.euroslag.com/products/statistics/2012/

Introduction

Steel slag in asphalt mixtures

- **Extensive use mainly limited by the high bulk density of such material than natural aggregates (higher transportation costs)**
- The absorption is often high leading to more asphalt binder required
- The risk of groundwater pollution by elution should be assessed
- Steel slag could be subjected to expansion due to hydration of free lime or magnesium oxide

Introduction

Steel slag in asphalt mixtures

EN 13043: "Aggregates for bituminous mixtures…"

- Manufactured aggregate

aggregate of mineral origin resulting from an industrial process involving thermal or other modification

Annex A

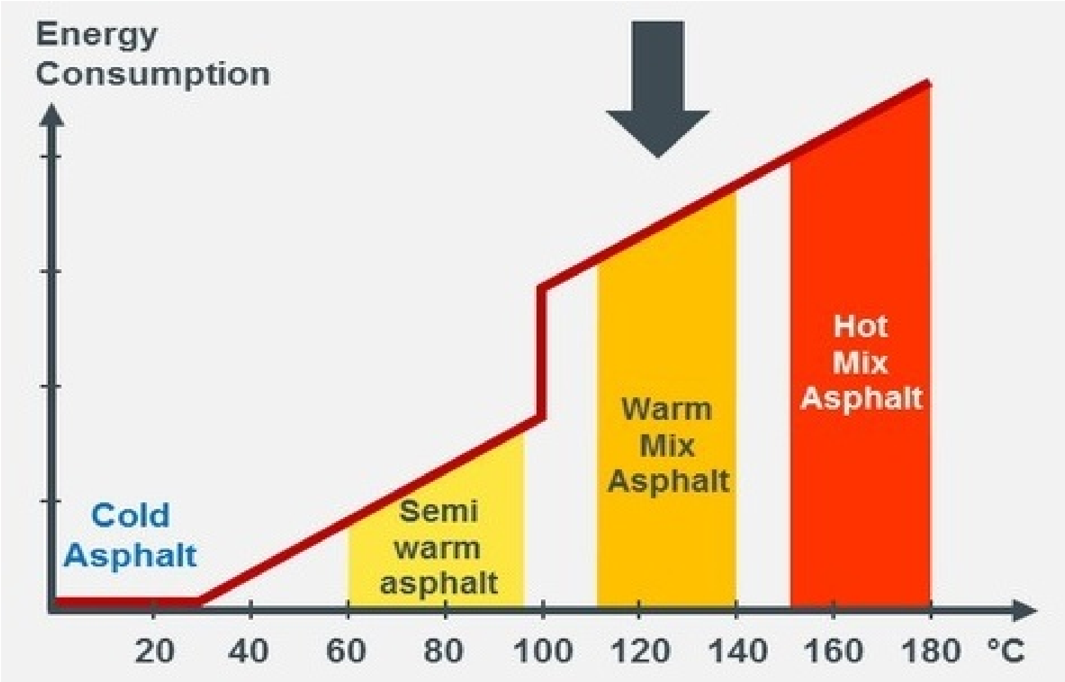
Nr.	Source	Sub-number	Specific material	History of use	Special requirements in standard	Additional requirements identified for inclusion
D	Iron and steel industry	D1	Granulated blast furnace slag (GBS) (vitrified)	No	–	–
		D2	Air-cooled blast furnace slag (ABS) (crystallized)	Yes	Yes	No
		D3	Basic oxygene furnace slag (converter slag, BOS)	Yes	Yes	No
		D4	Electric arc furnace slag (from carbon steel production, EAF C)	Yes	Yes	No
		D5	Electric arc furnace slag (from stainless/high alloy steel production, EAF S)	Yes	Yes	No
		D6	Ferrochromium slag	Yes	Yes	No

volume stability

Introduction

Warm Mix Asphalt (WMA)

- WMA is a modified asphalt concrete which can be produced, applied and compacted at lower temperatures (100–140 °C) than HMA



Introduction

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Warm Mix Asphalt (WMA)

- WMA is a modified asphalt concrete which can be produced, applied and compacted at lower temperatures (100–140 °C) than HMA

- Reduced energy consumption
- Reduced gas and fumes emissions
- Lower production costs
- Better working environment

- Longer hauling distances
- Extended construction periods
- Reduced binder aging
- Early traffic opening

Introduction

Warm Mix Asphalt (WMA)

- WMA is a modified asphalt concrete which can be produced, applied and compacted at lower temperatures (100–140 °C) than HMA

- Lack of consolidated experience
- Costs of warm products
- Plant modification
- Choice of the technology
- Lack of technical specifications

- Higher rutting potential
- Coating and bonding problems
- Reduced interface shear strength
- Greater moisture susceptibility

Introduction

Warm Mix Asphalt (WMA)

- Specific technologies (additives and/or water injection systems)
- Many different products available on the market

Main categories:
- Organic (wax) WMA additives
- Foaming WMA processes (water-based or water-containing)
- Chemical WMA additives



Introduction

Warm Mix Asphalt (WMA)

- WMA chemical additives are usually formed by a package of products (emulsifiers, surfactants, polymers, additives, adhesion promoters)
- Lower mixing and compaction temperatures due to the reduced friction at the interface between bitumen and aggregates

Outline

I. Introduction

II. Research Objective and Approach

III. Experimental Plan

IV. Materials

V. Methodologies and Results

VI. Conclusions

VII. Further Studies

Research Objective and Approach

What's new?

- Research approach
  - ✓ Multi-scale analysis (bitumens, mastics, mixtures)
- Warm technology
  - ✓ Chemical tensoactive additive
- EAF steel slag
  - ✓ Higher fine fraction (0/4 mm) content
- Methods
  - ✓ Original tests and/or data analysis

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Research Objective and Approach

Goal

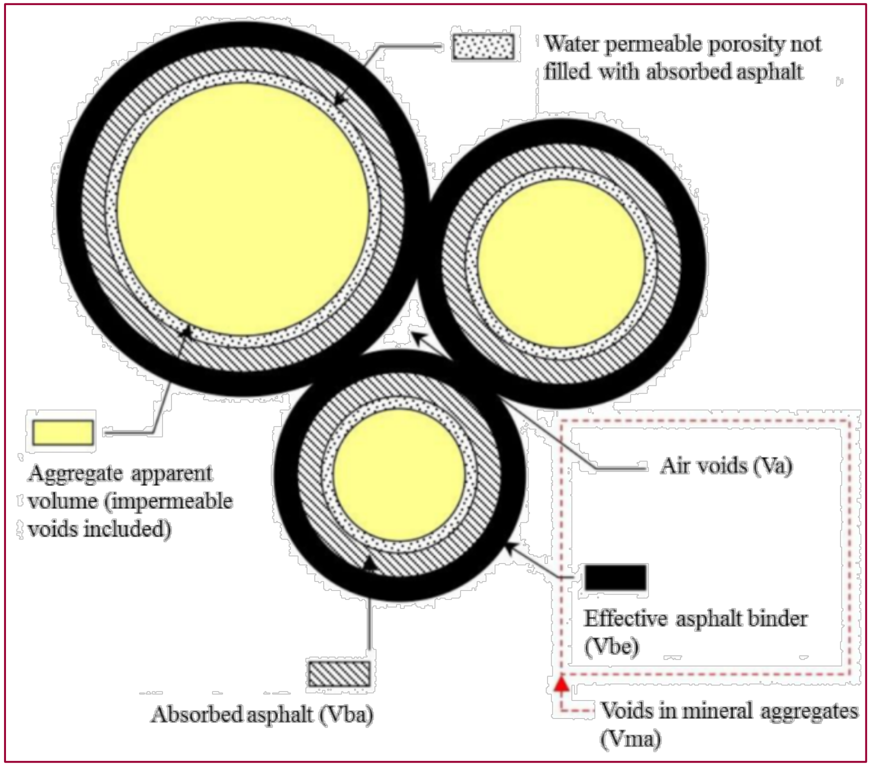
- **Feasibility of using EAF steel slag (fine fraction included) as aggregate in dense graded WMA mixes**
- Influence of the warm chemical additive on the binder and mixtures properties
  - Workability
  - Physical-chemical affinity
  - Midrange and high service temperature properties

Resarch Objective and Approach

Multi-scale analysis

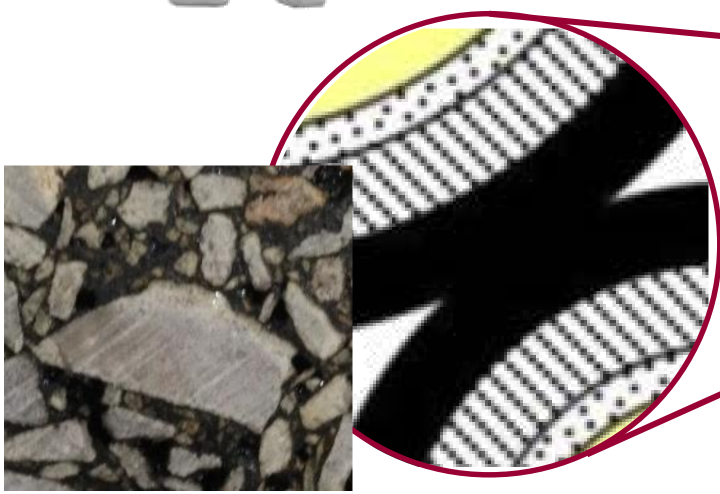
Asphalt concrete

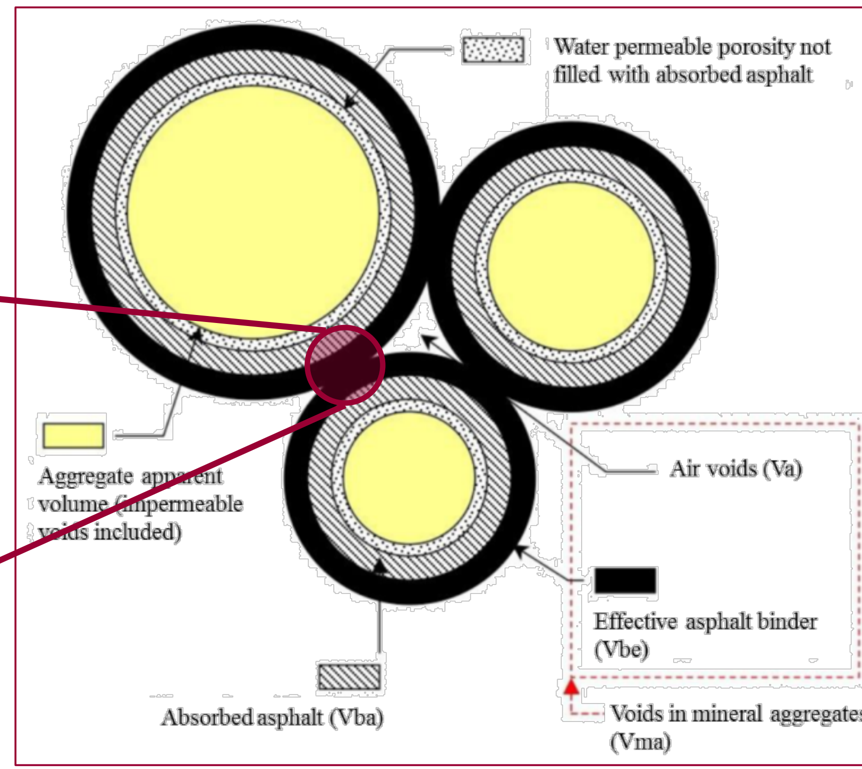
Mixture Scale



Resarch Objective and Approach

Multi-scale analysis



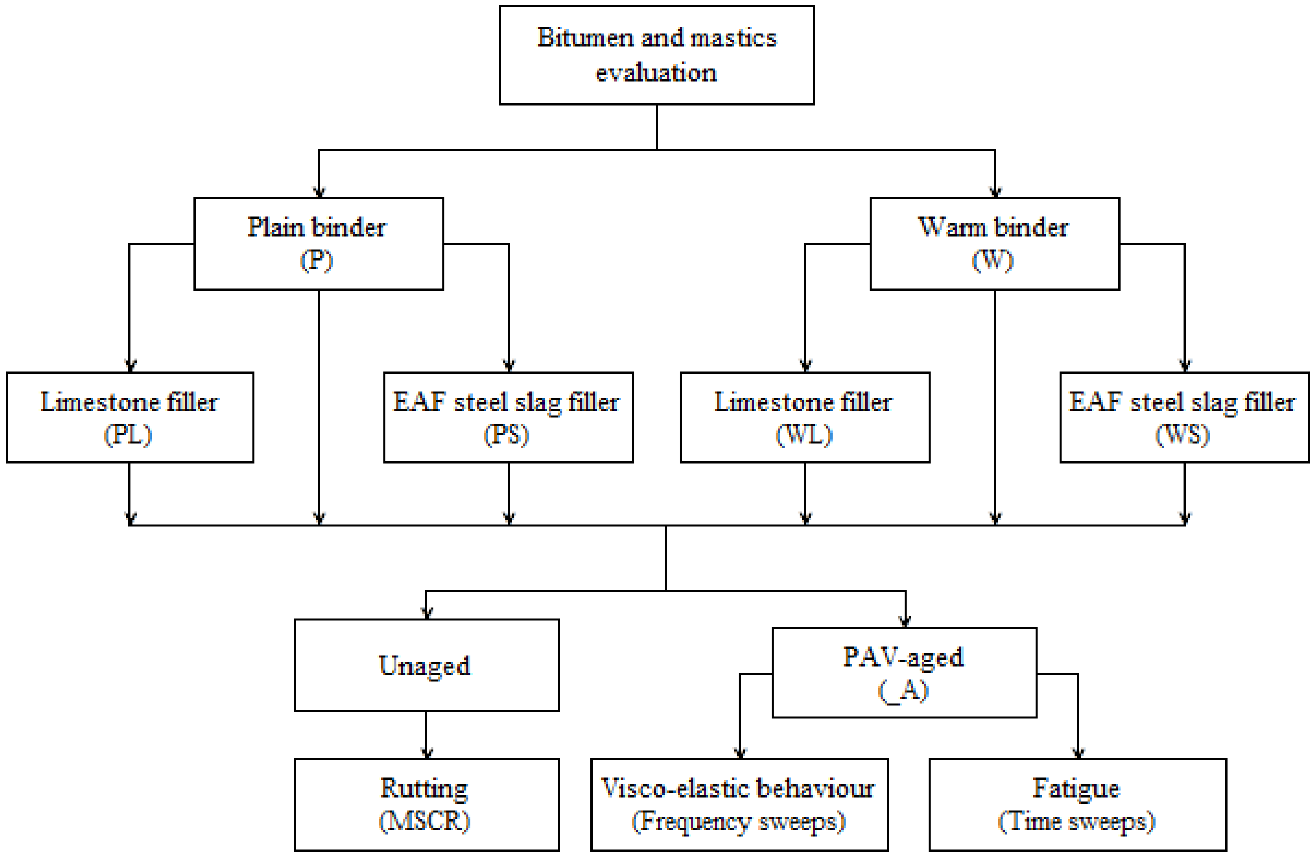


Bitumen-Mastic scale

Outline

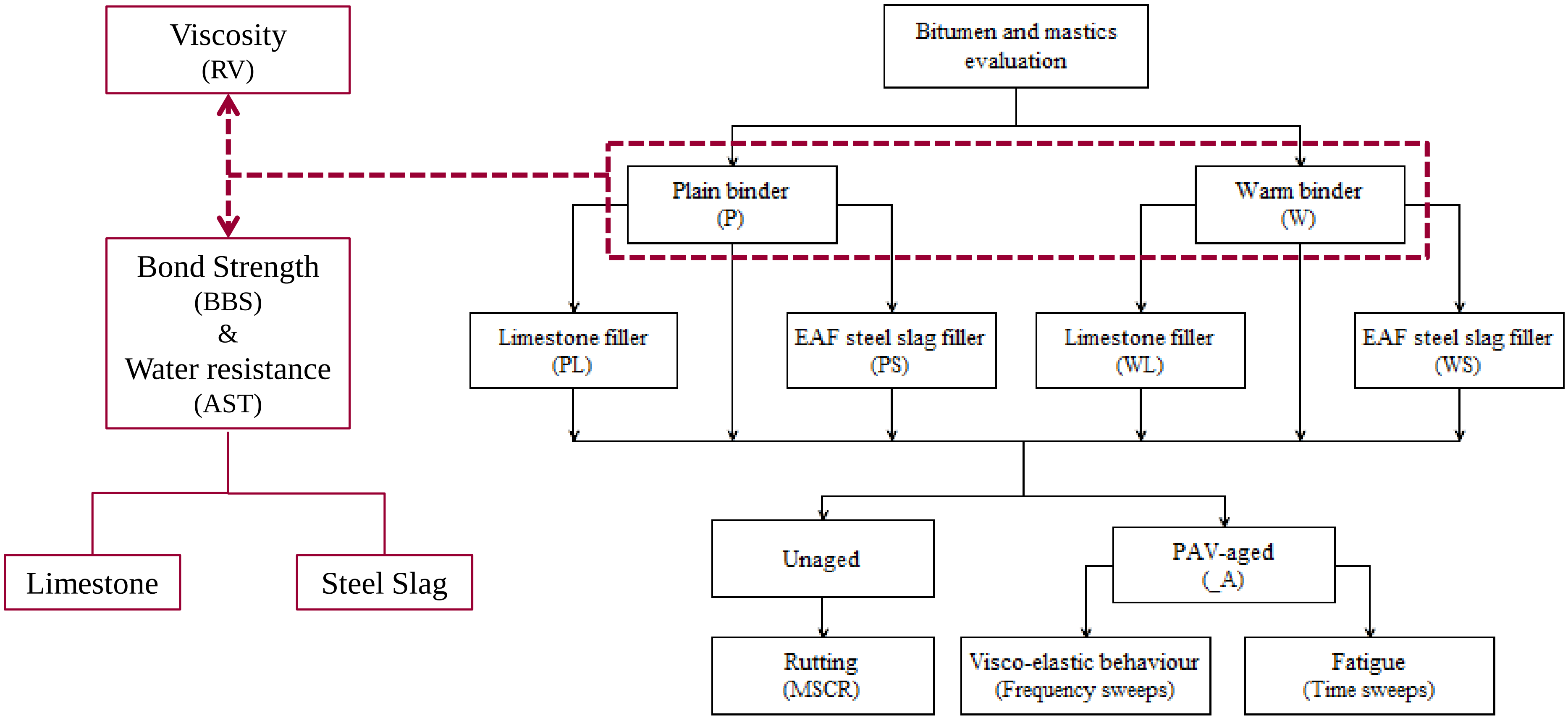
Experimental Plan

Bitumen-Mastic scale



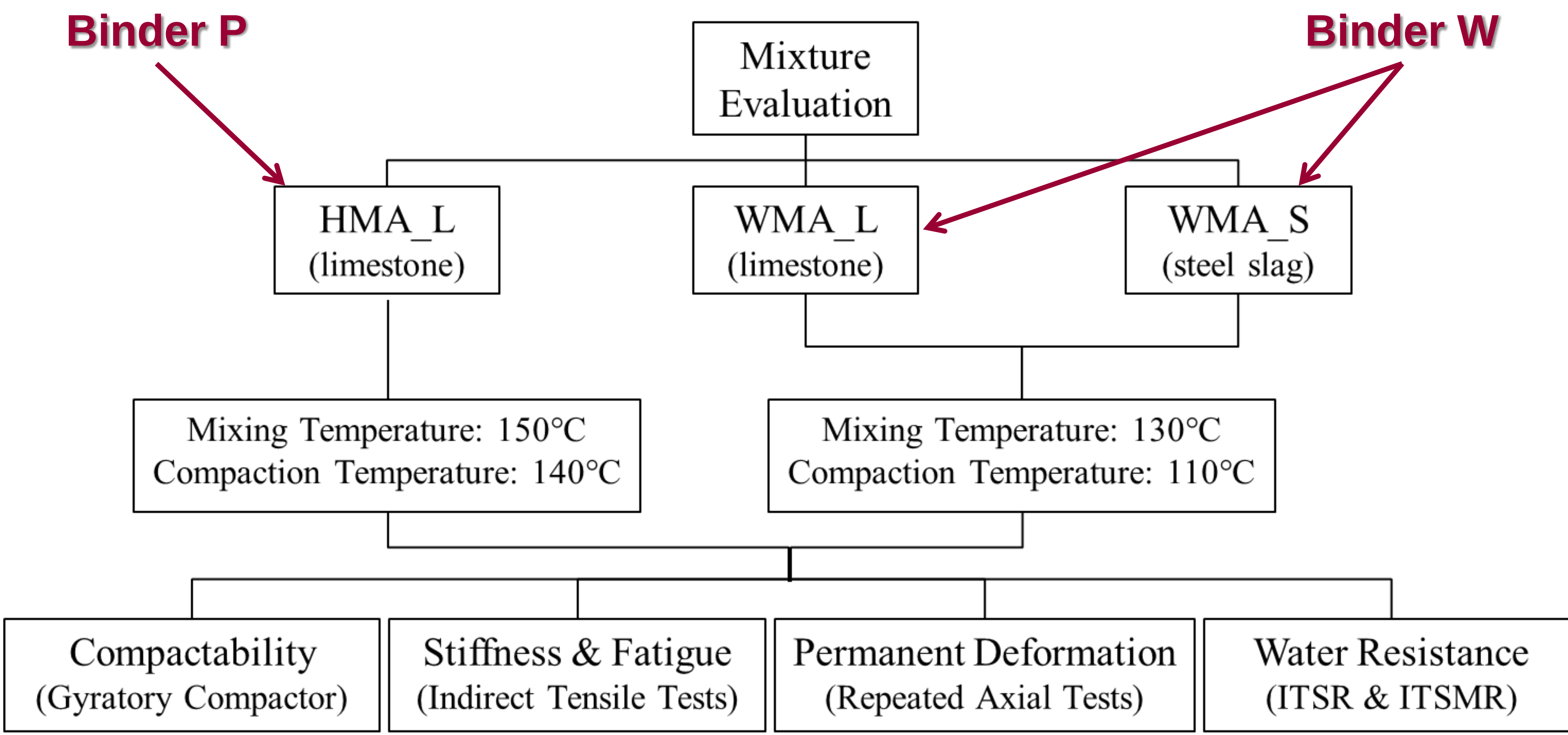
Experimental Plan

Bitumen-Mastic scale



Experimental Plan

Mixture scale



Outline

Materials

Bitumen-Mastic scale

- 35/50 penetration grade bitumen
- Commercial chemical WMA additive (water-free liquid product containing surface active agents) dosed at 0.5% by weight of binder
- Limestone and EAF steel slag filler

Materials

Bitumen-Mastic scale

- Plain and warm-modified bitumens
- Four mastics at a constant filler/bitumen **volume** ratio (27% filler and 73% binder) prepared at 150°C
- Unaged and long-term aged (PAV) conditions

Material code	Filler type	Bitumen Type	Bitumen aging
P	-	Plain (hot) bitumen	unaged
P_A	-	Plain (hot) bitumen	PAV-aged
PL	Limestone	Plain (hot) bitumen	unaged
PL_A	Limestone	Plain (hot) bitumen	PAV-aged
PS	EAF steel slag	Plain (hot) bitumen	unaged
PS_A	EAF steel slag	Plain (hot) bitumen	PAV-aged
W	-	Warm bitumen	unaged
W_A	-	Warm bitumen	PAV-aged
WL	Limestone	Warm bitumen	unaged
WL_A	Limestone	Warm bitumen	PAV-aged
WS	EAF steel slag	Warm bitumen	unaged
WS_A	EAF steel slag	Warm bitumen	PAV-aged

Materials

Mixture scale

- Plain and warm-modified bitumens
- Crushed limestone aggregate and EAF steel slag (fines included)

Materials

Mixture scale

- Plain Hot Mix Asphalt **HMA_L** (reference mixture)
  - 100% limestone aggregates
  - 5.5% of P binder by weight of aggregates (15% by volume)

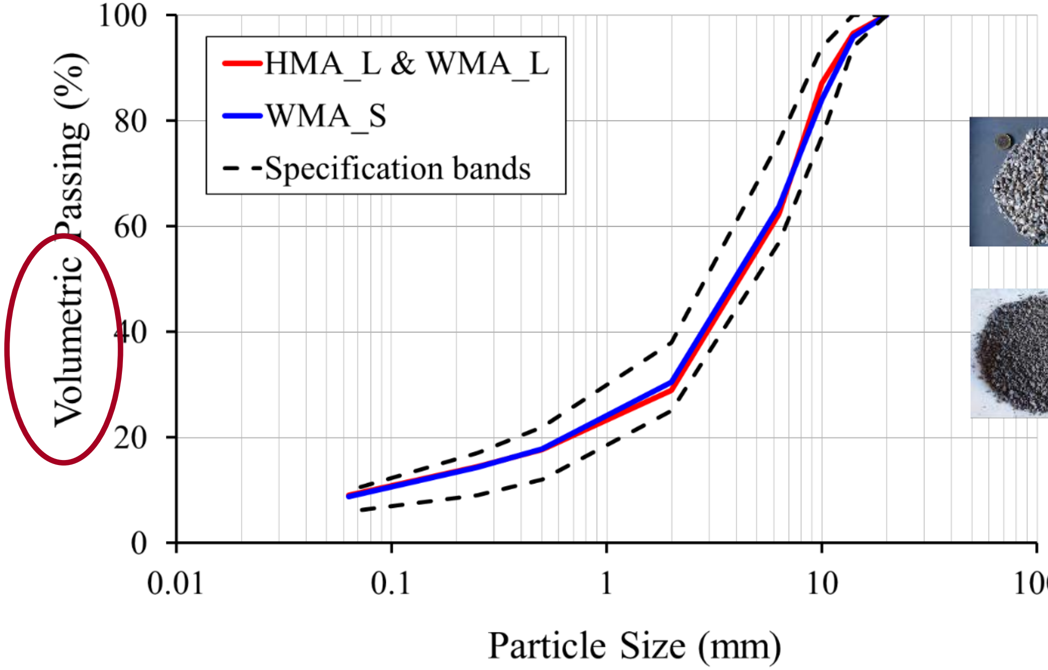
- Plain Warm Mix Asphalt **WMA_L**
  - 100% limestone aggregates
  - 5.5% of W binder by weight of aggregates (15% by volume)

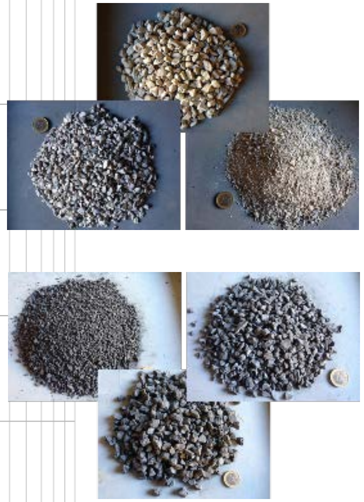
- Warm Mix Asphalt containing steel slag **WMA_S**
  - 60% limestone – 40% steel slag by total weight of aggregates (68% limestone – 32% steel slag by volume)
  - 4.9% of W binder by weight of aggregates (15% by volume) (<u>same volumetric proportions</u>)

Materials

Mixture scale

Mixtures	Limestone dosages (%)					Steel slag dosages (%)		
	12/20	8/12	4/8	0/4	Filler	8/12	4/8	0/4
HMA_L & WMA_L	5	15	37	38	5	-	-	-
WMA_S	5	7	20	23	5	10	15	15





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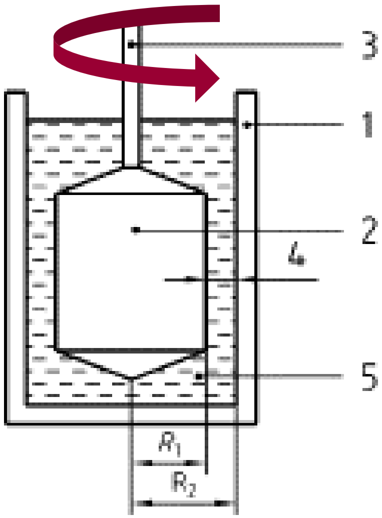
Methodologies and Results

Bitumen-Mastic scale

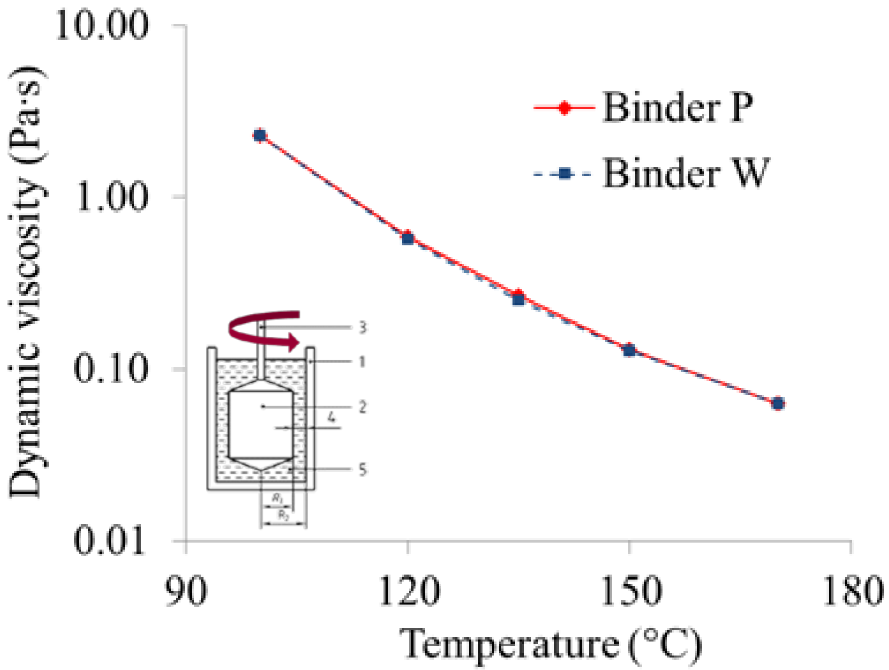
- **Dynamic viscosity tests (EN 13302)**
  - Workability

Coaxial viscometer
T = 100÷170 °C
unaged binder



Methodologies and Results

Binder viscosity



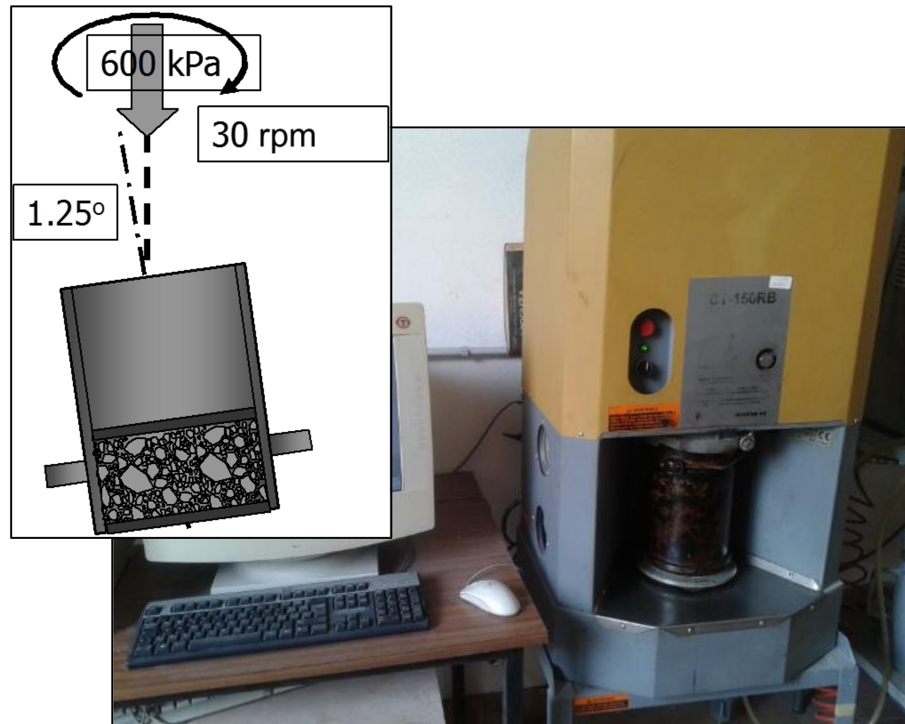
- The warm additive did not influence the viscosity of the plain binder
- Mixing and compaction temperatures cannot be viscosity-based

Methodologies and Results

Mixture scale

- **Superpave Gyratory Compactor – SGC (EN 12697-31)**

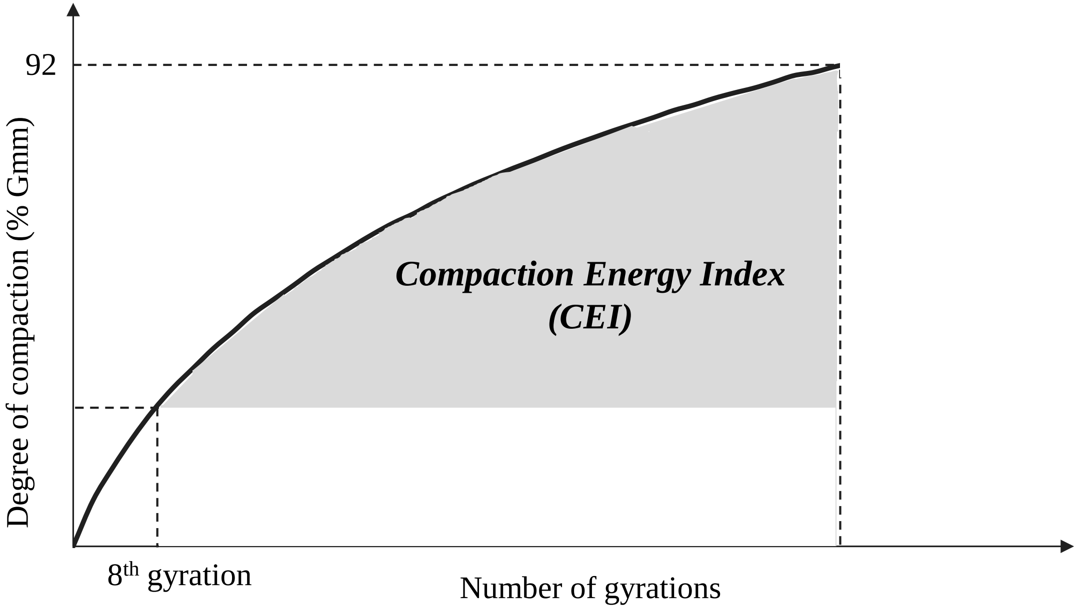
Diameter = 150 mm
Target void content = 3%
100 gyrations
Height = 65 mm (by sawing)



Methodologies and Results

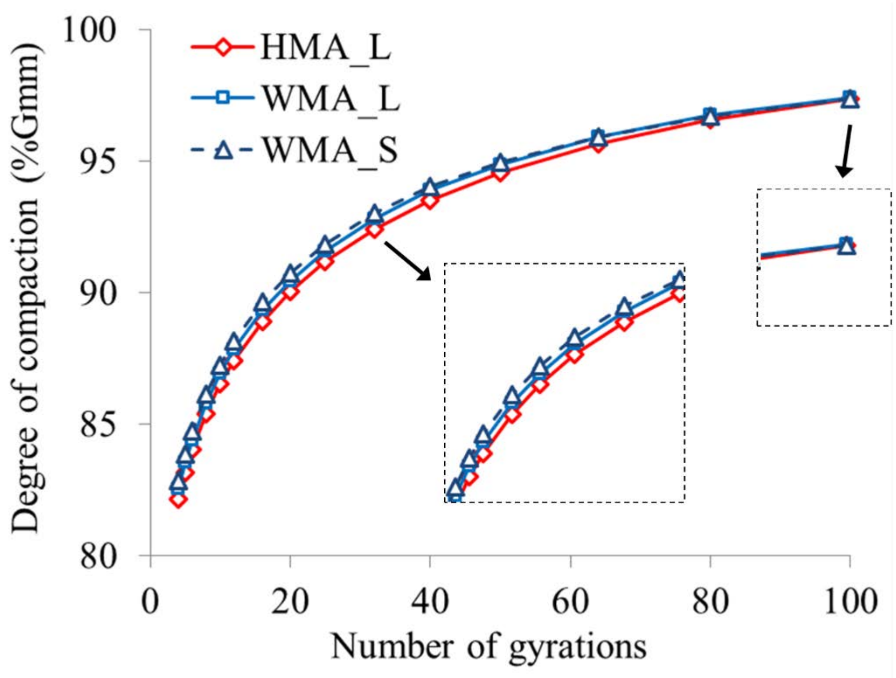
Mixture scale

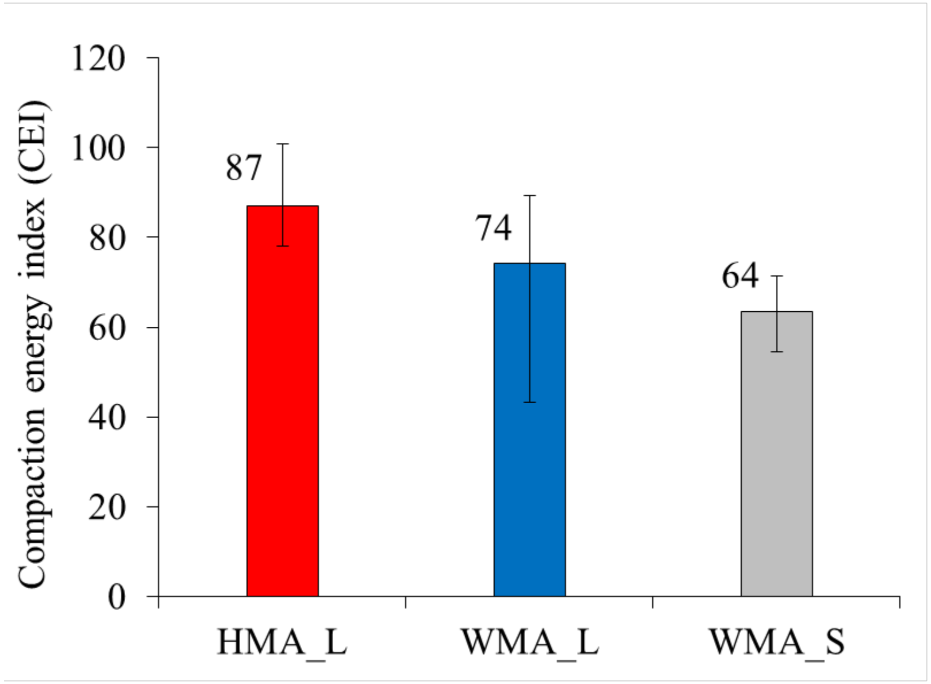
- **Workability assessment**
  - final air void content
    - mathematical G_{mm}
    - SSD bulk density
  - SGC densification curves
    - CEI value



Methodologies and Results

Mixture Compactability





- Effectiveness of the WMA additive in promoting compaction (first phase)
- EAF steel slag guaranteed a further increase in workability

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Methodologies and Results

Bitumen-Mastic scale

Ancona Stripping Test (AST)

- Water resistance (affinity between aggregate and bitumen)

≈ Boiling water stripping method (EN 12697-11)
Uncompacted bitumen-coated aggregate
60 g aggregate (85 g steel slag) and 3 g bitumen
Immersion in boiling water for 45 minutes

Methodologies and Results

Bitumen-Mastic scale

- **Ancona Stripping Test (AST)**

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Bitumen coverage (BC) by digital image analysis

Methodologies and Results

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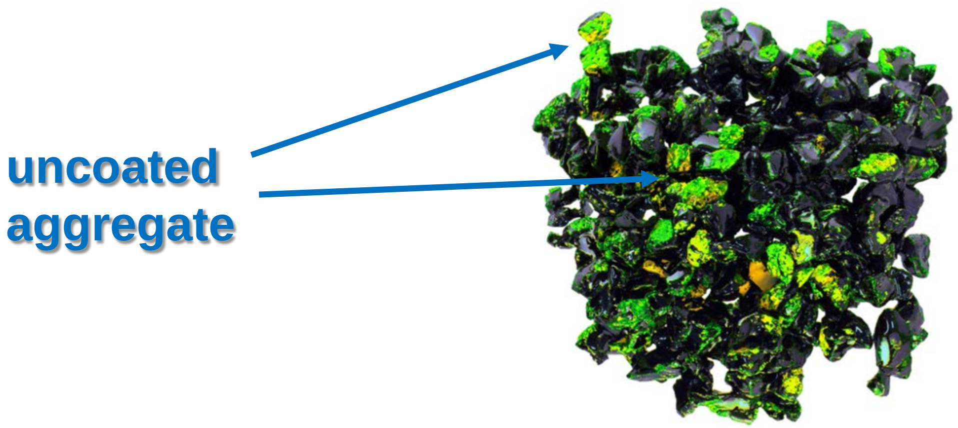

Methodologies and Results

Binder-Aggregate Stripping Susceptibility

Binder **P** + Agg. **L**
BC = 80.2%

Binder **P** + Agg. **S**
BC = 73.1%

Binder **W** + Agg. **L**
BC = 96.2%

Binder **W** + Agg. **S**
BC = 92.3%

- High anti-stripping performance using WMA chemical additive
- Slightly lower moisture resistance for steel slag (lower alkalinity)

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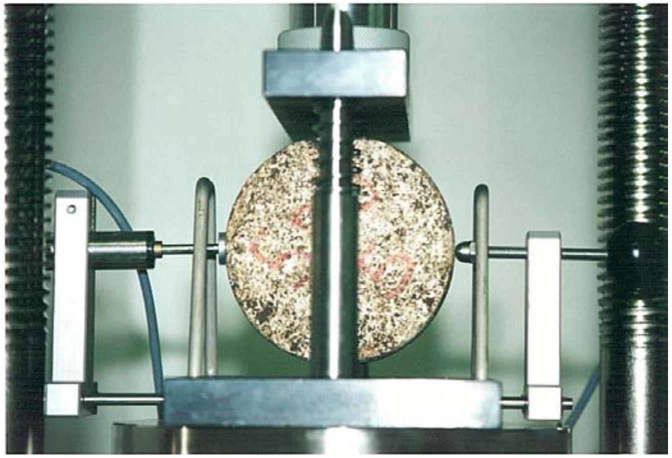
Methodologies and Results

Mixture scale

- **ITS & ITSM ratios**

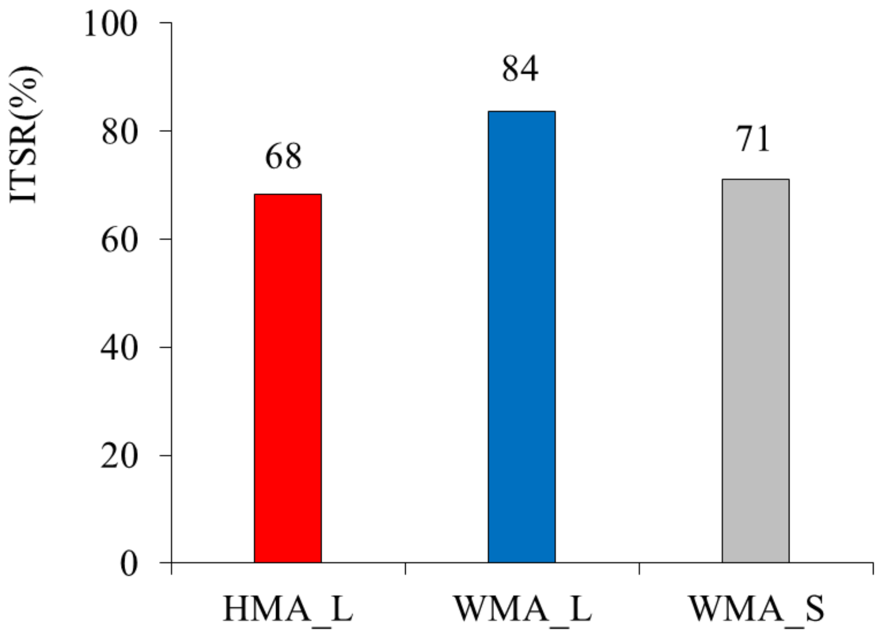
  - Water resistance (affinity between aggregate and bitumen)

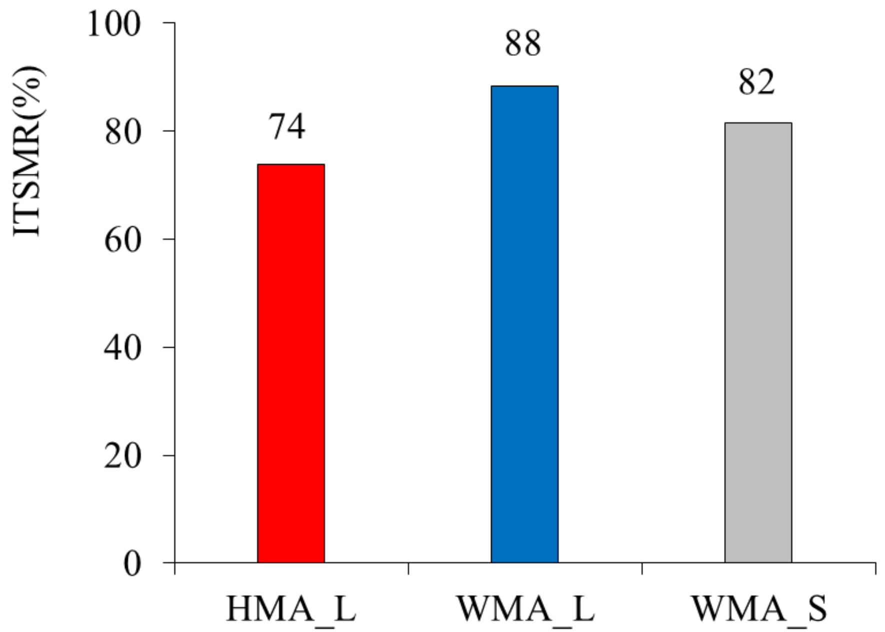
wet conditioning for 15 h at -18 °C and 24 h at 60 °C (ASTM D4867)
Indirect tensile strength (ITS) test at 25 °C and 50 mm/min (EN 12697-23)
Indirect tensile stiffness modulus (ITSM) test at 25 °C
3 replicates



Methodologies and Results

Water Resistance of Mixtures





- Confirmation of results obtained through the stripping tests

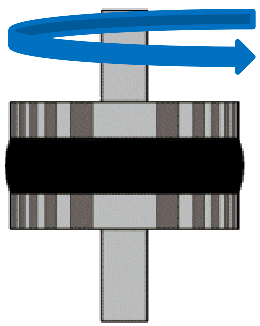
Methodologies and Results

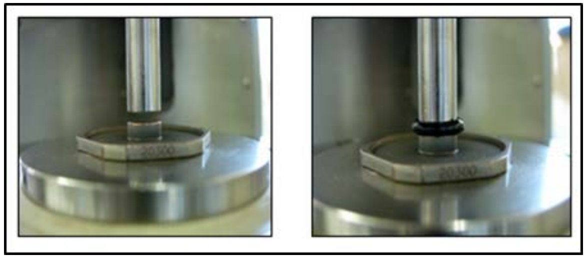
Bitumen-Mastic scale

- **Dynamic shear rheometer (DSR) tests**

  - Midrange service temperature properties

Linear viscoelastic behaviour (|G*| and δ)
Strain-controlled (0.05%) frequency sweeps (0.1÷100 rad/s)
T = 16÷58 °C
Long-term aged binder
8 mm diameter with 2 mm gap – 20 mm diameter with 1 mm gap





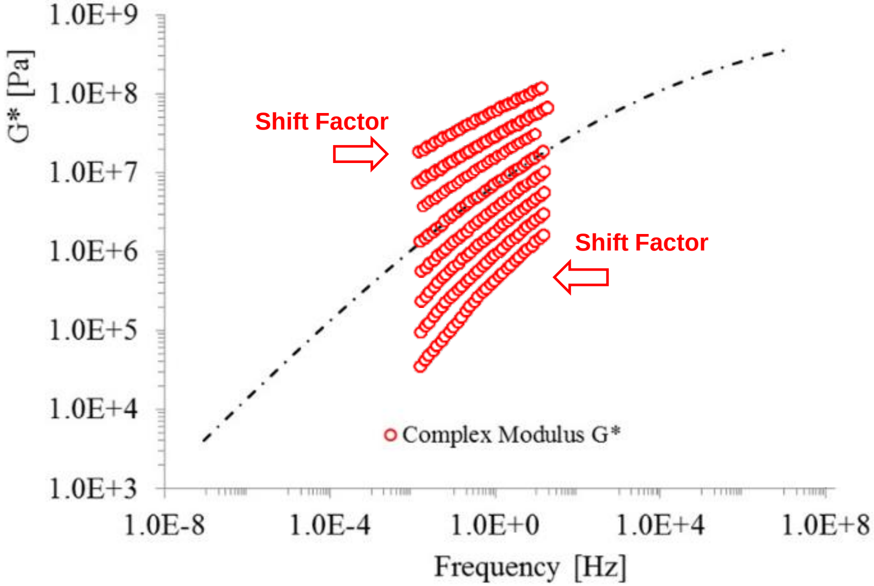
Methodologies and Results

Bitumen-Mastic scale

- **Dynamic shear rheometer (DSR) tests**

  - Midrange service temperature properties

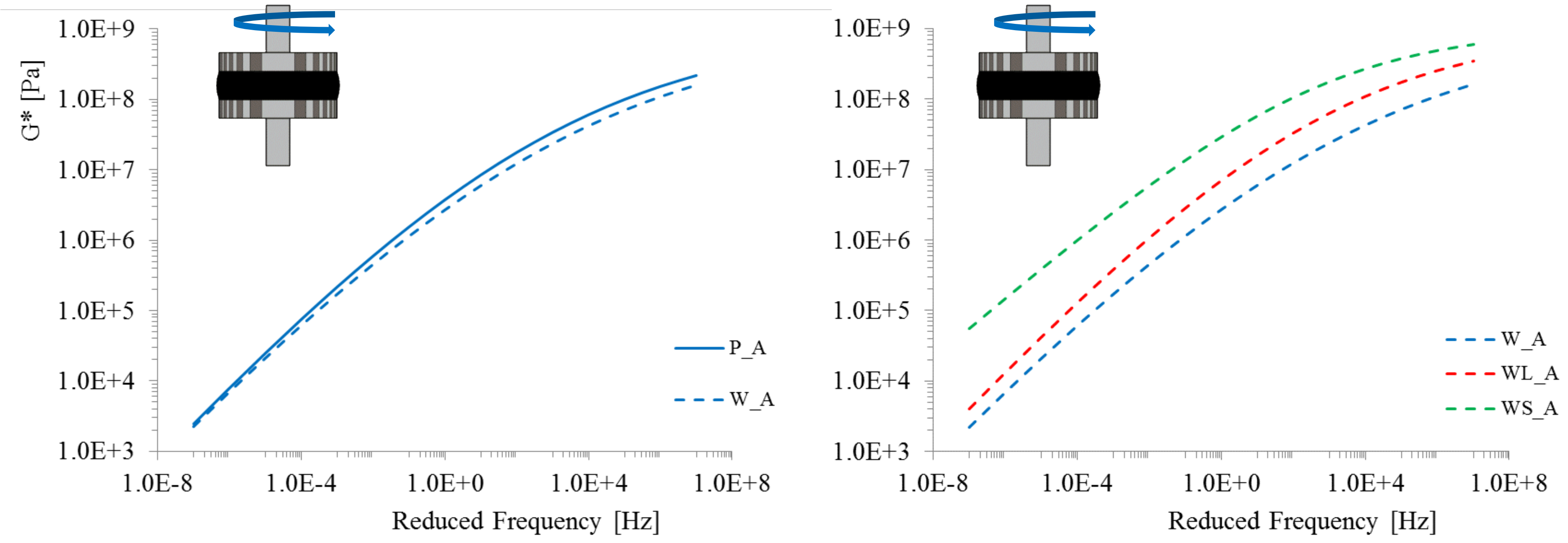
Master curves applying the **time-temperature superposition principle**



$$G^*(f') = G_e \frac{G_g - G_e}{\left[1 + \left({}^{f_c}/_{f'}\right)^k\right]^{m_e/k}}$$

Methodologies and Results

Visco-elastic behaviour of bitumens and mastics



- Quasi-negligible stiffness decrease at high reduced frequencies of W
- Stiffness increase due to the addition of fillers (in particular the slag)

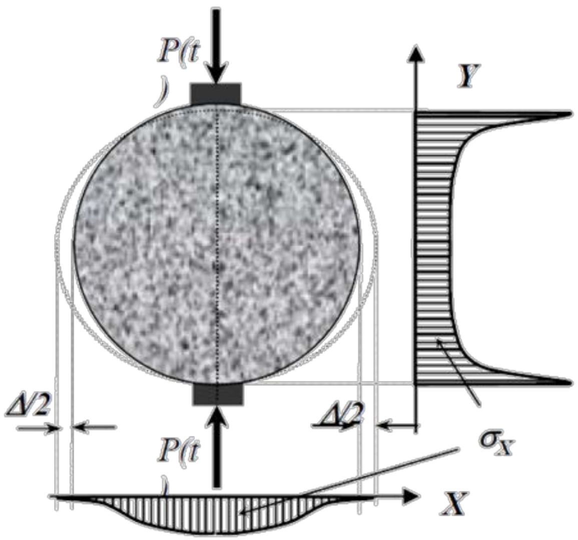
Methodologies and Results

Mixture scale

- **ITSM tests (EN 12697-26/C)**

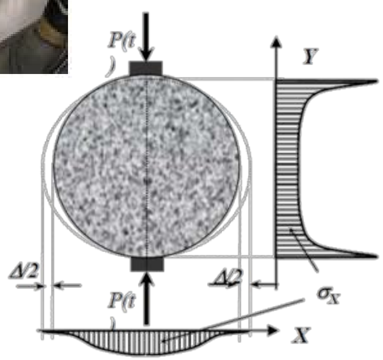
  - Midrange service temperature properties

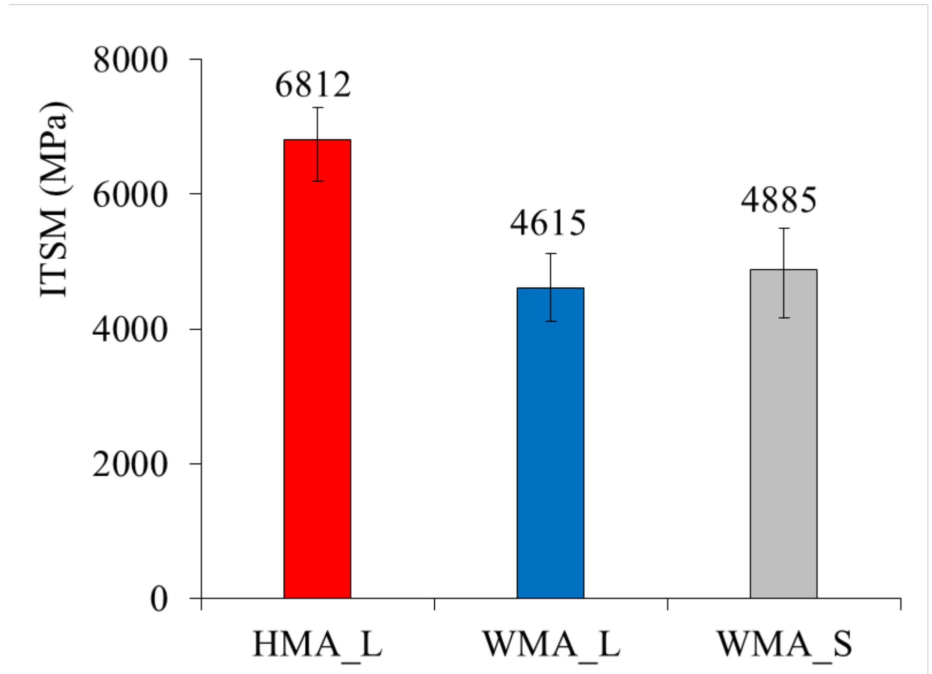
five load pulses
horizontal deformation = 5 μm
rise-time = 124 ms
T = 20 °C
Poisson's ratio = 0.35
8 replicates



Methodologies and Results

Mixture Stiffness





- Lower stiffness of warm mixes (lower oxidative hardening)
- Slight increase in stiffness thanks to the inclusion of EAF steel slag

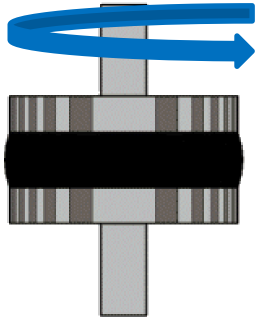
Methodologies and Results

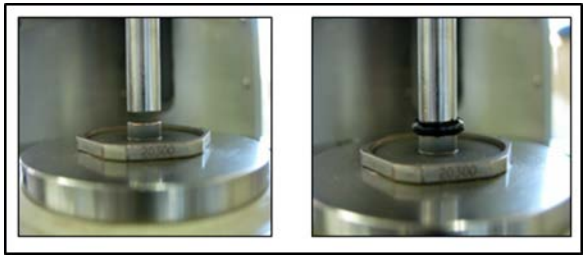
Bitumen-Mastic scale

- **Dynamic shear rheometer (DSR) tests**

  - <u>Midrange service temperature properties</u>

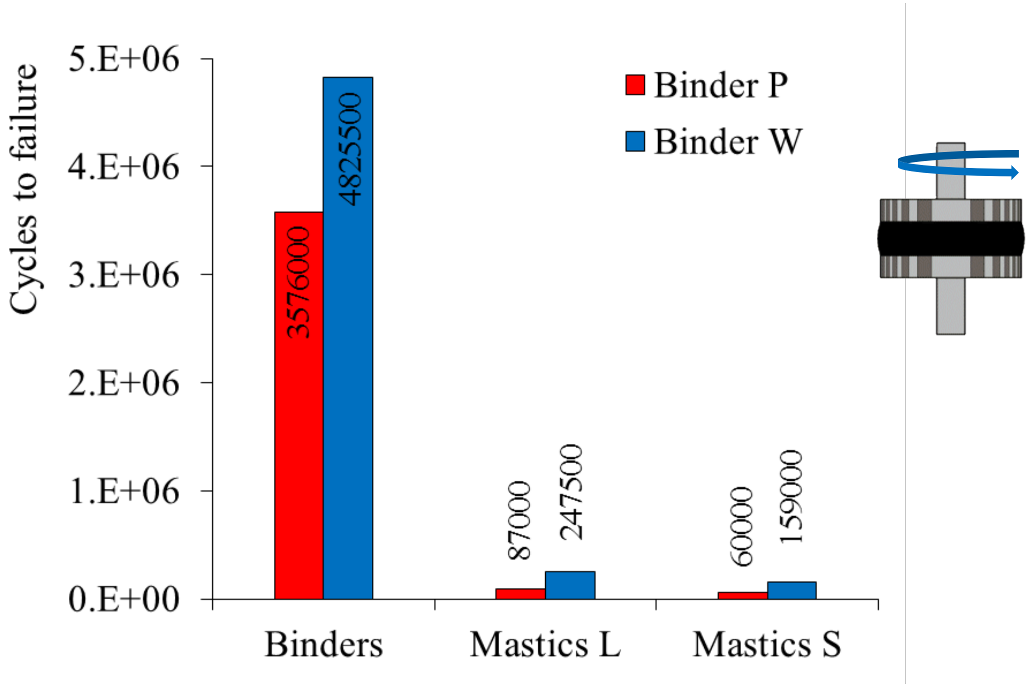
Fatigue resistance (50% reduction in initial complex modulus G*)
Strain-controlled (1.0%) repeated loading time sweeps (10 Hz)
T = 20 °C
Long-term aged binder
8 mm diameter with 2 mm gap





Methodologies and Results

Fatigue resistance of bitumens and mastics



- Warm additive led to a higher fatigue resistance
- Stiffening effect reflects in lower fatigue resistance

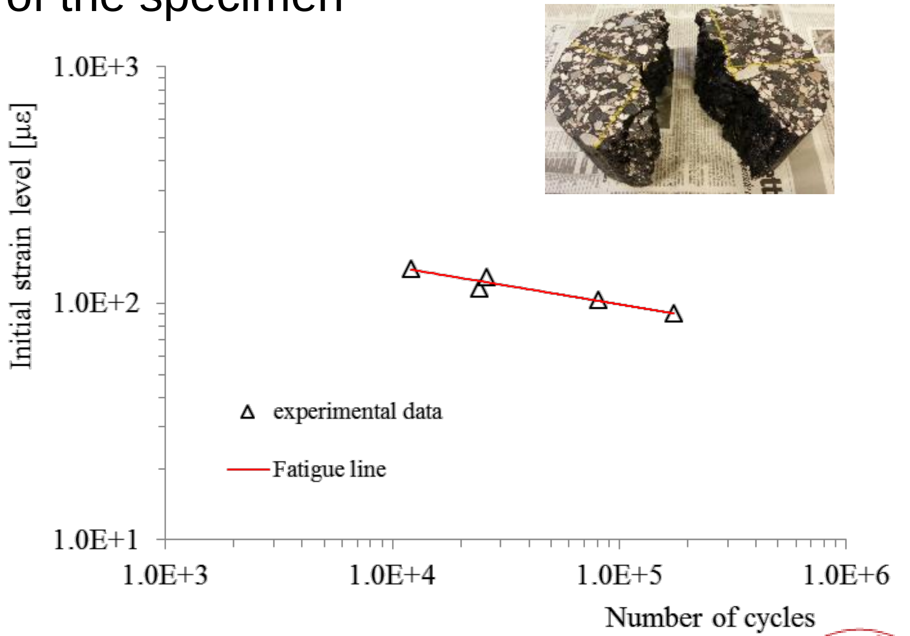
Methodologies and Results

Mixture scale

- **ITFT tests (BS DD ABF)**

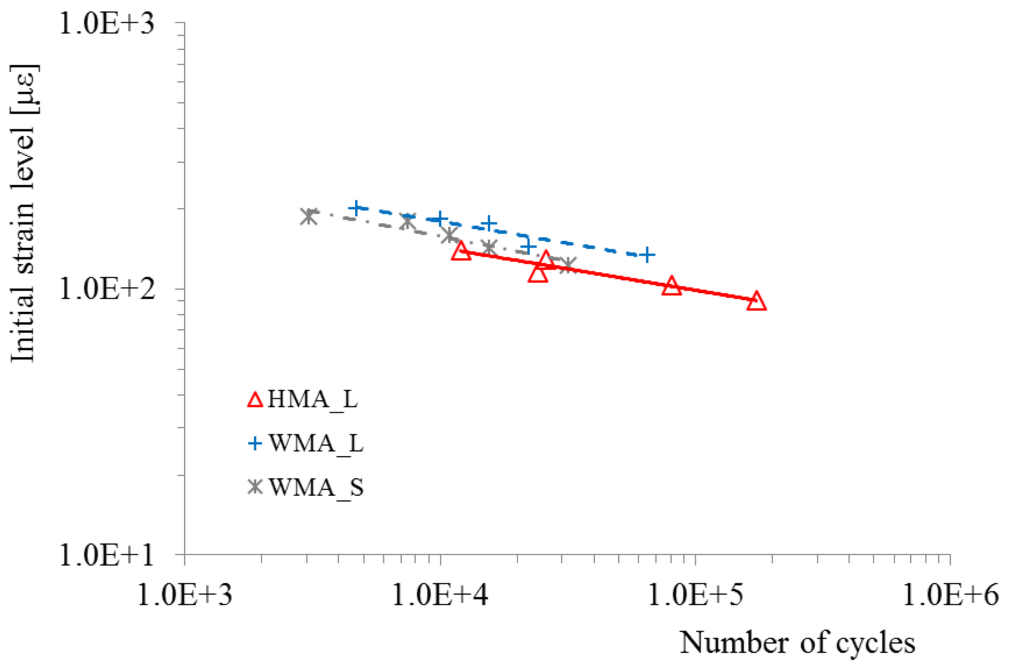
  - Midrange service temperature properties

load pulses (repetition period = 1.5 s)
failure criterion = complete fracture of the specimen
fatigue curves
5 stress levels = 300÷500 kPa
rise-time = 124 ms
T = 20 °C
5 replicates



Methodologies and Results

Fatigue Resistance of Mixtures



- Slightly higher fatigue resistance of warm mixtures
- Slightly lower fatigue performance of the WMA containing steel slag

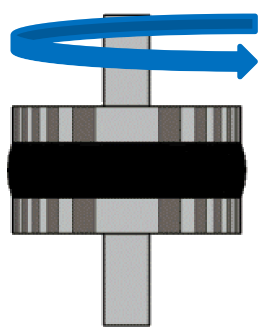
Methodologies and Results

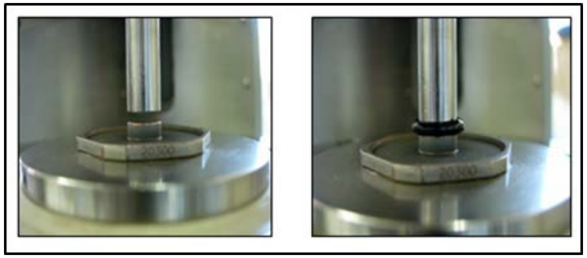
Bitumen-Mastic scale

- **Dynamic shear rheometer (DSR) tests**

  - High service temperature properties

Multiple Stress Creep Recovery (MSCR) tests (EN 16659)
10 creep-recovery cycles (1 s creep loading 9 s recovery time)
T = 58÷76 °C
Stress levels = 0.1, 3.2 and 10 kPa
Unaged binder
20 mm diameter with 1 mm gap





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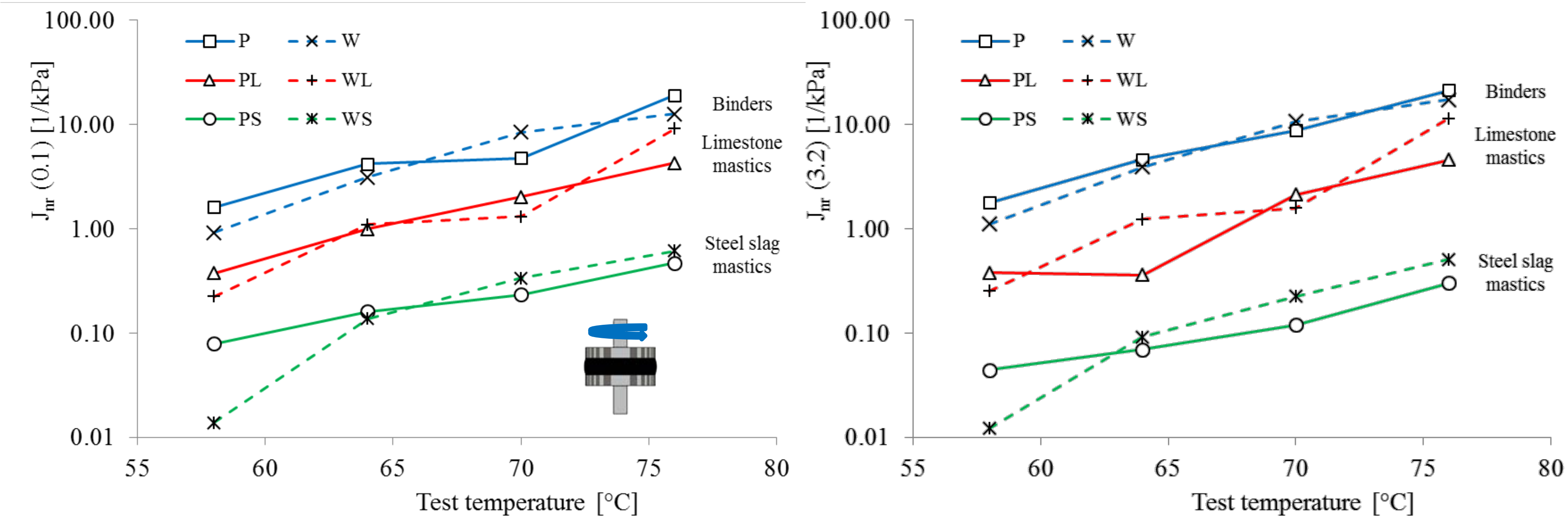
Methodologies and Results

High service temperature behaviour of bitumens and mastics



- Quasi-negligible influence of the warm additive
- Stiffening effect reflects in higher rutting resistance (in particular EAF)

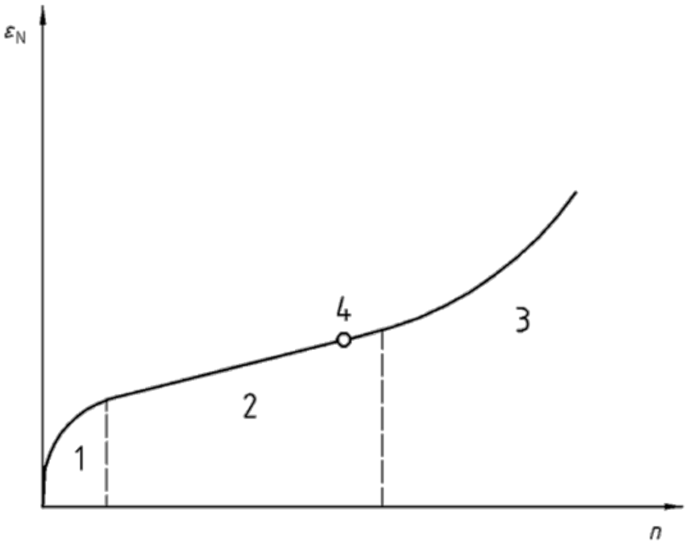
Methodologies and Results

Mixture scale

- **RLA tests (EN 12697-25/A)**

  - <u>High service temperature properties</u>

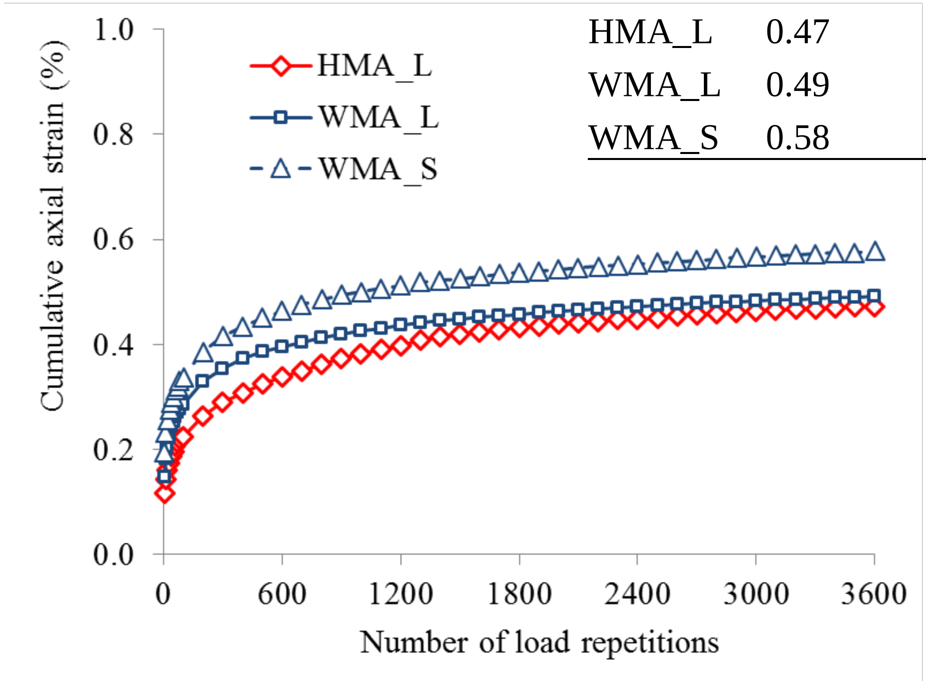
cyclic axial block-pulse pressure
axial strain & creep rate
3600 loading pulses at 0.5 Hz
stress level = 100 kPa
T = 40 °C
3 replicates

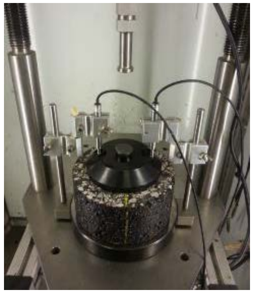


Results and Analysis

Permanent Deformation Resistance of Mixtures

Mixture	Final cumulative strain (%)	Creep rate (μstrain/cycle)
HMA_L	0.47	0.28
WMA_L	0.49	0.22
WMA_S	0.58	0.26





- WMA/EAF steel slag did not seem to penalize rutting resistance

Outline

Conclusions

- The **warm chemical additive** does not influence viscosity and stiffness of the binder while enhancing its fatigue resistance and affinity with aggregates
- Clear stiffening effect of the **EAF steel slag** filler improving anti-rutting properties but reducing fatigue resistance and affinity with asphalt
- The **warm chemical additive** guarantees adequate workability (higher with **EAF steel slag**) without affecting permanent deformation and extending fatigue life of the mixtures (lower stiffness due to less oxidative hardening)

Conclusions

- The influence of reduced temperatures and warm technology mainly hid the contribution (negative or positive) of **EAF steel slag** aggregates on binder-aggregate affinity, stiffness, fatigue resistance and rutting behavior

Outline

Further Studies

- Physical-chemical interaction
- Low temperature cracking
- ….
- <u>Field validation</u>

Publications

- M. Pasetto, G. Giacomello, E. Pasquini, F. Canestrari, "*Effect of warm mix chemical additives on the binder-aggregate bond strength and high-service temperature performance of asphalt mixes containing electric arc furnace steel slag*", RILEM Bookseries, Vol. 11, 2015 – Proceedings, 8th RILEM International Symposium SIB2015, Ancona, 2015
- M. Pasetto, G. Giacomello, A. Baliello, E. Pasquini, "*Rheological Characterization of Warm-Modified Asphalt Mastics Containing Electric Arc Furnace Steel Slags*", Advances in Materials Science and Engineering, Vol. 2016, 2016. doi: 10.1155/2016/9535940
- M. Pasetto, E. Pasquini, G. Giacomello, A. Baliello, "*Warm chemical additive to improve water resistance of asphalt mixtures containing steel slags: a multi-scale approach*", Sixteenth LJMU Annual International Conference on Asphalt, Pavement Engineering and Infrastructure, Liverpool, 2017.
- M. Pasetto, A. Baliello, G. Giacomello, E. Pasquini, *"Comprehensive performance characterization of warm mix asphalt containing steel slags: a laboratory study"*, 7th International EATA Conference – EATA2017, 2017
- M. Pasetto, A. Baliello, G. Giacomello, E. Pasquini, "*Sustainable solutions for road pavements: a multi-scale characterization of warm mix asphalts containing steel slags*", Journal of Cleaner Production, Vol. 166, 2017. doi: 10.1016/j.jclepro.2017.07.212
- M. Pasetto, A. Baliello, G. Giacomello, E. Pasquini, "*Steel slag as valuable aggregate in eco–friendly mixtures for asphalt pavements*", Submitted to Seventeenth LJMU Annual International Conference on Asphalt, Pavement Engineering and Infrastructure, Liverpool, 2018

Thank you for your attention

QUESTIONS?

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