BITUMEN HANDBOOK 2024

ORLEN Asfalt

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2024

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ORLEN Asfalt sp. z o.o., Poland

Authors:
Krzysztof Błażejowski, Ph.D Civ. Eng.
Marta Wójcik-Wiśniewska, M.Sc. Chem. Eng.
Wiktoria Baranowska, M.Sc. Chem. Eng.
Przemysław Ostrowski, M.Sc. Civ. Eng.

ORLEN Asfalt sp. z o.o.
ul. Łukasiewicza 39, 09-400 Płock
phone: (+48) 242 56 98 74
fax: (+48) 243 67 91 09
e-mail: asfalt@orlen-asfalt.pl

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DEAR READERS!

It is with great satisfaction that we present the eighth edition of the English version of the Bitumen Handbook, the only publication of its kind in Poland, which is a structured collection of expertise on bituminous binders and information on their effective practical application. For the past 17 years, ORLEN Asfalt has been supporting the road construction industry in Poland and neighbouring countries by providing up-to-date information on bitumens and asphalt mixes.

This Handbook describes the properties of bitumen, its functionality and many issues related to their production, logistics or use in the production of asphalt mixes. Therefore, the expertise presented here can be useful at any stage of a road construction project − from design, through research and development, finally to paving. Here in the Bitumen Handbook's we explain the basic issues related to the use of bitumens, as well as more complex issues related to testing their properties. The Handbook constitutes a valuable resource for those who are new to working with bitumen, as well as experts in the field.

We are aware of the fact that the Polish version of the Handbook is used by Polish civil engineering faculty students, and its versions published in other languages form a valuable source of information for foreign students. We are proud of the fact that our work contributes to supporting future engineers to be employed in the Polish road construction industry.

This Handbook edition is slightly different from the previous ones. It focuses more on environmental protection issues, eco-friendly solutions, etc., which obviously results from the transformation that our economy has been undergoing and other changes introduced in the European Union's strategies. It is not important whether these changes are already comprehensively present in the road construction industry in Poland and neighbouring countries, but we are aware of the fact that they may soon change its image and the way it operates. We strive to be prepared for this moment, and this is also what the information provided in this Handbook is intended for.

ORLEN ASFALT SP. Z O.O.

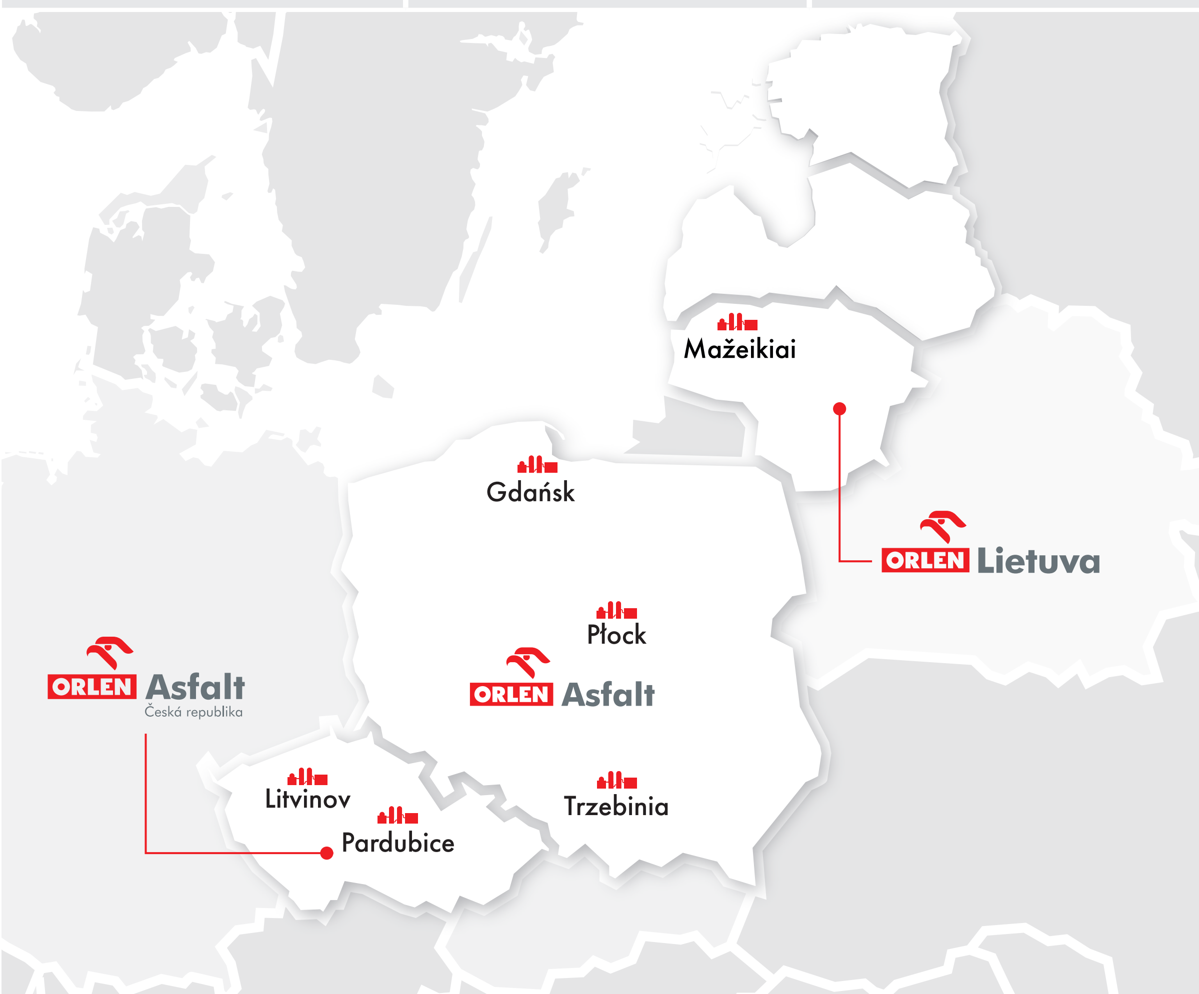
The company is a part of the ORLEN multi-utility concern and one of the major suppliers of bituminous binders used for road surface production in Central Europe. Every year, our products are exported to over 40 countries around the world. In line with the strategy adopted by ORLEN Asfalt its commercial activity is focused mostly on the Polish market, with over 70 percent of the sales volume.

As part of ORLEN Group's bitumen production segment, we supply products from six production centres located in Poland (Płock, Gdańsk, Trzebinia), the Czech Republic (Pardubice, Litvinov) and Lithuania (Mažeikiai). Such factors as process development and sales consolidation have enabled us to meet the ongoing bitumen market demand. In 2017 − 2022 (before merging with the LOTOS Group), the ORLEN Group supplied, on average, approx. 1.5 million tonnes of bitumen annually.

Since 2003, the ORLEN Asfalt company has also been at the forefront of bitumen technology development:

- We have implemented over 100 research projects.
- We have marketed 16 new products.
- We cooperate with local governments and universities in the field of environmentally friendly bitumen technology development.
- We have published 17 editions of the Bitumen Handbook in four language versions.

MANUFACTURING CENTRES		
PŁOCK, GDAŃSK, TRZEBINIA (POLAND)	LITVINOV, PARDUBICE (CZECHIA)	MAŽEIKIAI (LITHUANIA)
PAVING GRADE BITUMEN POLYMER MODIFIED BITUMEN HIGHLY MODIFIED BITUMEN	PAVING GRADE BITUMEN HARD PAVING GRADE BITUMEN MULTIGRADE BITUMEN POLYMER MODIFIED BITUMEN HIGHLY MODIFIED BITUMEN INDUSTRIAL BITUMEN OXIDISED BITUMEN	PAVING GRADE BITUMEN V6000 BITUMEN V12000 BITUMEN



I. BITUMINOUS BINDERS AND THEIR PROPERTIES

#bitumen, #properties, #statistics, #PMB, #HiMA

1.1. INTRODUCTION

Bitumen (*asphalt or asphalt cement* [USA]) is a complex mixture of macromolecular hydrocarbons of different homologous series[1] and heterocyclic compounds[2], forming a dispersible colloidal system of a complex composition and chemical structure [1, 2]. It is a brown or black thermoplastic binding material with a consistency ranging from a viscous fluid at high temperatures to a vitreous solid at low temperatures [3], totally or partially soluble in toluene. Bitumen can be in the form of organogenic rock[3], as natural deposits, i.e. **natural bitumen**, or a product obtained as a result of petroleum processing, i.e. **petroleum bitumen** [4].

Moreover, bituminous binders used in road pavements are **construction products**, the marketing and production of which is governed by Regulation (EU) no. 305/2011 of the European Parliament and of the Council of 9 March 2011, and, additionally, in Poland by the Act on Construction Products and other secondary legislation.

Paving grade and polymer modified bitumen produced by the ORLEN Group meet the requirements of European standards, i.e. **EN 12591** and **EN 14023**, respectively [5, 6]. These standards are part of the package of European standards for bituminous binders Fig. 1.1.).

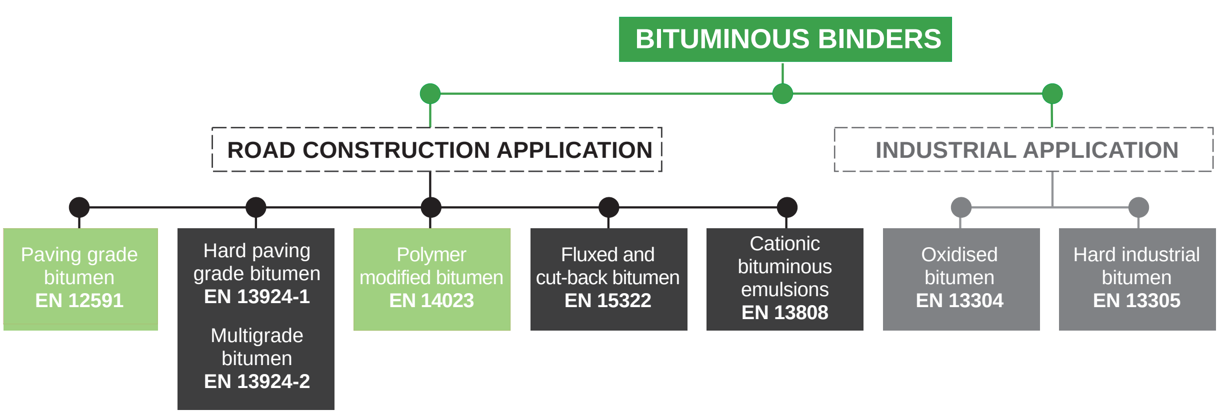


Fig. 1.1. *Attribution of European Standards to various types of binders. Standards referring to paving grade and polymer modified bitumen are highlighted in green.*

1) A homologous series is a set of chemical compounds with similar chemical structures and properties which can be defined with a common molecular formula. Examples of homologous series include alkanes, alkenes or alkynes, which differ only in the number of $-CH_2-$ groups, and which can be defined with a general molecular formula. Individual compounds belonging to the same series are called homologues.

2) Heteroorganic compounds include chemical compounds in which at least one carbon atom in the main (hydrocarbon) chain has been replaced by another element, e.g. oxygen, nitrogen, or sulfur.

3) Organogenic rock is sedimentary rock formed by plant or animal organism remains accumulation or sediment precipitation as a result of the physiological activity of these rock-forming organisms; organogenic rocks include some limestones (including shell limestone), chalk, radiolarites, phosphorites, (rock and brown) coal and peat.

During the production season, bituminous binders are manufactured in numerous batches. Each batch must be tested for specific properties according to the product standards and the Factory Production Control principles, before it is released for sale. An important feature of products from various production batches, both for the manufacturer and the user, is the homogeneity of their properties.

Observation of individual batch properties is each time burdened with a random error and does not allow to formulate any conclusions regarding their significance. Only an analysis of as large a number of results as possible using correct statistical tools allows one to discover and understand certain regularities that characterise a given set of results and to observe the relations between them [7].

This chapter provides information on the requirements formulated by bitumen binders, their intended use and properties, as defined in EN 12591 and EN 14023. It also contains data regarding bitumen binder density and polymer bitumen micro-structure. Statistical parameters for laboratory test results regarding selected properties of bituminous binders produced by the ORLEN Group (Płock and Trzebinia plants) in the period from 2020 to 2022 are presented in the second section of the chapter (see 1.5 STATISTICAL ANALYSIS OF BITUMEN PARAMETERS). The tests were performed in accredited units of ORLEN Laboratorium S.A.

1.2. BITUMINOUS BINDERS – REQUIREMENTS

1.2.1. REFERENCE DOCUMENTS

As was mentioned above, bituminous binders used in road construction are "**construction products**" the marketing and production of which is governed by Regulation (EU) no. 305/2011[4] of the European Parliament and of the Council of 9 March 2011, and, additionally, in Poland by the Act on Construction Products and other secondary legislation. The requirements specified for construction products apply to binders used in the road construction industry, but do not apply to oxidised (industrial) bitumen, i.e. usually a raw material used to manufacture products other than those used in road construction projects (sealants, insulation materials, roofing paper, etc.).

In the case of binders for road construction applications, requirements have been introduced for each type of bitumen that must be met in order for the product to be marketed.

The conformity of paving grade binder properties with the requirements of the relevant standard and values specified therein (including grades for polymer modified bitumen) should be demonstrated by:

- initial type tests;
- Factory Production Control (FPC).

As per bitumen related standards, a manufacturer is obliged to implement, document and maintain the Factory Production Control system. Such a system should comprise of procedures, regular inspections and tests whose results must be used for the finished product quality assessment. Each standard also specifies requirements regarding the manufacturing equipment and machinery inspections and maintenance described in Annex Z.

4) As of the date of translation of the Polish version of the Bitumen Handbook 2024 the proposal for a novel Regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of construction is under finalisation – following the meeting of the Permanent Representatives Committee on 2/02/2024, the final compromise text was approved. While reading the Handbook, it is important to note that this data is up to date.

The property control methods, including the elements mentioned below, are also defined:

- all properties, according to the provision related to type tests, must be subject to testing at least once in a year;
- regular monitoring of product quality should consist of type verification, and frequency of monitoring must be documented and ensure that the properties remain essentially similar to those defined during the initial type tests.

Binders used for construction of roads, airports and other road traffic-carrying surfaces are covered by the “2+” conformity verification and assessment system which requires every manufacturer to implement the Factory Production Control system certified by an FPC Certificate issued by a notified body. Annex ZA also includes the procedure for product conformity assessment, division of responsibilities between the manufacturer and the notified body, a chapter on certification and declarations of performance, CE marking and labelling.

Table 1.1. presents bituminous binders currently marketed by the ORLEN Group with reference documents in force. Product groups offered by ORLEN Asfalt are marked in bold; they are described in the following sections with regard to properties, requirements and recommended applications.

Table 1.1.
Attribution of European Standards to various types of binders and numbers of FPC Certificates for production sites within ORLEN Group

BITUMINOUS BINDER TYPE	REFERENCE DOCUMENT	FPC CERTIFICATE NO.
Paving grade bitumen	**EN 12591**	**1434-CPR-0338 in Płock and Gdańsk 1020-CPR-090031819 in Litvinov 1020-CPR-090030197 in Pardubice 1567-CPR-0064 in Mažeikiai**
Hard paving grade bitumen Multigrade bitumen	EN 13924-1 EN 13924-2	1020-CPR-090033991 14 0300SV/ITC/a in Pardubice
Polymer modified bitumen Highly modified bitumen	**EN 14023**	**1434-CPR-0339 in Płock and Gdańsk 1434-CPR-0186 in Trzebinia 1023-CPR-1055F in Pardubice**
Fluxed and cut-back bitumen	EN 15322	not manufactured
Cationic bitumen emulsions	EN 13808	1023-CPR-0629F in Pardubice
Oxidised bitumen	EN 13304	not applicable; not a construction product
Hard industrial bitumen	EN 13305	not applicable; not a construction product

1.2.2. BITUMEN CLASSIFICATION

1.2.2.1. Paving grade bitumen

Paving grade bitumens offered by ORLEN Asfalt are manufactured in accordance with the EN 12591: 2009 standard.

The EN 12591:2009 standard *Bitumen and bituminous binders. Specifications for paving grade bitumens* is a partially classifying standard, i.e. most of the requirements are obligatory, but CEN member countries have the freedom to select some of them. This standard sets out the principles of defining properties and adequate testing techniques for bituminous binders used for construction and maintenance of roads, airports and other road traffic-carrying surfaces. It also includes all requirements regarding the conformity assessment.

Requirements of paving grade bitumen types, manufactured in accordance with the EN 12591:2009 standard, are labelled according to classification provided in Table 1.2.

Table 1.2.
Classification of paving grade bitumen types manufactured acc. to EN 12591

BITUMINOUS BINDER	PAVING GRADE BITUMEN
Reference document	EN 12591:2009
Standard designation of bituminous binder	XX/YY
Main type of bituminous binder supplied by ORLEN Group	20/30, 35/50, 35/50 WMA*, 50/70, 50/70 WMA*, 70/100, 100/150, 160/220

Notes to designations:
XX – lower penetration limit at 25°C for a given bitumen type [0.1 mm] as per EN 1426;
YY – upper penetration limit at 25°C for a given bitumen type [0.1 mm] as per EN 1426;
WMA (Warm Mix Asphalt) – paving grade bitumen with this designation is used in asphalt mixes used in the "warm mix" technology – see Chapter 3.

1.2.2.2. Polymer modified bitumen

Polymer modified bitumen (PMB) types offered by ORLEN Asfalt are manufactured according to the EN 14023:2010 standard.

The EN 14023:2010 standard *Bitumen and bituminous binders. Specification framework for polymer modified bitumen* is a fully classification standard. It means that it provides a set of properties and various requirement levels (classes) assigned to them. It assumes that each Member State of CEN selects the properties and the related requirement levels. This enables each Member State to specify its own requirements to be met by polymer modified bitumen used on its territory. This differentiation results from diverse climate conditions in various parts of Europe, different permissible vehicle axle loads and many other technological factors. The list of requirements applicable to Poland is provided in the National Annex to this standard (latest edition from 2020).

The EN 14023:2010 standard contains a set of basic and additional properties, which are contained in three separate tables:

- **Table 1** – Required properties of polymer modified bitumens;
- **Table 2** – Properties related to legal regulations or other country-specific conditions;
- **Table 3** – Additional properties.

The standard also includes all requirements regarding the assessment of conformity.

Polymer modified bitumen manufactured according to the requirements of the EN 14023:2010 standard are labelled according to classification provided in table 1.3.

Table 1.3.
Classification of polymer modified bitumen types manufactured acc. to EN 14023

BITUMINOUS BINDER	MODIFIED BITUMEN
Reference document	PN-EN 14023:2011/Ap2:2020
Standard designation of bituminous binder	PMB X/Y-Z
Main type of bituminous binder supplied by ORLEN Group	ORBITON 10/40-65 ORBITON 25/55-60 ORBITON 45/80-55 ORBITON 45/80-65 ORBITON 65/105-60

Notes to designations:
X – lower penetration limit at 25°C [0.1 mm] as per EN 1426;
Y – upper penetration limit at 25°C [0.1 mm] as per EN 1426;
Z – lower softening point (R&B) limit [°C] as per EN 1427.
PMB stands for Polymer Modified Bitumen (usually replaced by the manufacturer's trade name).

This Handbook contains a detailed description of ORBITON polymer modified binders manufactured for road construction industry applications in Poland. ORLEN Asfalt also offers ORBITON polymer modified binders adapted to local requirements of countries to which these PMB are exported (e.g. Romania, Lithuania, Latvia, Czechia, Slovakia, Germany, Hungary). The types of bitumens produced are shown in Table 1.4.

Table 1.4.
Main types of modified bitumen supplied by the ORLEN Group

TYPES OF ORBITON MODIFIED BITUMEN ACC. TO NATIONAL ANNEX FOR POLAND	TYPES OF ORBITON MODIFIED BITUMEN ACC. TO REQUIREMENTS APPLICABLE IN OTHER EU STATES
10/40-65; 25/55-60; 45/80-55; 45/80-65; 65/105-60	25/55-55 EXP; 25/55-60 EXP; 25/55-65 EXP; 45/80-75 SK

1.2.2.3. Highly modified bitumen

Analogously to modified bitumens, highly modified bitumens are manufactured and classified according to EN 14023:2010 *Bitumen and bituminous binders. Specification framework for polymer modified bitumen*. The highly modified bitumen classification is shown in Table 1.5. In Poland, these binders are designated and referred to as "HiMA" which is an abbreviation of the term used in the USA, i.e. *Highly Modified Asphalt*.

Table 1.5.
Classification of highly modified bitumen types manufactured acc. to EN 14023

BITUMINOUS BINDER	HIGHLY MODIFIED BITUMEN
Reference document	PN-EN 14023:2011/Ap2:2020-02
Standard designation of bituminous binder	PMB X/Y-Z
Main type of bituminous binder supplied by ORLEN Group	ORBITON 25/55-80 HiMA ORBITON 25/55-80 HiMA WMA* ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA* ORBITON 65/105-80 HiMA

Notes to designations:
X – lower penetration limit at 25°C [0.1 mm] as per EN 1426;
Y – upper penetration limit at 25°C [0.1 mm] as per EN 1426;
Z – lower softening point (R&B) limit [°C] as per EN 1427.
PMB stands for Polymer Modified Bitumen (usually replaced by the manufacturer's trade name).
WMA stands for *Warm Mix Asphalt*, i.e highly modified bitumens with improved workability – see Chapter 3. ORBITON HiMA – bitumen trade name

1.2.3. REQUIREMENTS FOR BITUMEN

1.2.3.1. Paving grade bitumen

Table 1.6. presents general requirements regarding paving grade bitumen, according to information provided in to the EN 12591:2009 standard

Table 1.6.

Requirements regarding paving grade bitumen of the penetration values from 20 × 0.1 to 220 × 0.1 mm, acc. to the EN 12591:2009 standard

	PROPERTY	TEST METHOD	UNIT	PAVING GRADE BITUMEN TYPE					
				20/30	35/50	50/70	70/100	100/150	160/220
Properties applied to all paving grade bitumen types specified in this Table	Penetration at 25°C	EN 1426	0.1 mm	20-30	35-50	50-70	70-100	100-150	160-220
	Softening point	EN 1427	°C	55-63	50-58	46-54	43-51	39-47	35-43
	Resistance to hardening at 163°C	EN 12607-1 (RTFOT method)							
	Retained penetration		%	≥ 55	≥ 53	≥ 50	≥ 46	≥ 43	≥ 37
	Softening point increase		°C	≤ 8	≤ 8	≤ 9	≤ 9	≤ 10	≤ 11
	Change of mass* (absolute value)		%	≤ 0.5	≤ 0.5	≤ 0.5	≤ 0.8	≤ 0.8	≤ 1.0
	Flash point	EN ISO 2592	°C	≥ 240	≥ 240	≥ 230	≥ 230	≥ 230	≥ 220
	Solubility	EN 12592	% (m/m)	≥ 99.0	≥ 99.0	≥ 99.0	≥ 99.0	≥ 99.0	≥ 99.0
Properties adapted to country-specific conditions	Penetration index	EN 12591 Annex A	—	NR	NR	NR	NR	NR	NR
	Dynamic viscosity at 60°C	EN 12596	Pa · s	NR	NR	NR	NR	NR	NR
	Fraass breaking point	EN 12593	°C	NR	≤ - 5	≤ - 8	≤ - 10	≤ - 12	≤ - 15
	Kinematic viscosity at 135°C	EN 12595	mm^2/s	NR	NR	NR	NR	NR	NR

* change of mass may be a positive or negative value
NR (No Requirement) indicates that there are no requirements for a specific property.

1.2.3.2. Polymer modified bitumen

The National Annex to EN 14023:2010 published with an amendment: Ap2:2020-02 in 2020 is a set of properties and requirement levels for these properties for six polymer modified bitumen typed used in Poland. The requirements given in the National Annex have been established by the working team of the Subcommittee for Bitumen of Technical Committee 222 of the Polish Committee for Standardization.

A division by type and requirements for polymer modified bitumen is shown in Table 1.7.

Table 1.7.
Division based on types and requirements for polymer modified bitumen in Poland acc. to National Annex to standard PN-EN 14023:2011/Ap2:2020-02

PROPERTY			TEST METHOD	UNIT	POLYMER MODIFIED BITUMEN TYPE					
					PMB 10/40-65		PMB 25/55-60		PMB 45/80-55	
					RANGE	CLASS	RANGE	CLASS	RANGE	CLASS
Basic properties		Penetration at 25°C	EN 1426	0.1 mm	10-40	2	25-55	3	45-80	4
		Softening point	EN 1427	°C	≥ 65	5	≥ 60	6	≥ 55	7
	Cohesion**	Force ductility tested using ductilometer (50 mm/min)	EN 13589 EN 13703	J/cm^2	≥ 2 at 10°C	6	≥ 2 at 10°C	6	≥ 3 at 5°C	2
		Tensile test at 5°C (100 mm/min)	EN 13587	J/cm^2	NR	0	NR	0	NR	0
		Vialit pendulum test (impact method)	EN 13588	J/cm^2	NR	0	NR	0	NR	0
		Change of mass after hardening*	EN 12607-1	% m/m	≤ 0.5	3	≤ 0.5	3	≤ 0.5	3
		Retained penetration at 25°C after hardening	EN 12607-1 EN 1426	%	≥ 60	7	≥ 60	7	≥ 60	7
		Softening point increase after hardening	EN 12607-1 EN 1427	°C	≤8	2	≤ 8	2	≤ 8	2
		Flash point	EN ISO 2592	°C	≥ 235	3	≥ 235	3	≥ 235	3
Additional properties		Fraass breaking point	EN 12593	°C	≤ -5	3	≤ -10	5	≤ -15	7
		Elastic recovery at 25°C	EN 13398	%	≥ 60	4	≥ 60	4	≥ 70	3
		Elastic recovery at 10°C	EN 13398	%	NR	0	NR	0	NR	0
		Plasticity range	EN 14023	°C	NR	0	NR	0	NR	0
		Drop in softening point after EN 12607-1	EN 12607-1 EN 1427	°C	TBR	1	TBR	1	TBR	1
		Elastic recovery at 25°C after EN 12607-1	EN 12607-1 EN 13398	%	≥ 50	4	≥ 50	4	≥ 50	4
		Elastic recovery at 10°C after EN 12607-1	EN 12607-1 EN 13398	%	NR	0	NR	0	NR	0
		Storage stability – difference in softening point	EN 13399 EN 1427	°C	≤ 5	2	≤ 5	2	≤ 5	2
		Storage stability – difference in penetration	EN 13399 EN 1426	0.1 mm	NR	0	NR	0	NR	0

* – change of mass may be a positive or negative value
** – depending on the end use, only one method for determining cohesion should be selected. The cohesion determination by the Vialit method (EN 13588) should only be selected for bitumen for surface treatment
NR – No Requirement
TBR – To Be Reported

Table 1.7. c.d.

Division based on types and requirements for polymer modified bitumen in Poland acc. to National Annex to standard PN-EN 14023:2011/Ap2:2020-02

PROPERTY			TEST METHOD	UNIT	POLYMER MODIFIED BITUMEN TYPE					
					PMB 10/40-65		PMB 25/55-60		PMB 45/80-55	
					RANGE	CLASS	RANGE	CLASS	RANGE	CLASS
Basic properties	Penetration at 25°C		EN 1426	0.1 mm	45-80	4	65-105	6	90-150	8
Basic properties	Softening point		EN 1427	°C	≥ 65	5	≥ 60	6	≥ 45	9
Basic properties	Cohesion**	Force ductility tested using ductilometer (50 mm/min)	EN 13589 EN 13703	J/cm²	≥ 2 at 10°C	6	≥ 3 at 5°C	2	NR	0
Basic properties	Cohesion**	Tensile test at 5°C (100 mm/min)	EN 13587	J/cm²	NR	0	NR	0	NR	0
Basic properties	Cohesion**	Vialit pendulum test (impact method)	EN 13588	J/cm²	NR	0	NR	0	≥ 0.7	2
Basic properties	Change of mass after hardening*		EN 12607-1	% m/m	≤ 0.5	3	≤ 0.5	3	≤ 0.5	3
Basic properties	Retained penetration at 25°C after hardening		EN 12607-1 EN 1426	%	≥ 60	7	≥ 60	7	≥ 50	5
Basic properties	Softening point increase after hardening		EN 12607-1 EN 1427	°C	≤ 8	2	≤ 10	3	≤ 10	3
Basic properties	Flash point		EN ISO 2592	°C	≥ 235	3	≥ 235	3	≥ 235	3
Additional properties	Fraass breaking point		EN 12593	°C	≤ -15	7	≤ -15	7	≤ -18	8
Additional properties	Elastic recovery at 25°C		EN 13398	%	≥ 80	2	≥ 70	3	≥ 50	5
Additional properties	Elastic recovery at 10°C		EN 13398	%	NR	0	NR	0	NR	0
Additional properties	Plasticity range		EN 14023	°C	NR	0	NR	0	NR	0
Additional properties	Drop in softening point after EN 12607-1		EN 12607-1 EN 1427	°C	TBR	1	TBR	1	TBR	1
Additional properties	Elastic recovery at 25°C after EN 12607-1		EN 12607-1 EN 13398	%	≥ 60	3	≥ 60	3	≥ 50	4
Additional properties	Elastic recovery at 10°C after EN 12607-1		EN 12607-1 EN 13398	%	NR	0	NR	0	NR	0
Additional properties	Storage stability – difference in softening point		EN 13399 EN 1427	°C	≤ 5	2	≤ 5	2	≤ 5	2
Additional properties	Storage stability – difference in penetration		EN 13399 EN 1426	0.1 mm	NR	0	NR	0	NR	0

* – change of mass may be a positive or negative value

** – depending on the end use, only one method for determining cohesion should be selected. The cohesion determination by the Vialit method (EN 13588) should only be selected for bitumen for surface treatment

NR – No Requirement

TBR – To Be Reported

1.2.3.3. Highly modified bitumen

The division into types, classes and requirements for highly modified bitumen in Poland is provided in the National Annex (NA), table NA.2, to PN-EN 14023:2011 issued in February 2020 by the Polish Committee for Standardization. This data is presented in Table 1.8.

Table 1.8.
Division based on types and requirements for highly modified bitumen in Poland acc. to National Annex (NA), table NA.2, to standard PN-EN 14023:2011/Ap2:2020-02

PROPERTY		METHOD TESTS	UNIT	ORBITON 25/55-80 HIMA		ORBITON 45/80-80 HIMA		ORBITON 65/105-80 HIMA	
				REQUIREMENT	CLASS	REQUIREMENT	CLASS	REQUIREMENT	CLASS
Penetration at 25°C		EN 1426	0.1 mm	25 to 55	3	45 to 80	4	65 to 105	3
Softening point		EN 1427	°C	≥ 80	2	≥ 80	2	≥ 80	2
Cohesion	Force ductility tested using ductilometer (50 mm/min)	EN 13589 EN 13703	J/cm^2	≥ 0,5 at 15°C	8	≥ 2 at 10°C	6	≥ 1 at 5°C	4
Resistance to hardening	Change of mass	EN 12607-1	%	≤ 0,5	3	≤ 0,5	3	≤ 0,5	3
	Retained penetration		%	≥ 60	7	≥ 60	7	≥ 60	7
	Increase in softening point		°C	≤ 8	2	≤ 8	2	≤ 8	2
Flash point		EN ISO 2592	°C	≥ 235	3	≥ 235	3	≥ 235	3
Fraass breaking point		EN 12593	°C	≤ -15	7	≤ -18	8	≤ -18	8
Elastic recovery at 25°C		EN 13398	%	≥ 80	2	≥ 80	2	≥ 80	2
Plasticity range		EN 14023 Subsection 5.2.8.4	°C	NR	0	NR	0	NR	0
Drop in softening point after EN 12607-1		EN 1427	°C	TBR	1	TBR	1	TBR	1
Elastic recovery at 25°C after EN 12607-1		EN 13398	%	≥ 50	4	≥ 60	3	≥ 70	2
Storage stability Difference in softening point		EN 13399 EN 1427	°C	≤ 5	2	≤ 5	2	≤ 5	2
Storage stability Difference in penetration		EN 13399 EN 1426	0.1 mm	NR	0	NR	0	NR	0

* change of mass may be a positive or negative value
NR – No Requirement
TBR – To Be Reported

1.3. BITUMEN CHARACTERISTICS

1.3.1. PAVING GRADE BITUMEN

Paving grade bitumens are the most popular binders for hot asphalt mixtures (HMA) used for road pavement construction.

Paving grade bitumens supplied by ORLEN Asfalt are manufactured mostly using the vacuum residue continuous oxidation system employing the BITUROX® technology.

All paving grade bitumens offered by ORLEN Asfalt are classified as paving grade bitumens with the penetration range of 20 ÷ 220 [0.1 mm], tested at 25°C.

1.3.2. POLYMER MODIFIED BITUMEN

Polymer modified bitumens represent a group of binders for road construction applications designed specifically to improve the durability of asphalt pavements and to counteract the most frequent road problems, such as rutting of pavements carrying heavy traffic load, low-temperature cracking of wearing courses during winter and fatigue-related cracks.

Bitumen properties can be improved by introducing various additives. ORLEN Asfalt offers bitumen modified with SBS elastomer (Styrene-Butadiene-Styrene) which extends the temperature range in which the binder retains its viscoelastic properties. This binder type production is based on a physical method involving mechanical mixing of the bitumen with the polymer, with the possible use of various additives. The primary feedstock for polymer modified bitumen production comprises special bitumens (base bitumens) of properties adequate for modification. Polymer modified bitumen production involves the introduction of the polymer into hot bitumen, mixture grinding in a high-shear mill and its final dissolution and homogenisation. SBS elastomer (see Figure 1.2. for its various structures) application in the production process helps achieve substantial benefits in terms of bitumen properties in high and low temperatures. Asphalt pavements with using PMB are more durable than paving grade bitumen.

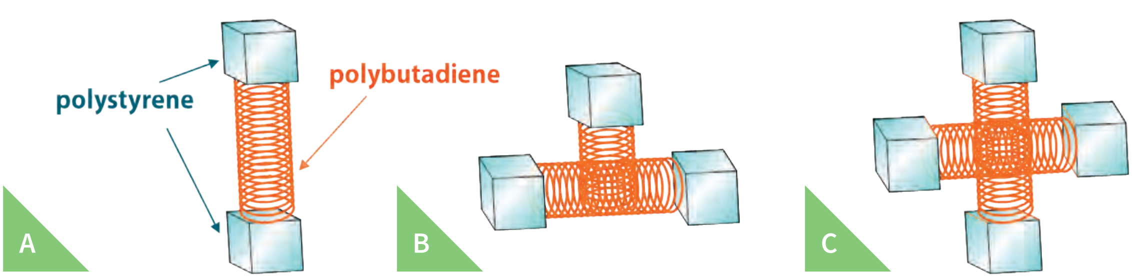


Fig. 1.2. *Various structures of SBS block copolymer: (A) SBS with linear structure; (B) SBS with branched structure; (C) SBS with star-shaped (radial) structure*

1.3.3. HIGHLY MODIFIED BITUMEN

The primary purpose behind the HiMA binder is to counteract pavement failure and rut formation and to increase the fatigue life of bitumen courses. Application of substantially higher quantities of the special SBS elastomer in the bitumen production process helps to achieve above-standard properties of the bituminous binder at high and low temperatures. In structural terms, HiMA courses retain very high tolerance to increased tensile strain (i.e. fatigue). Research and implementation work related to highly modified bitumen has demonstrated that they have above-standard functional properties. They are characterise by a very good resistance to rutting and excellent fatigue strength and failure resistance.

Ring and Ball (R&B) softening point of HiMA binders is above 80°C, regardless of hardness. This means that whether ORBITON HiMA with the penetration value of 50 or 100 is used, the properties at a high temperature will be similar. This is due to the reversed polymer phase and the dominant influence of the polymer on the properties of this type of bitumen.

1.3.4. BITUMEN COMPARISON

Figure 1.3. presents the Pen25-R&B (Penetration at 25°C vs Softening Point Ring&Ball) chart comparing all bituminous binder types. There is a noticeable difference in the relationship between Pen25 (hardness) and the softening point, which for paving grade bitumens (without modifiers) is straightforward (the lower the penetration value is, then the higher the softening point is); for modified bitumens, this relationship is disrupted by the influence of the SBS polymer network, and in the case of highly modified bitumens (HiMA), it is no longer relevant due to polymer-bitumen phase reversal.

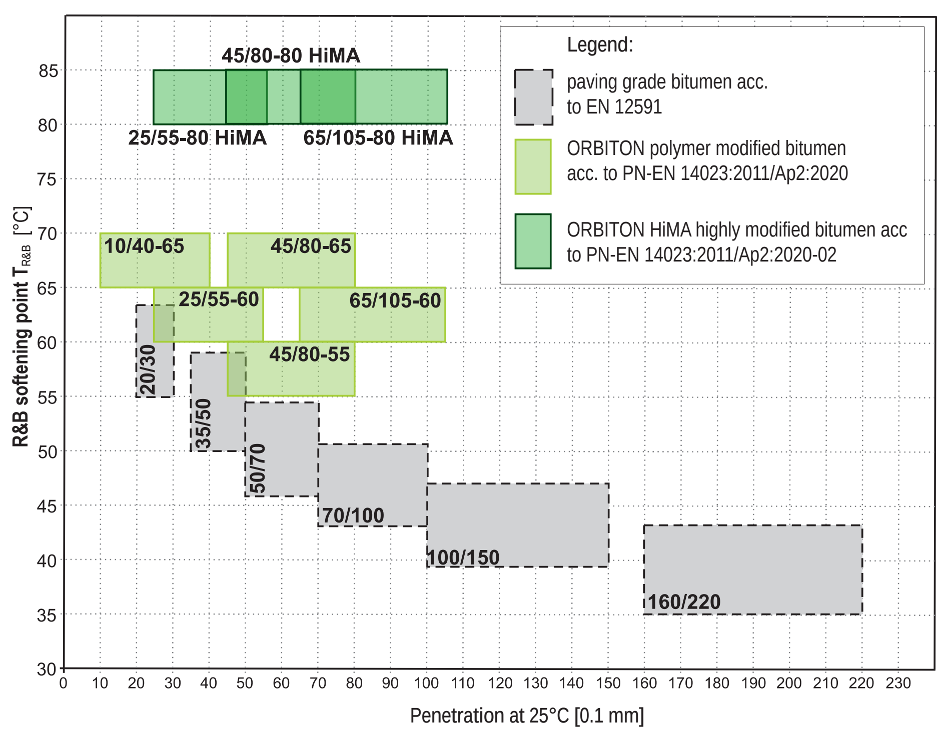


Fig. 1.3. *Location of paving grade, polymer modified and highly modified bitumens on the Pen25-R&B chart*

1.4. BITUMEN APPLICATIONS

1.4.1. PAVING GRADE BITUMEN

The typical applications of individual types of paving grade bitumen are presented below

Paving grade bitumen 20/30 is the hardest paving grade bitumen offered by the ORLEN Group. Its high softening point and high sensitivity to low-temperature failure makes it suitable solely for application in binder and base courses of high-stiffness modulus asphalt concrete (AC EME[5]) in Polish regions with suitable climate. Courses containing bitumen 20/30 should not be left over the winter period without being covered with the next course. Additionally, for national roads in Poland, WT-2, part I of 2014 [8] specifies special requirements and climate zones where specific types of binders (paving grade 20/30 or polymer modified) are used in AC EME.

Paving grade bitumen 35/50 can be used to produce asphalt concrete mixes (AC) for base and binder courses, or for wearing courses as mastic asphalt (MA) used for roads designed to carry light traffic load. The 35/50 bitumen should not be used in wearing courses from mixes other than MA. Paving grade bitumen 35/50 WMA – see chapter 3.

Paving grade bitumen 50/70

Paving grade bitumen 50/70 can be used primarily for wearing course mixes, provided that they comply with the requirements concerning resistance to rutting. The use of 50/70 bitumen for the production of base and binder courses also requires verification of the mix resistance to rutting. Using 50/70 bitumen for production of any pavement course designed to carry slow traffic load (slow lanes, approaches to crossroads, etc.) is not recommended. Paving grade bitumen 50/70 WMA – see chapter 3.

Paving grade bitumen 70/100 can be used, to a limited extent, for asphalt concrete mixes and SMA mixes in wearing courses on roads designed for light traffic, on the assumption that the mix resistance to rutting is confirmed. It can also be used to manufacture bitumen emulsions.

Paving grade bitumens 70/100, 100/150 and 160/220 comprise a group of binders designed for the production of bitumen emulsions for various applications.

5) AC EME is the designation for high-stiffness modulus Asphalt Concrete (EME Enrobé à Module Elevé in France). Other designations of this mixture are WMS (in Poland) or HMB (High Modulus Base in the USA and UK).

Table 1.9. summarises the recommendations for the use of paving grade bitumen for road construction in Poland.

Table 1.9.
Recommended application of paving grade bitumens from ORLEN Asfalt depending on the road surface course and traffic load

COURSE	TRAFFIC LOAD*		
	KR 1-2	KR 3-4	KR 5-7
Base	–****	20/30**, 35/50, 35/50 WMA, 50/70, 50/70 WMA	20/30**, 35/50, 35/50 WMA
Binder	50/70, 50/70 WMA	20/30**, 35/50, 35/50 WMA, 50/70, 50/70 WMA	20/30**, 35/50, 35/50 WMA
Wearing	35/50***, 35/50 WMA***, 50/70, 50/70 WMA, 70/100	35/50***, 35/50 WMA***, 50/70, 50/70 WMA	–

* Traffic load (Polish abbreviation – KR) are specified in million axles 100 kN, carried in service life, single tire is used as standard. KR1-2 (below 0.5), KR3-4 (0.5 – 7.3), KR5-7 (7.3 – 52+)
** for AC EME only
*** for mastic asphalt MA only
**** pavement structure for KR1 and KR2 traffic categories does not contain the base course

Due to the risk of rutting, the use of paving grade bitumens should always be preceded by testing the mix resistance to rutting, according to EN 12697-22 (method B, small-size apparatus, in the air, temperature +60°C, 10,000 cycles). The above refers especially to road sections located within crossroad zones, slow traffic zones, parking zones, etc.

1.4.2. POLYMER MODIFIED BITUMEN

ORBITON polymer modified bitumens represent a group of binders intended for use in pavements designed to carry heavy traffic load, or in special pavements (on bridges, thin wearing courses, etc.). Well-designed asphalt mixes produced using these bitumens demonstrate much better properties than their paving grade counterparts of similar hardness.

The range of applications for polymer modified bitumens is very broad, both in terms of asphalt mix types and road traffic categories. Typical applications of individual types of polymer modified bitumen are shown below.

ORBITON 10/40-65 is the hardest polymer modified bitumen currently manufactured by the ORLEN Group. Its very high softening point renders it suitable for base and binder courses of high-stiffness modulus asphalt concrete AC EME. It can also be used for conventional asphalt concrete mixes. Rutting resistance test results for asphalt mixes containing this type of bitumen demonstrate that it is suitable for pavements carrying slow and heavy traffic load, such as parking lots, slow traffic lanes and crossroads. This type of bitumen is not recommended for use in wearing courses and bridge pavement courses.

ORBITON 25/55-60 is one of the most popular polymer modified bitumen types. It is used in asphalt concrete base and binder courses mixes and for AC ME high-stiffness modulus asphalt concrete mix (at the required stiffness modulus exceeding 14,000 MPa). It can also be used in the SMA mix for wearing, binder and base courses for sections carrying slow and heavy traffic and in mastic asphalt mixtures (MA).

ORBITON 45/80-55 is one of the most popular polymer modified bitumen types. It is designed for application in all types of asphalt mixes for wearing courses: AC, SMA, PA, BBTM, AUTL.

ORBITON 45/80-65 is designed for use in wearing courses and for special applications. It is characterised by very high elasticity, high softening point and favourable characteristics in low temperatures. The high polymer content makes it difficult to incorporate in thin layers in adverse weather conditions (quick stiffening of layer, compaction problems). The high softening point and modification level render it suitable for application at locations where high tensile strength and fatigue resistance are necessary in combination with excellent low-temperature properties. ORBITON 45/80-65 has been primarily designed for application in wearing courses, as well as for porous asphalt (PA) mixes.

ORBITON 65/105-60 is designed for use in hot asphalt mixes for wearing courses, within mixes having a good mineral matrix. It is produced using soft base bitumen with a high polymer content, which results in a product with excellent low-temperature properties and elasticity. ORBITON 65/105-60 is characterised by higher penetration at 25°C in comparison to PMB 45/80-65 and at the same time demonstrates high levels of cohesion and flexibility. The combination of those features renders the product a very good binder for thin-layered mixtures of non-continuous mineral matrix. Such applications include PA, BBTM and AUTL mixes for thin wearing courses and SMA mixes. Those are primarily special wearing courses and wearing courses used in low-temperature locations. This binder can also be used in bridge deck mixtures, whenever excellent elasticity of the binder is required.

Figure 1.4 shows application examples of ORBITON polymer-modified bitumen for pavement courses.

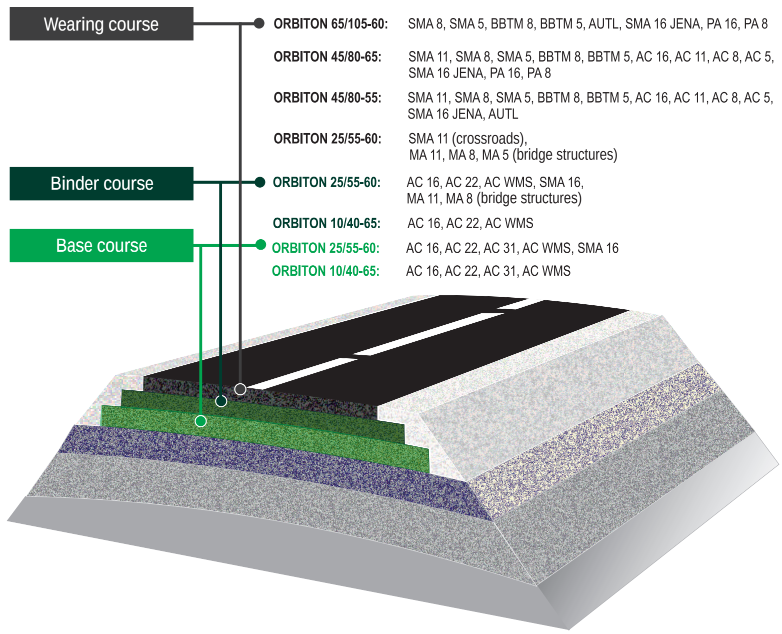


Fig. 1.4.
Proposed use of ORBITON polymer modified bitumen for conventional asphalt pavement construction [proprietary]

Additionally, based on previous experience, Tables 1.10 and 1.11 show recommendations for the use of polymer modified bitumen for the construction of road and bridge pavements in Poland.

Table 1.10.
Recommended application of polymer modified bitumen supplied by ORLEN Asfalt depending on the ***road pavement course and traffic load***

COURSE	TRAFFIC LOAD**		
	KR 1-2	KR 3-4	KR 5-7
Base	—	ORBITON 10/40-65 ORBITON 25/55-60	ORBITON 10/40-65 ORBITON 25/55-60
Binder	ORBITON 45/80-55	ORBITON 10/40-65 ORBITON 25/55-60	ORBITON 10/40-65 ORBITON 25/55-60
Wearing	ORBITON 45/80-55 ORBITON 45/80-65 ORBITON 65/105-60	ORBITON 25/55-60* ORBITON 45/80-55 ORBITON 45/80-65 ORBITON 65/105-60	ORBITON 45/80-55 ORBITON 45/80-65 ORBITON 65/105-60

* in high-load locations (crossroads, slow lanes)
** Description in table 1.9.

Table 1.11.
Recommended application of polymer modified bitumen supplied by ORLEN Asfalt depending on the ***bridge pavement course***

COURSE	BINDERS
Binder	ORBITON 25/55-60
Wearing	ORBITON 25/55-60* ORBITON 45/80-55 ORBITON 45/80-65 ORBITON 65/105-60

* for MA mastic asphalt

1.4.3. HIGHLY MODIFIED BITUMEN

ORBITON HiMA binders are particularly suitable for applications requiring very high durability, such as:
- asphalt pavements subjected to very high stress and strain;
- asphalt base courses with very high fatigue performance;
- asphalt courses with high resistance to low temperature.

Highly modified bitumens are also particularly suitable for long-service-life pavements, such as perpetual pavements. Application of ORBITON HiMA in the special anti-fatigue (AF) layer allows the achievement of a very long pavement service life.

Recommended applications of individual types of highly modified bitumen are shown below.

ORBITON 25/55-80 HiMA ("hard HiMA") is designed for special courses requiring exceptional deformation resistance (parking lots for heavy vehicles, container terminals, etc.) and where very heavy, slow traffic load takes place. Since this binder is very hard, **it should be used only in justified cases** and suitable site conditions need to be ensured. It should be clearly stated that **ORBITON 25/55-80 HiMA is not a direct replacement for PMB 25/55-60 and is not intended for AC EME**. For typical pavement structures, ORBITON 45/80-80 HiMA is recommended instead of ORBITON 25/55-80 HiMA.

ORBITON 25/55-80 HiMA WMA – see chapter 3. Used as ORBITON 25/55-80 HiMA.

ORBITON 45/80-80 HiMA ("medium HiMA") is suitable for all bitumen courses of asphalt pavements: bitumen base, including perpetual pavements, binder courses and wearing courses subject to very high loads. This universal binder combines elasticity with a very good rutting resistance.

ORBITON 45/80-80 HiMA WMA – see chapter 3. Used as ORBITON 45/80-80 HiMA.

ORBITON 65/105-80 HiMA ("soft HiMA") is mainly suitable for wearing courses and special technologies, e.g. SAMI courses ("hot spray" application). Due to its top fatigue properties, it can be a component of anti-fatigue (AF) layers in the perpetual pavements. Another application of this binder is the production of bitumen emulsions intended for the slurry seal or surface dressing. Wherever high water tightness and elasticity is needed, ORBITON 65/105-80 HiMA may be used for the mastic asphalt (MA).

Figures 1.5 and 1.6 can be used to select the right type of ORBITON HiMA for an asphalt pavement structure.

Fig. 1.5.
Proposed use of ORBITON HiMA binders for conventional asphalt pavement structures (note: MA mixes for special applications and engineering structures) [proprietary]

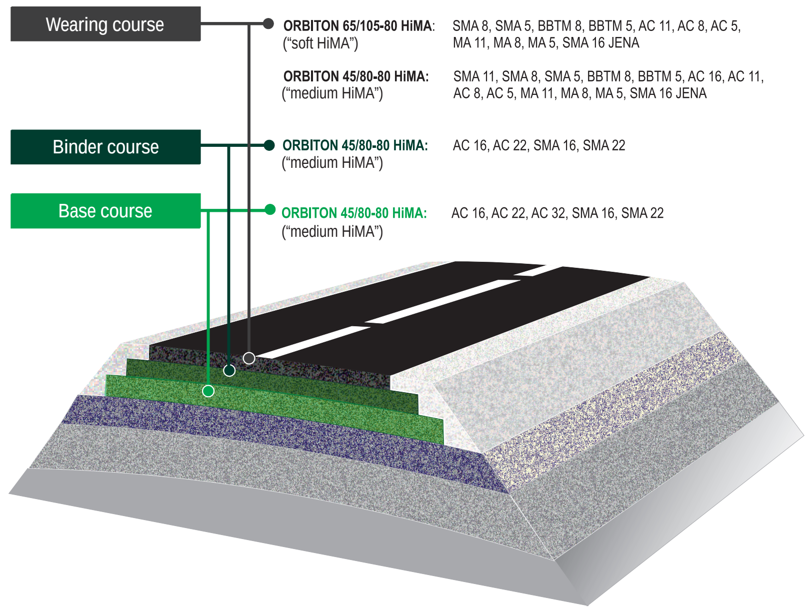
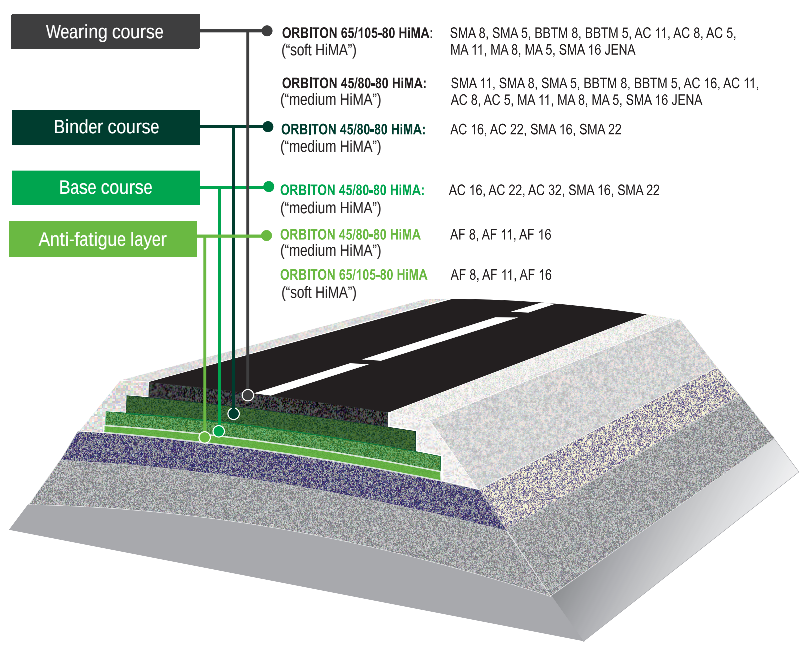


Fig. 1.6.
Proposed application of ORBITON HiMA binders for a modern perpetual-pavement structure [proprietary}



The designation of the "AF" anti-fatigue mixtures in Fig. 1.6 refers to asphalt mixes with special properties other than those typical of a base course. These may be regular mixes with modified properties (e.g. reduced content of voids) or special mixes tailored to separate specifications.

The data in Figures 1.5 and 1.6 may differ from the information given in WT-2 2014, i.e. the decision on the specific use of a given binder is up to the Investor/Designer.

Tables 1.12. and 1.13. show recommended applications of the highly modified bitumen depending on the road pavement course.

Table 1.12.
Recommended applications of ORBITON HiMA binders depending on the **road pavement course and traffic load**

COURSE	TRAFFIC LOAD**		
	KR 1-2	KR 3-4	KR 5-7
Base	—	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA	ORBITON 25/55-80 HiMA* ORBITON 25/55-80 HiMA WMA* ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA
Binder	—	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA	ORBITON 25/55-80 HiMA* ORBITON 25/55-80 HiMA WMA* ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA
Wearing	—	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA

* only special applications
** description in table 1.9.

Table 1.13.
Recommended applications of ORBITON HiMA binders depending on the **bridge pavement course**

COURSE	BINDERS
Binder	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA
Wearing	ORBITON 45/80-80 HiMA ORBITON 45/80-80 HiMA WMA ORBITON 65/105-80 HiMA

Well-designed asphalt mixes produced using highly modified bitumens (HiMA) guarantee achieving much better properties as compared to their counterparts of similar hardness (paving grade and modified bitumens). For more details on designing asphalt mixtures and pavements with ORBITON HiMA, see the ORLEN Asfalt publication: Mieszanki i nawierzchnie z ORBITON HiMA [Asphalt mixtures and pavements with ORBITON HiMA] [9].

Order or download the publication:
Mieszanki i nawierzchnie z ORBITON HiMA
[Asphalt mixtures and pavements with ORBITON HiMA].

SCAN ME!

1.5. STATISTICAL ANALYSIS OF BITUMEN PARAMETERS

1.5.1. INTRODUCTION TO STATISTICS

The term ‘statistics’ is derived from the Latin word “status” meaning “state” or “condition”. The origins of statistics date back to the ancient times, when general population censuses were first conducted. Nowadays, the term statistics has a much broader meaning and is used in numerous fields [10]. The statistics we are interested in is defined as an independent scientific discipline dealing with quantitative methods of studying regularities in populations and providing reliable information about these regularities characterised by numbers [11]. The description of surrounding phenomena and objects and the evaluation of relations between them, including the assessment of quality and homogeneity of individual batches of bituminous binders, is possible with the use of correct tools such as statistical methods.

In statistics, three basic areas of activity can be distinguished [12]:

- informative – presents a complete and objective picture of the phenomena studied;
- analytical – allows the determination of factors that shape particular processes and phenomena;
- prognostic – facilitates prediction of the development direction for the events studied.

Statistics as a scientific discipline can be divided into two main fields [7, 13, 14]:

- descriptive statistics, or statistical description, dealing with methods of collecting, processing and presenting data with its summary description;
- mathematical statistics, or statistical inference, which covers methods of investigating dependencies and regularities in an analysed set of data.

Statistical study is a set of activities performed on a specific statistical population in order to determine the properties that characterise the studied set [12].

Statistical population is a set of any elements, e.g. people, objects, events, etc. characterised by at least one common feature with different values. This population must be uniquely defined in terms of the object, space and time [7, 13].

Statistical unit is the smallest element of a statistical population that is included in a statistical study [13].

Statistical characteristic (variable) is a property of the statistical units constituting a defined statistical population [12].

For example, in statistical testing of bituminous binder performance:

- statistical population = all production batches of paving grade bitumen 35/50 in 2022;
- statistical unit = a single production batch of paving grade bitumen 35/50, e.g. manufactured on 25/09/2022;
- statistical characteristic = penetration of the paving grade bitumen 35/50.

Statistics is an excellent tool for seeking answers to questions concerning the world around us. However, this tool should be used reasonably and skilfully [15], otherwise it may lead to erroneous or different interpretations of the results obtained.

1.5.1.1. Statistical parameters, definitions

Statistical parameters can be defined as numerical quantities that make it possible to describe the structure of the statistical population under study in a systematic manner.

Statistical parameters can be divided into several general categories [7, 13]:

- measures of position – also known as average measures describing the statistical population without taking into account the differences between individual units of this population. These measures characterise the similarity of the population taking into account the analysed variable. Position measures are divided into classical (e.g. arithmetic mean) and positional (e.g. modes, quartiles) measures;
- measures of variability – also known as dispersion measures, describe a statistical population taking into account differences between particular units belonging to the population. Measures of variability characterise the degree of variation in the population taking into account the variable trait under analysis. Measures of variability can be divided into classical (variance, standard deviation, typical range, classic coefficient of variation) and positional (e.g. range, quartile deviation) measures;
- measures of asymmetry – measures of skewness specifying the distribution direction of the variables in the population and to what extent the distribution of a given characteristic deviates from the symmetric distribution;
- measures of concentration – describe the concentration degree of particular observations around the mean value (kurtosis) or the degree of the distribution unevenness of a phenomenon in a population.

The most common statistical measures used to describe the bituminous binders produced by ORLEN Group are:

Arithmetic mean, x_{mn} – a conventional measure of location, the sum of the values of a variable characteristic divided by the number of units of a finite statistical population:

$$x_{mn} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

where:

x_i – value of the variable trait/value of a single determination result

n – size of the population/number of obtained results

The main disadvantage of the arithmetic mean is its sensitivity to extreme values of a characteristic.

Lower quartile (first quartile), Q_1 – positional measure of position; the value of a variable dividing the tested population in such a way that 25% of it elements ordered in a non-decreasing sequence are below this value. Graphical representation of the value is shown in Fig. 1.7a.

Median (second quartile), *Me* or Q_2 – a positional measure of position; the value of a variable dividing the studied population in half, in such a way that below and above its value there are respectively half of the units of the population (Fig. 1.7b.).

For an n-odd non-decreasing sequence of observed values, the median is the middle value in the series. For an n-even non-decreasing sequence, the median is the arithmetic mean of the two middle values. It can be determined graphically or by calculation.

Upper quartile (third quartile), Q_3 – a positional measure of position; it is the value of observation dividing the examined population in such a way that 75% of the units of the population ordered in a non-decreasing sequence are below this value. Graphical representation of the value is shown in Fig. 1.7c.

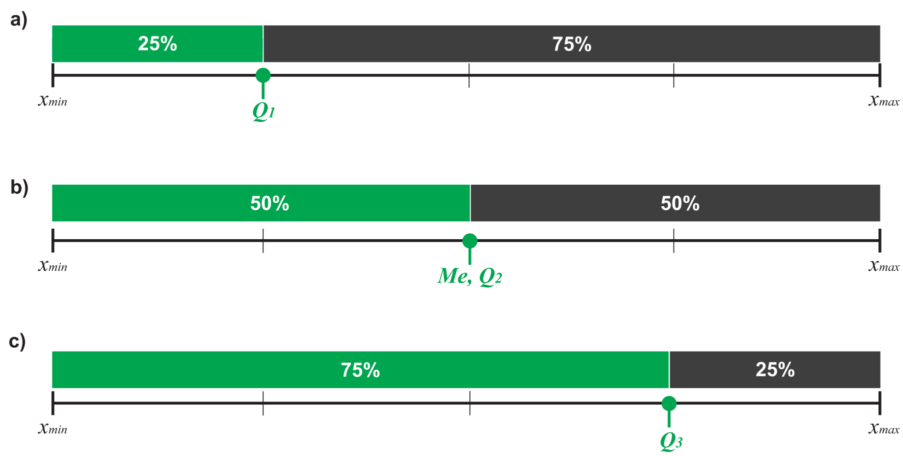


Fig. 1.7. *Graphical representation of the median and other quartiles*

Standard deviation, σ – defined as a conventional measure of variation indicating the extent to which the values are dispersed around the mean value. If all the results were the same, the standard deviation would be zero. In other cases, this number is a positive value. Hence, the greater the value of the standard deviation, the greater the dispersion of the results around the mean [15]. The standard deviation is calculated according to the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{mn})^2}{n}}$$

in which:

x_i – value of the variable trait/value of a single determination result

x_{mn} – arithmetic mean of the variable/arithmetic mean of the obtained results

n – size of the population/number of obtained results

The standard deviation for normal distribution is connected with the three-sigma rule of thumb, which states that practically the whole statistical community is contained in the interval $x_{mn} \pm 3\sigma$. At the same time "practically the whole" means 99.73%, thus 3 out of 1000 results of determinations may be outside the interval [16].

The typical range x_{typ} is the area containing units of a statistical population that differ from the mean by maximum one standard deviation.

$$x_{mn} - \sigma < x_{typ} < x_{mn} + \sigma$$

This interval contains about 68% of the units of the tested population.

Range, R – positional measure of variation, which is the difference between the highest and the lowest value of a variable:

$$R = x_{max} - x_{min}$$

where:

x_{max} – maximum value of the variable

x_{min} – minimum value of the variable

Quartile range, IQR – a measure of variation, which is the difference between the third and the first quartile. It defines the range containing 50% of the units of the tested population:

$$IQR=Q_3-Q_1$$

1.5.1.2. Statistical data presentation methods

There are various forms of presenting a statistical material. Tables are the basic way of publishing data, but it also can be done using descriptive characteristics, analytical formulas or a graphical form. Graphical presentation of data helps to analyse and observe regularities that cannot be seen only on the basis of calculated statistical parameters.

One of the most popular forms of presenting data is a **histogram** (Fig. 1.8.) – a graph of the distribution (frequency of occurrence) of a studied characteristic in the form of a bar chart. The width of each bar corresponds to a certain range of the examined characteristic, i.e a class interval. The height of the bars on the histogram, on the other hand, can represent:

frequency of determination results – the ratio of the number of results obtained with the same value to the total size of the statistical population under study. For example: during the production season "penetration at 25°C" of bitumen 50/70 was determined 100 times (for 100 production batches), the result of 60 [0.1 mm] was obtained 43 times, therefore the frequency of results in class 60 is 43/100 = 0.43. The frequency can also be expressed as a percentage, in which case it means the percentage share of the particular result in the tested statistical population (in this example, it is 43%);

size of determination results – the number of results obtained with the same value or in the same class.

Another way of presenting the results is a box plot (Fig. 1.8.) commonly referred to as a **box and whisker plot** [17]. It contains information on the location, dispersion and shape of the distribution of the analysed data. A box plot can describe various statistical parameters. In the most common case, the length of the box is equal to the interquartile range (IQR or the difference Q3 – Q1, i.e. the range between 25% and 75% of the sequence of results). The minimum and maximum values are determined by characteristic lines called whiskers. Inside the box, a vertical line marks the median value. If the median is in the middle of the box, it can be concluded that the distribution of a given characteristic is **symmetric** (the case presented in Fig. 1.8.).

In a situation where the median divides the box into two unequal parts and the whiskers are of different lengths, an **asymmetric distribution** can occur, which means that the results of a given variable are not arranged symmetrically around the mean. Depending on the length of the whiskers – longer on the right or left – we encounter a right-side or a left-side asymmetry respectively.

The histogram together with a box plot for the exemplary parameter under study is presented in Fig. 1.8, while the graphical interpretation of the histogram bars is presented in Fig. 1.9. To avoid misunderstandings that may arise during the interpretation of class intervals on histograms, the following interpretation of Fig. 1.9. should be adopted: the given class interval 60, 65> denotes a right-closed interval, i.e. it includes numbers 61, 62, 63, 64, 65.

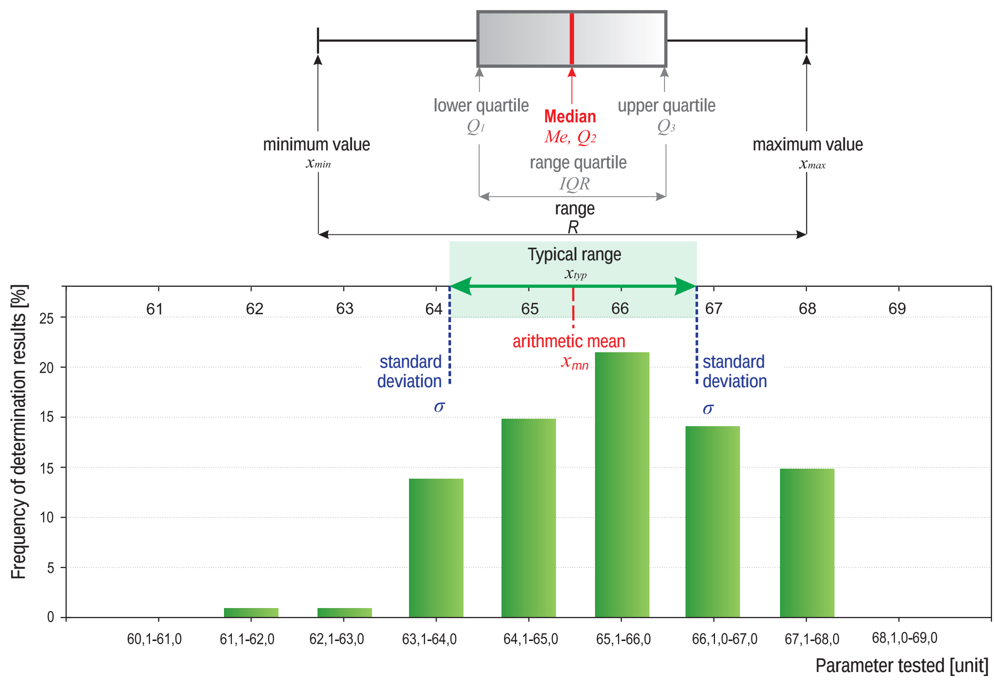


Fig. 1.8. *Histogram and box-and-whisker plot for the exemplary tested parameter*

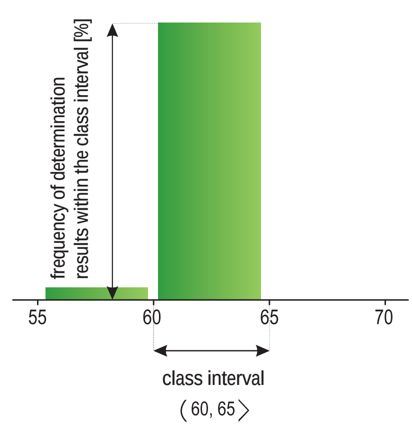


Fig. 1.9. *Graphical interpretation of histogram bars*

1.5.1.3. Interpretation of test (acceptance) results

Occasionally, there is a dispute between a customer and a bituminous binder supplier over the quality of the delivered product. Take for example the requirement for penetration at 25°C for 35/50 paving grade bitumen. When the result of Pen25 = 34 [0.1 mm] is received from the laboratory, does it really mean that the delivered product does not conform to the specification?

The result of testing any parameter, such as the aforementioned penetration at 25°C of the 35/50 paving grade bitumen obtained in a given laboratory will always differ from the actual value of that feature.

The actual value of a given parameter is an abstract notion and, obviously, it is not known to the person performing the test (if it were known, then the measurement would be unnecessary) [18].

The limited accuracy of the measurement equipment, the influence of variable external conditions on the tested sample and the measurement system, as well as insufficient knowledge of all the circumstances influencing the given test, cause that the obtained result will differ from the real (i.e. true) value of the measured parameter by a certain amount.

Therefore, a measurement of a given property allows only for estimation of its approximate value. The result of a measurement obtained in the laboratory should never be expected strictly equal to the real value of the tested characteristic. It should only be assumed that it is within a certain range oscillating around the true value of the tested parameter.

1.5.1.4. Definitions related to correct interpretation of test results

Two concepts are inherent in any laboratory test: measurement error and uncertainty of measurement.

Measurement error is the discrepancy between the result obtained and the true value of the feature under test, which is usually unknown. It should be understood as an inherent part of the measurement process and not as an error resulting from a mistake alone. Measurement error is directly related to the given measurement method. In laboratory work, the following types of measurement errors are distinguished [19, 20]:

- systematic errors – errors remain constant when performing a series of measurements of a given characteristic under the same conditions (the same apparatus, the same operator etc.). They result from imperfections in the measurement instruments and methods. An example of a systematic error is e.g. the error of indication of a measuring instrument, provided on the calibration certificate.
- random errors – errors that vary in an unpredictable and random way when making a large number of measurements of the same property under practically unchanging conditions. The main causes of random error occurrence include:
  - imperfect senses of the operator and lack of sufficient concentration during a test;
  - scattered readings of measuring instruments;
  - short-term changes in various external factors (e.g. increase in room temperature, change in mains voltage, etc.).

  Reduction of the impact of random errors is achieved by repeated measurements of the same characteristic and taking the arithmetic mean as the final result.
- excessive errors – errors called mistakes or coarse errors; they result from incorrectly performed measurements and cause open distortion of the measurement result.

If several different measurement errors are superimposed on the result of a given test, the obtained result will be completely different from the true one.

Uncertainty of measurement is a parameter closely related to the obtained result. It characterises the dispersion of values that can be attributed to a given measured value [21]. When reporting the result of a test for a given parameter, quantitative information ("uncertainty" is always a number) about the accuracy of the test should also be given, i.e. the previously calculated uncertainty of measurement [21, 22][6].

The uncertainty of measurement of a given parameter is determined by many factors, e.g. measuring instrument accuracy, external factors, such as temperature, pressure, humidity, shocks, vibrations, as well as various kinds of random errors, errors of the method or errors resulting from the evaluation of the result.

Graphically, uncertainty of measurement can be represented as follows:

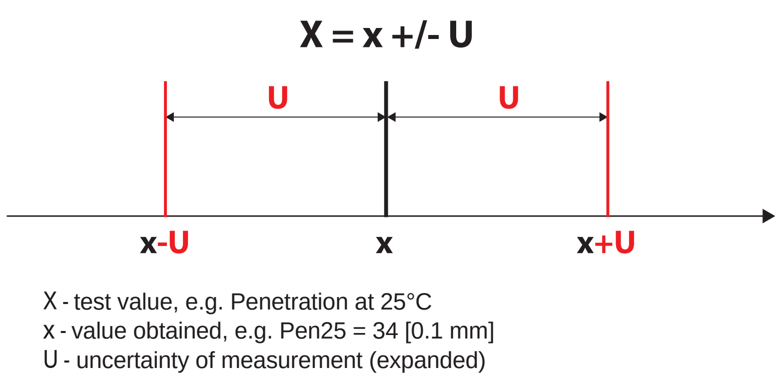


Fig. 1.10. *Graphical interpretation of uncertainty of measurement [20]*

Thus, it can be stated that the uncertainty of measurement is the interval within which the true value of the tested parameter (variable) falls within a given probability (confidence interval).

For the example discussed earlier, the result of the penetration test together with the estimated measurement uncertainty should therefore be written as follows:

$$Pen25 = 34 \pm U \text{ [0.1mm], for the confidence interval } p = \ldots$$

where:

U – the determined uncertainty of measurement for the laboratory

p – the adopted confidence interval

A **confidence interval** is used to indicate the reliability of finding a particular result within a certain specified framework. It is always defined by an adopted confidence interval, usually expressed as a percentage; for example a "95% confidence interval". The extreme points of this interval are called confidence limits.

Formally, a 95% confidence interval means that when repeating a given study under unchanging conditions, the interval will contain the true values of the results 95% of the time.

6) Different ways of calculating the uncertainty of measurement are described in publications [21] and [22].

The graphical interpretation of the different confidence intervals for a normal distribution can be presented in the following manner:

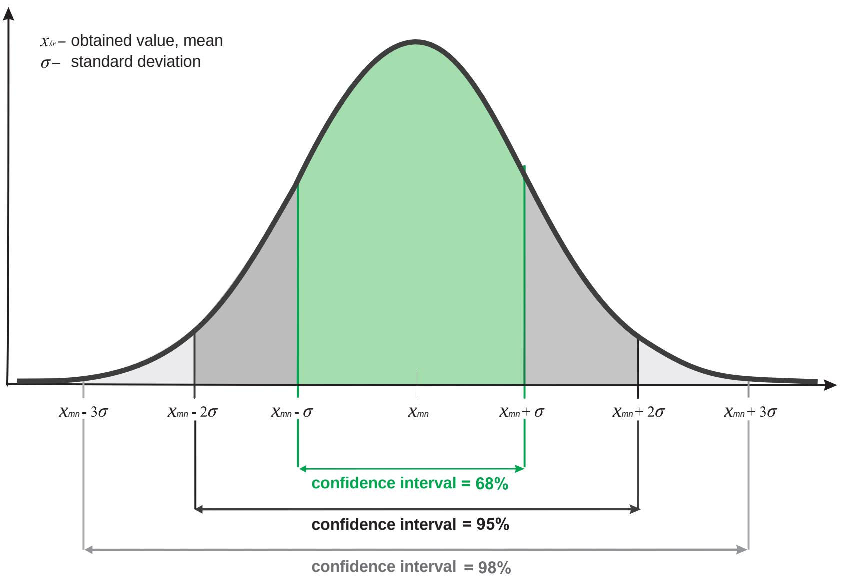


Fig. 1.11. *Graphical interpretation of different confidence intervals for a normal distribution [20]*

Two further concepts that are inextricably linked to the tests performed in the laboratory are **precision and accuracy**. Although in everyday language these two words mean more or less the same thing, in the context of scientific testing methods, they carry distinctive meanings.

A measurement system can be precise but inaccurate, accurate but imprecise, accurate and precise, or inaccurate and imprecise. An explanation of the meaning of the combination of these terms is shown in Fig. 1.12.

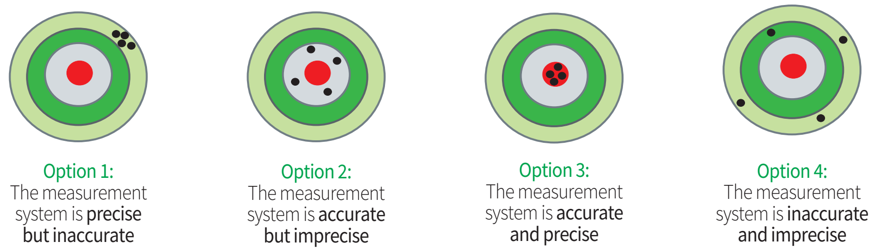


Fig.1.12. *Graphical interpretation of test precision and accuracy*

A measurement is considered valid if it is both accurate and precise – option 3 in Fig. 1.12.

Test accuracy is characterised indirectly by the opposite property: error or uncertainty of measurement. It defines the degree of approximation of the measurement result to the true value of the measured characteristic.

Test precision, on the other hand, is the degree of agreement between individual results of a given analysis (in other words – the scatter of results), when a given test procedure is applied to repeated independent determinations of a given sample.

The most common measure of test precision is standard deviation, relative standard deviation or coefficient of variation.

Two further concepts are also inseparably connected with precision (scatter of results) of a given test: repeatability and reproducibility.

Repeatability (r) – precision of results obtained under the same measurement conditions (same laboratory, analyst, measuring instrument, reagents, etc.).

Reproducibility (R) – precision of results obtained in different laboratories using a given analytical procedure.

Repeatability and reproducibility are parameters specific to a given measurement method and they are usually given in the relevant functional standards. The repeatability and reproducibility values for the parameter of penetration of paving grade bitumen, specified in the functional standard of bitumen penetration, i.e. EN 1426, are shown in Table 1.14.

Table 1.14.
Repeatability and reproducibility values for the penetration parameter of paving grade bitumen

MEASUREMENT CONDITIONS	PENETRATION IN 0.1 mm	REPEATABILITY, r	REPRODUCIBILITY, R
Temperature: 25°C Needle weight: 100 g Load time: 5 s	< 50 ≥ 50	2 4% of mean value	3 6% of mean value

1.5.1.5. Test result interpretation as per ISO 4259

ISO 4259 *Petroleum and related products. Precision of measurement methods and results (5 parts)* discusses issues related to correct interpretation of bituminous binder test results.

This standard is referenced in every standard containing requirements for bituminous binders and is binding for both the manufacturer and the customer.

Limits of the characteristic

As previously written, the actual value of the tested parameter can never be determined accurately in a laboratory. The parameter is measured in the laboratory using a standardised test method, the results of which may show a certain scatter defined by its repeatability and/or reproducibility.

When evaluating a test result, it is important to determine the limit or limits of the true value of the tested characteristic. The limit may be unilateral (no less than/no more than) or bilateral:

- bilateral limit (upper and lower) – example: penetration at 25°C from 50 to 70 [0.1 mm];
- unilateral limit (upper or lower – Fraass breaking point = not higher than -15°C or elastic recovery at 25°C = not lower than 80%. Sometimes, there is an additional implicit limit, e.g. in the case of solubility with a unilateral requirement of “not lower than 99%”, there is logically an additional limit of 100% – in such cases the unilateral limit becomes a bilateral one. The same is true for the elastic recovery, which also cannot be greater than 100%.

In ISO 4259, the upper limit is designated as A_1 and the lower limit as A_2.

Determination of limits in specifications

At this point, it is necessary to add a few words about creating specifications (requirements). The rules given in ISO 4259 clearly indicate that the limit value of the tested characteristic should take into account the reproducibility of the adopted test method, as follows:

- for a bilateral limit (A1 and A2), the specified range should not be smaller than four times the reproducibility value R:

$$(A_1 - A_2) \geq 4 \cdot R$$

- for a unilateral limit (A_1 or A_2), the specified range should not be smaller than twice the reproducibility value R:

$$A_1 \geq 2 \cdot R \quad \text{or} \quad A_2 \geq 2 \cdot R$$

If the condition $(A_1 - A_2) \geq 4 \cdot R$ is not fulfilled, then either the limits of the requirement should be widened or a test method with better precision should be sought. This means that the requirements for a characteristic in the specification must take into account the precision of the test method. Otherwise, conflicts between the supplier and the customer are inevitable.

Evaluation of the measurement result for compliance with the specification

If the only source of information about a product parameter is a single result[7], then it should be assumed that the characteristics of that product are within the requirement range with a 95% confidence level only if the test result (denoted here as Y) is as follows:

- for the unilateral upper limit A_1:

$$Y > A_1 + 0{,}59 \cdot R$$

- for the unilateral lower limit A_2:

$$Y < A_2 - 0{,}59 \cdot R$$

- for the bilateral limit – respectively one of the requirements should be met (one, since a result outside the lower or upper limit of the requirement range is usually questioned).

Returning to the example with the penetration value of 35/50 paving grade bitumen, let us consider a situation where the customer has received a control test result from their own laboratory: Pen25 = 34 [0.1mm].

Knowing the above principles of interpretation and statistical analysis of test results, let us ask a question: is the obtained result consistent or inconsistent with the specification given in EN 12591? Can the customer conclude that they received a 35/50 paving grade bitumen or should they file a quality complaint because the penetration value is too low?

Let us designate the result, Pen25 = 34 [0.1 mm], as Y. The standard limits for 35/50 bitumen are:

- lower limit: A_2=35 [0.1 mm],
- upper limit: A_1=50 [0.1 mm].

Therefore, the result Pen25 = 34 [0.1mm] is just outside the lower specification limit A_2.

7) A single result in the case of the penetration test according to EN 1426 should be understood as the arithmetic mean of at least three measurements taken under the repeatable conditions of the method.

The standard for penetration testing of bituminous binders (EN 1426) specifies the method reproducibility of R = 3 [0.1mm] for bitumen with the penetration value at 25°C of less than 50 [0.1 mm].

Let us calculate if the supplier has supplied bitumen compliant with the standard:

$$35 - 0.59 \cdot 3 < Y < 50 + 0.59 \cdot 3$$

$$\mathbf{33.2 < Y < 51.8}$$

In this case, the test result of Y = 34 [0.1 mm] is within the specification limits extended by the uncertainty of the penetration measurement. To reject the delivery, the customer would have to find that the result is less than 33.2 [0.1 mm] or greater than 51.8 [0.1 mm] (Figure 1.13).

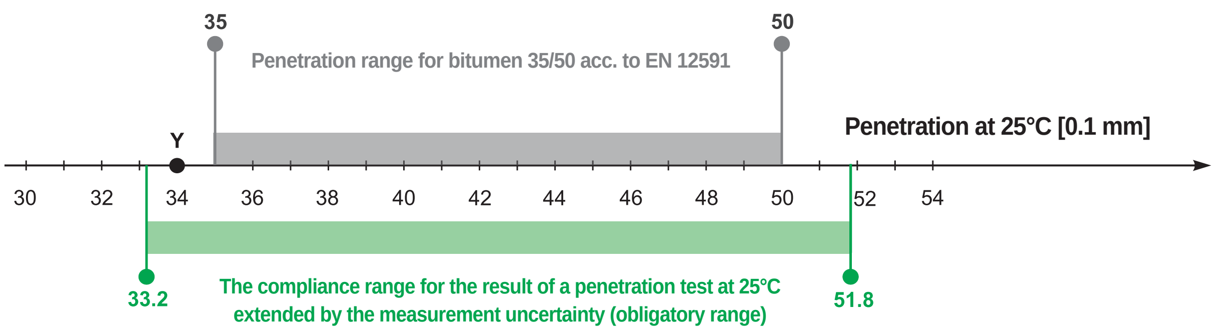


Fig. 1.13. *Illustration to the example – ranges of compliance for the penetration result extended by the value of measurement uncertainty [proprietary elaboration]*

Considering the above, it should be concluded that the supplied 35/50 paving grade bitumen with Pen = 34 [0.1 mm] is compliant with the standard, so there is no formal basis for an official quality complaint.

Contentious cases

In case a client and product supplier cannot reach an agreement regarding the supplied product quality, the procedure described in section 7 and Annex B to ISO 4259-2 (result acceptance and rejection during disputes) must be implemented.

1.5.2. RESULTS FOR BASIC BITUMINOUS BINDER PROPERTIES

This part of the chapter presents the results of the laboratory inspections of selected parameters of bituminous binders produced by the ORLEN Group (Płock and Trzebinia plants) in 2020 – 2022. The analysed data is presented by individual properties of bituminous binders.

Statistical data for all bituminous binders were included in tables and for selected characteristics (properties) of the most popular bituminous binders, the data were also presented in graphical form using histograms.

1.5.2.1. Penetration at 25°C

Penetration is a basic test for evaluating the consistency of bituminous binders, conventionally expressed as the depth to which a standardised steel needle penetrates vertically into the bitumen sample at a given temperature. The needle load is 100 g, and the load time is equal to 5 seconds. The test performance method is presented in Figure 1.14.

The penetration test is performed acc. to EN 1426. The measurement can be performed at different temperatures, but a measurement at 25°C is the basic way to classify bituminous binders according to the European standard.

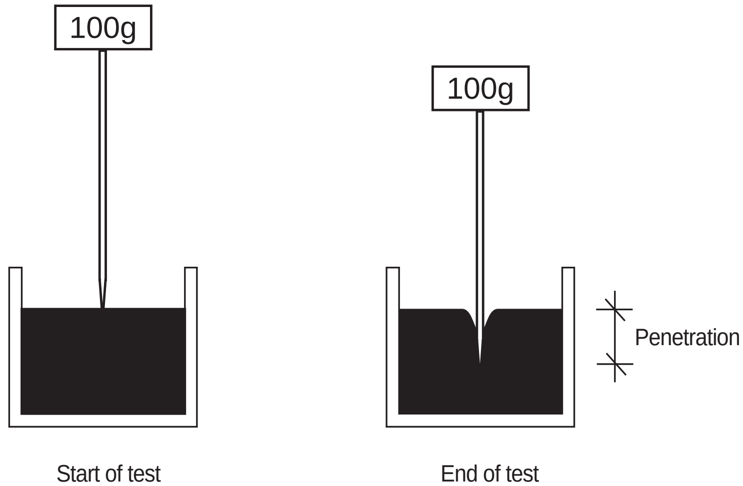


Fig. 1.14. *Penetration test performance method*

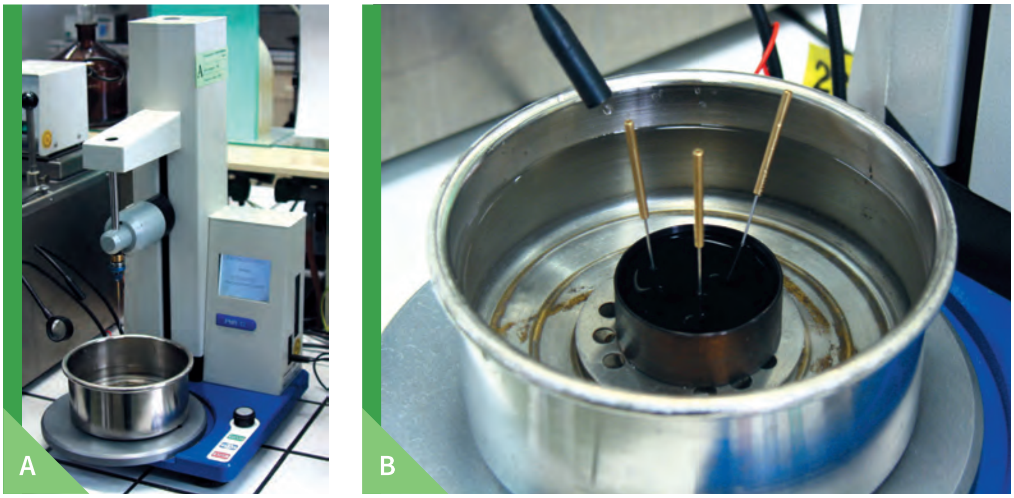


Fig. 1.15. *(A) General view of the penetration testing apparatus with a bitumen sample, (B) View of a bitumen sample after the test (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Statistical parameters of penetration determination results at 25°C for bitumens produced between 2020 and 2022 are shown in Table 1.15.

Table 1.15.
Statistical parameters of penetration determination results at 25°C for bitumens produced between 2020 and 2022

BINDER TYPE	REQUIREMENT** [0.1 mm]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
20/30	20 ÷ 30	27.7	1.4	26.3 ÷ 29.1	27	27	29	25 ÷ 30
35/50	35 ÷ 50	43.4	1.9	41.5 ÷ 45.3	43	42	45	39 ÷ 47
50/70	50 ÷ 70	61.1	3.3	57.9 ÷ 64.4	62	59	64	53 ÷ 67
70/100	70 ÷ 100	87.6	4.9	82.8 ÷ 92.5	88	84	91	77 ÷ 98
100/150	100 ÷ 150	122.6	7.9	114.7 ÷ 130.5	123	119	128	103 ÷ 135
160/220	160 ÷ 220	180.5	11.6	168.8 ÷ 192.1	178	173	187	163 ÷ 207
ORBITON 25/55-60	25 ÷ 55	36.4	3.5	32.9 ÷ 39.9	37	34	39	28 ÷ 43
ORBITON 45/80-55	45 ÷ 80	62.3	5.5	56.8 ÷ 67.7	64	59	66	48 ÷ 72
ORBITON 45/80-65	45 ÷ 80	57.1	3.5	53.6 ÷ 60.6	57	54	59	49 ÷ 64
ORBITON 25/55-80 HiMA	25 ÷ 55	48.0	4.2	43.8 ÷ 52.2	48	45	52	41 ÷ 53
ORBITON 45/80-80 HiMA	45 ÷ 80	62.6	6.3	56.3 ÷ 68.9	62	59	66	53 ÷ 80
ORBITON 65/105-80 HiMA	65 ÷ 105	80.0	**	**	80	**	**	67 ÷ 93

* for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** parameters not calculated, due to the insufficient number of results

Additionally, Figures 1.16. to 1.20. present histograms with box plots for penetration results of selected bitumens produced in the 2020-2022 period.

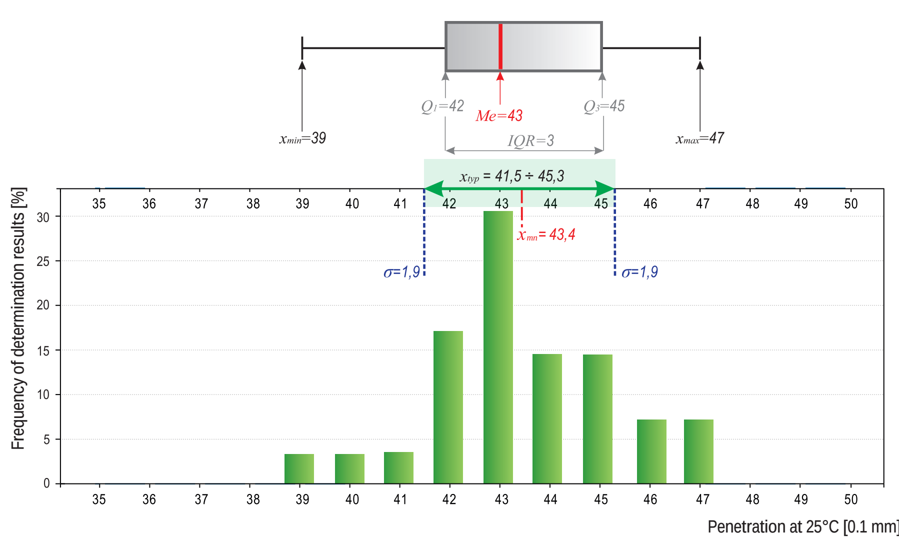


Fig. 1.16. *Histogram and box plot presenting the results of penetration determinations at 25°C of* **paving grade bitumen 35/50** *produced in the 2020-2022 period (standard range: 35-50 [0.1 mm])*

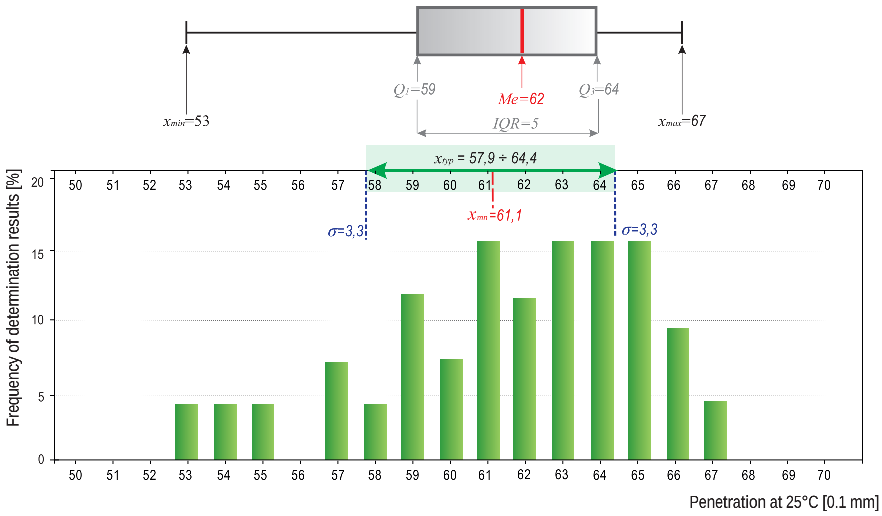


Fig. 1.17. *Histogram and box plot presenting the results of penetration determinations at 25°C of* **paving grade bitumen 50/70** *produced in the 2020-2022 period (standard range: 50-70 [0.1 mm])*

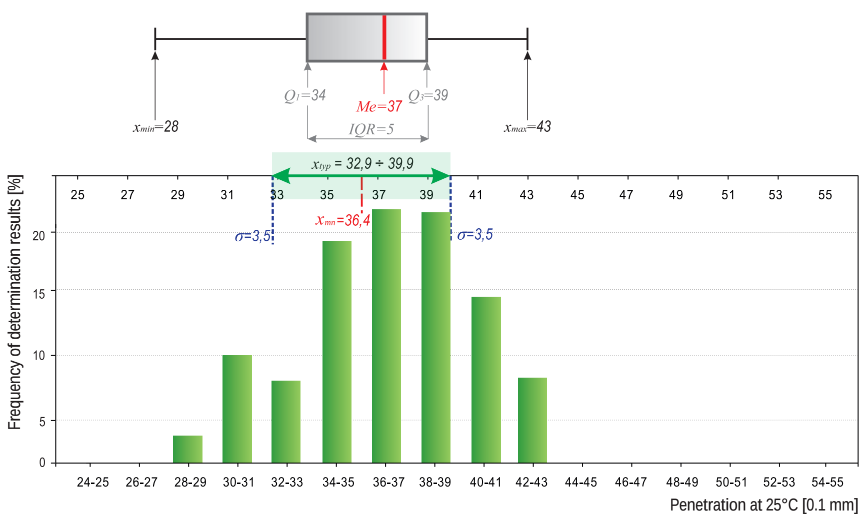


Fig. 1.18. *Histogram and box plot presenting the results of penetration determinations at 25°C of* **ORBITON 25/55-60** *binder produced in the 2020-2022 period (standard range: 25 – 55 [0.1 mm])*

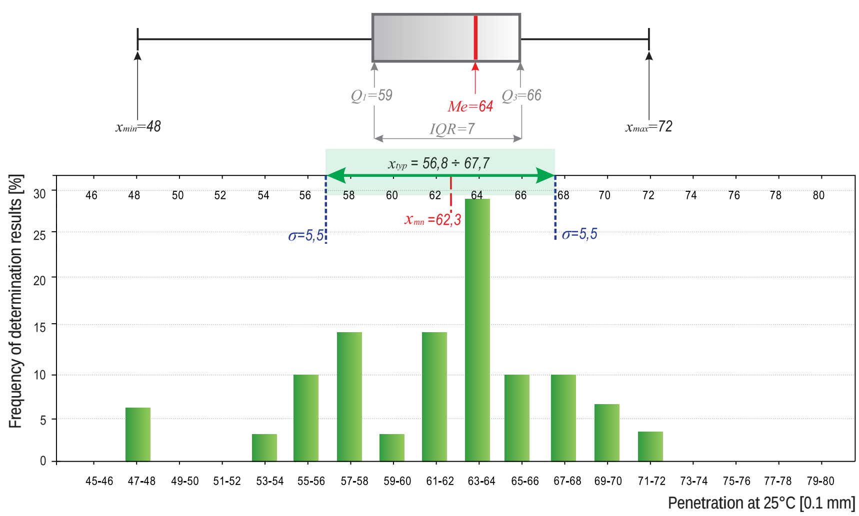


Fig. 1.19. *Histogram and box plot presenting the results of penetration determinations at 25°C of* **ORBITON 45/80-55** *binder produced in the 2020 – 2022 period (standard range: 45÷80 [0.1 mm])*

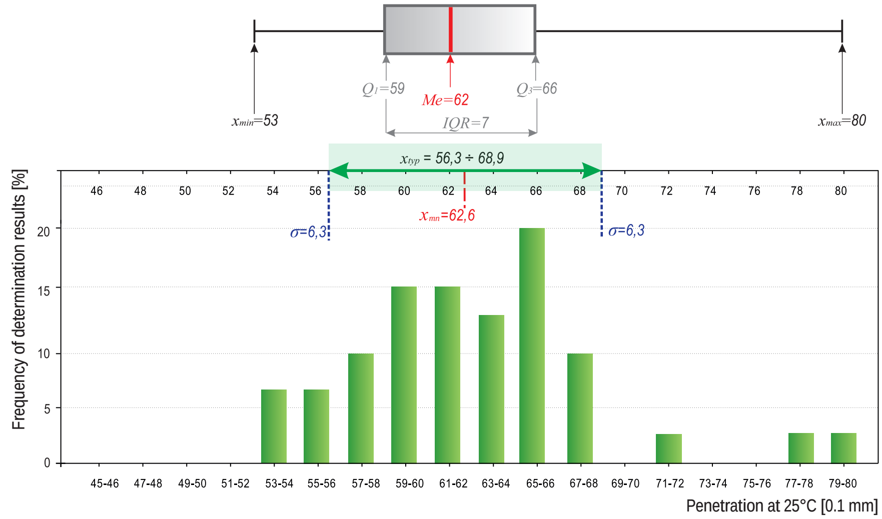


Fig. 1.20. *Histogram and box plot presenting the results of penetration determinations at 25°C of* ***ORBITON 45/80-80 HiMA*** *binder produced in the 2020 – 2022 period (standard range: 45 ÷ 80 [0.1 mm])*

1.5.2.2. Softening point

The softening point is the basic parameter determining bitumen properties at high service temperatures and represents a conventional approximate upper limit of the viscoelastic consistency.

The aim of the test is to determine the “conventional” temperature at which the bitumen reaches a given consistency. Testing the bitumen softening point is usually carried out using the “Ring and Ball” method in accordance with EN 1427.

Two bitumen samples placed in metal rings are heated in a controlled manner in a liquid (distilled water for the expected R&B from 28 to 80°C, glycerine for R&B from 80 to 150°C) in a glass beaker, and each ring filled with bitumen supports a steel ball. The assumed softening point is the average temperature at which both bitumen discs are softened to such a degree that each ball surrounded with an bitumen moves at the distance of 25.0 mm (± 0.4 mm). See Figure 1.21 which presents the principle for softening point (R&B) measurement performance.

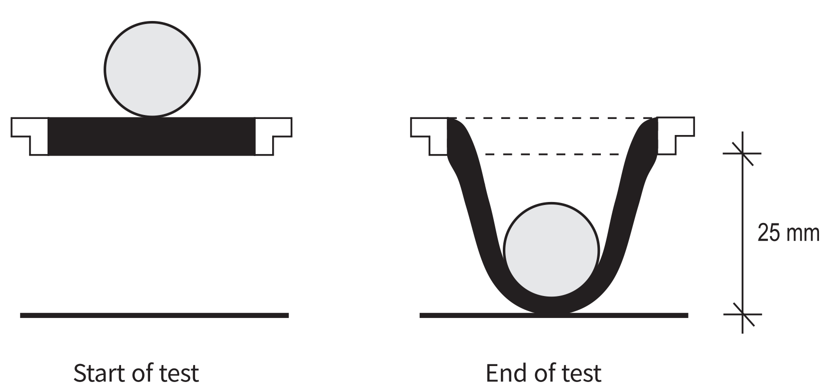


Fig. 1.21. *Principle for softening point (R&B) measurement performance*

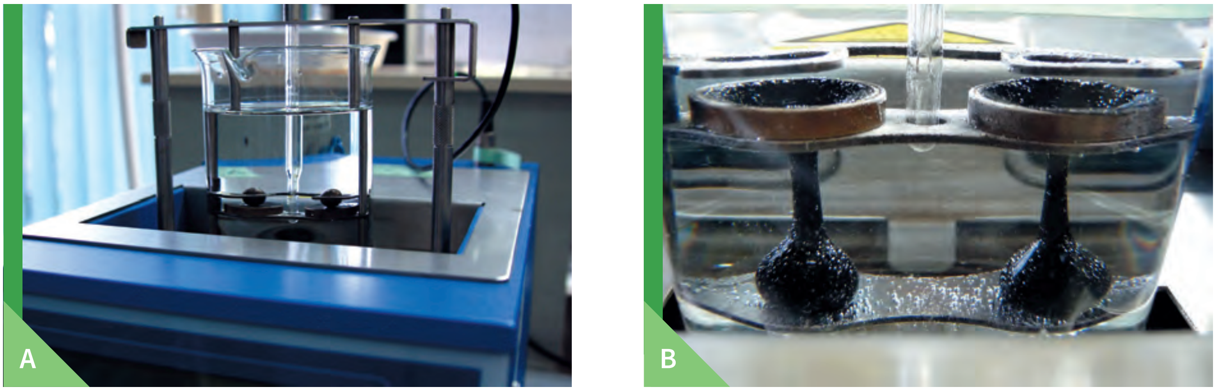


Fig. 1.22. *View of a bitumen sample before (A) and after (B) performing a softening point test with the R&B method (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Statistical parameters of softening point determination results for bitumen produced in the 2020-2022 period are listed in Table 1.16.

Table 1.16.
Statistical parameters of softening point determination results for bitumens produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT** [0.1 MM]	MEAN VALUE x_{mn}	STANDARD DEVIATION σ	TYPICAL RANGE x_{typ}	MEDIAN Me, Q_2	FIRST QUARTILE Q_1	THIRD QUARTILE Q_3	MIN-MAX VALUE $x_{min} - x_{max}$
20/30	55 ÷ 63	61.8	1.3	60.5 ÷ 63.0	62.6	60.6	62.8	56.8 ÷ 63.0
35/50	50 ÷ 58	54.4	1.1	53.3 ÷ 55.5	54.6	53.6	55.2	51.8 ÷ 56.6
50/70	46 ÷ 54	49.1	1.0	48.1 ÷ 50.1	49.2	48.2	50.0	46.6 ÷ 51.0
70/100	43 ÷ 51	45.1	0.8	44.3 ÷ 45.9	45.1	44.5	45.6	43.6 ÷ 46.6
100/150	39 ÷ 47	41.8	0.7	41.1 ÷ 42.5	41.8	41.4	42.2	40.6 ÷ 43.2
160/220	35 ÷ 43	38.4	0.7	37.7 ÷ 39.1	38.4	37.8	39.0	37.4 ÷ 39.6
ORBITON 25/55-60	≥ 60	68.2	6.1	62.0 ÷ 74.3	65.8	64.6	72.0	61.0 ÷ 92.0
ORBITON 45/80-55	≥ 55	64.7	5.7	59.0 ÷ 70.4	63.8	59.8	68.8	56.2 ÷ 77.8
ORBITON 45/80-65	≥ 65	80.0	7.1	72.9 ÷ 87.1	79.2	75.2	86.0	66.6 ÷ 94.0
ORBITON 25/55-80 HiMA	≥ 80	94.2	3.9	90.3 ÷ 98.1	94.0	91.0	95.5	90.0 ÷ 101.0
ORBITON 45/80-80 HiMA	≥ 80	92.8	2.6	90.2 ÷ 95.4	92.8	91.5	94.5	84.0 ÷ 97.0
ORBITON 65/105-80 HiMA	≥ 80	91.8	**	**	91.8	**	**	91.0 ÷ 92.5

* for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** parameters not calculated, due to the insufficient number of results

Additionally, Figures 1.23. to 1.27. present histograms with box plots for softening point results of selected bitumens produced in the 2020 – 2022 period.

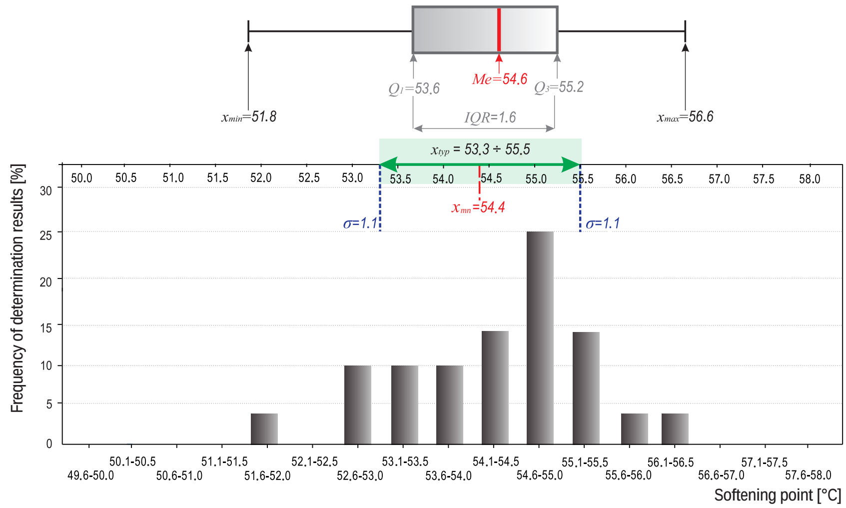


Fig. 1.23. *Histogram and box plot presenting the results of softening point R&B determinations for* ***paving grade bitumen 35/50*** *produced in the 2020 – 2022 period (standard range: 50 – 58 [°C])*

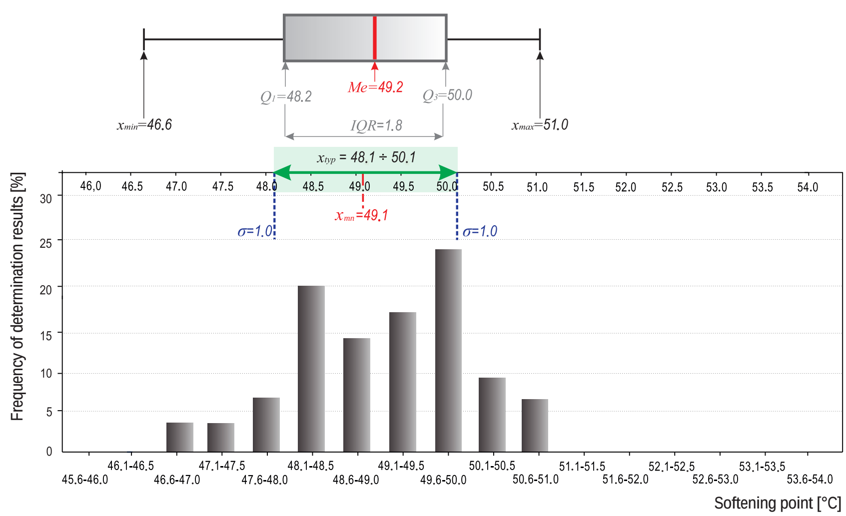


Fig. 1.24*. Histogram and box plot presenting the results of softening point R&B determinations for* ***paving grade bitumen 50/70*** *produced in the 2020 – 2022 period (standard range: 46 – 54 [°C])*

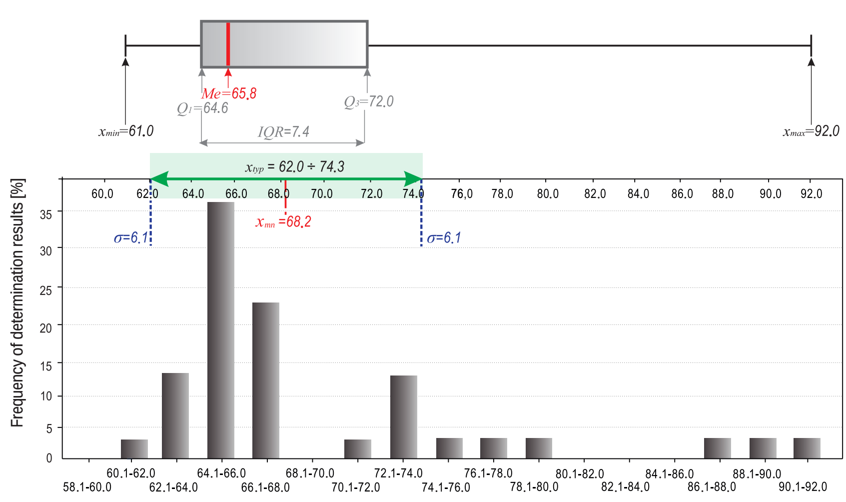


Fig. 1.25. *Histogram and box plot presenting the results of softening point R&B determinations for* ***ORBITON 25/55-60*** *binder produced in the 2020 – 2022 period (standard range: ≥ 60 [°C])*

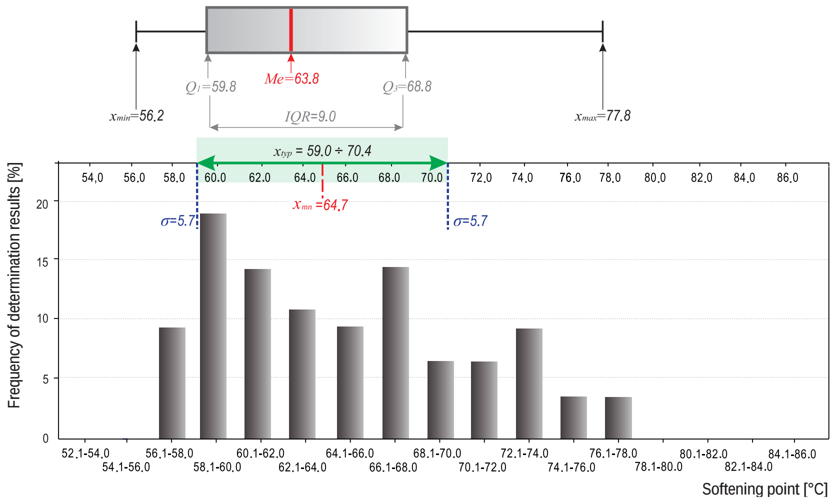


Fig. 1.26. *Histogram and box plot presenting the results of softening point R&B determinations for* ORBITON 45/80-55 *binder produced in the 2020 – 2022 period (standard range: ≥ 55 [°C])*

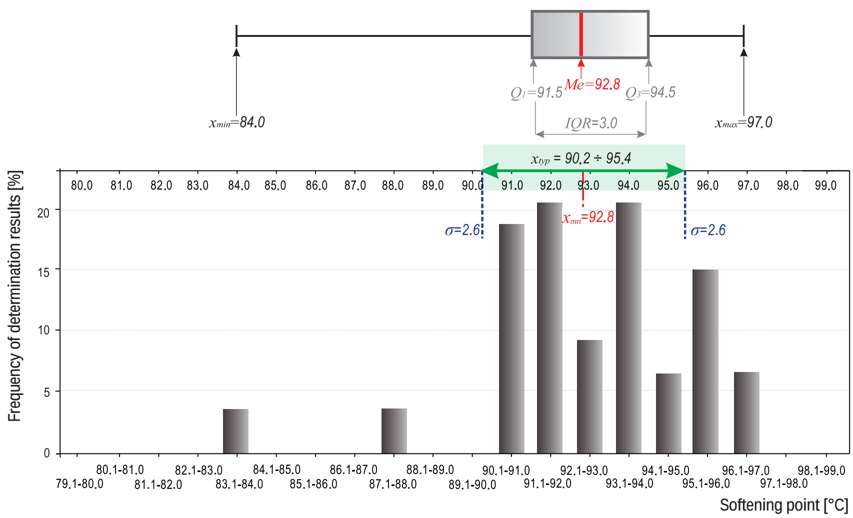


Fig. 1.27. *Histogram and box plot presenting the results of softening point R&B determinations for* ORBITON 45/80-80 HiMA *binder produced in the 2020 – 2022 period (standard range: ≥ 80 [°C])*

1.5.2.3. Fraass breaking point

The breaking point determines low-temperature bitumen properties and represents an approximate (conventional) lower limit of viscoelastic properties.

The Fraass breaking point test is performed according to the standard EN 12593.

The test consists in determining the temperature at which a 0.5 mm thick layer of bitumen spread on a thin steel plate with dimensions specified in the standard, placed in an apparatus, will break (see Fig. 1.29 a).

The specimen placed on the plate is subjected to cyclic mechanical bending and stress relief. The bending process occurs every 1°C while the air temperature around the specimen is steadily reduced, i.e. 1°C per minute. Each time the plate is bent, the bitumen layer on the specimen is observed and possible formation of cracks is recorded. The test ends when the first visible specimen failure is observed. Figure 1.28. presents the principle of performing breaking point measurements using the Fraass method.

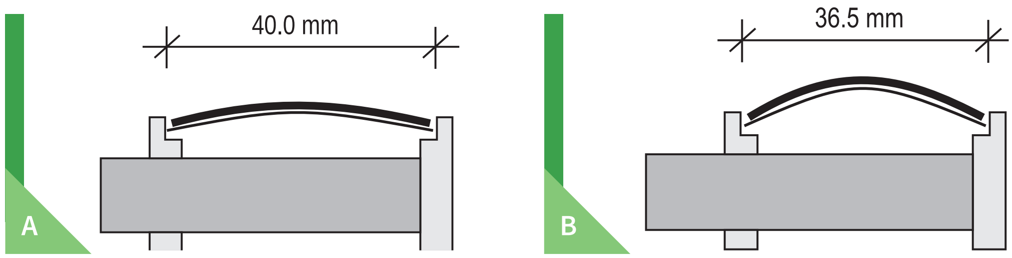


Fig. 1.28. *Principle of performing Fraass breaking point measurements, (A) plate with bitumen before bending; (B) plate with bitumen after bending – the moment of examination whether any bitumen cracks are observed*

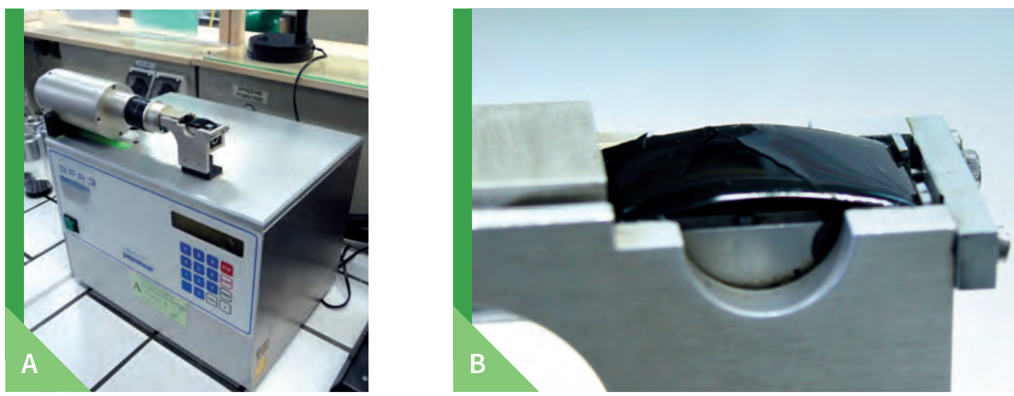


Fig. 1.29. *(A) General view of a Fraass breaking point testing apparatus and (B) view of a bitumen sample on the plate after the test with visible cracking (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Table 1.17. shows statistical parameters of Fraass breaking point test results for bitumens produced in the 2020 – 2022 period.

Table 1.17.
Statistical parameters of breaking point determination results for bitumens produced in the 2020 – 2022 period

BINDER TYPE	REQUI-REMENT** [0.1 mm]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
20/30	NR	-10.3	1.6	-11.9 ÷ -8.7	-10	-11	-9	-14 ÷ -8
35/50	≤ -5	-13.5	1.1	-14.6 ÷ -12.4	-13	-14	-13	-15 ÷ -11
50/70	≤ -8	-15.3	1.3	-16.5 ÷ -14.0	-15	-16	-14	-18 ÷ -13
70/100	≤ -10	-16.4	1.0	-17.4 ÷ -15.4	-17	-17	-16	-19 ÷ -14
100/150	≤ -12	-17.0	1.3	-18.3 ÷ -15.8	-17	-18	-16	-19 ÷ -14
160/220	≤ -15	-18.3	1.1	-19.4 ÷ -17.2	-18	-19	-18	-20 ÷ -16
ORBITON 25/55-60	≤ -10	-15.5	1.5	-17.1 ÷ -14.0	-15	-16	-14	-19 ÷ -13
ORBITON 45/80-55	≤ -15	-18.4	1.4	-19.8 ÷ -17.0	-19	-19	-18	-20 ÷ -15
ORBITON 45/80-65	≤ -15	-18.1	1.7	-19.7 ÷ -16.4	-18	-19	-17	-22 ÷ -15
ORBITON 25/55-80 HiMA	≤ -15	-20.8	0.7	-21.4 ÷ -20.1	-21	-21	-20	-22 ÷ -20
ORBITON 45/80-80 HiMA	≤ -18	-20.7	1.4	-22.1 ÷ -19.3	-21	-22	-20	-23 ÷ -18
ORBITON 65/105-80 HiMA	≤ -18	-20.5	**	**	-21	**	**	-21 ÷ -20

* for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** parameters not calculated, due to the insufficient number of results
NR – No Requirement

Additionally, Figures 1.30. – 1.34. present histograms with box plots for breaking point test results for selected bitumens produced in the 2020 – 2022 period.

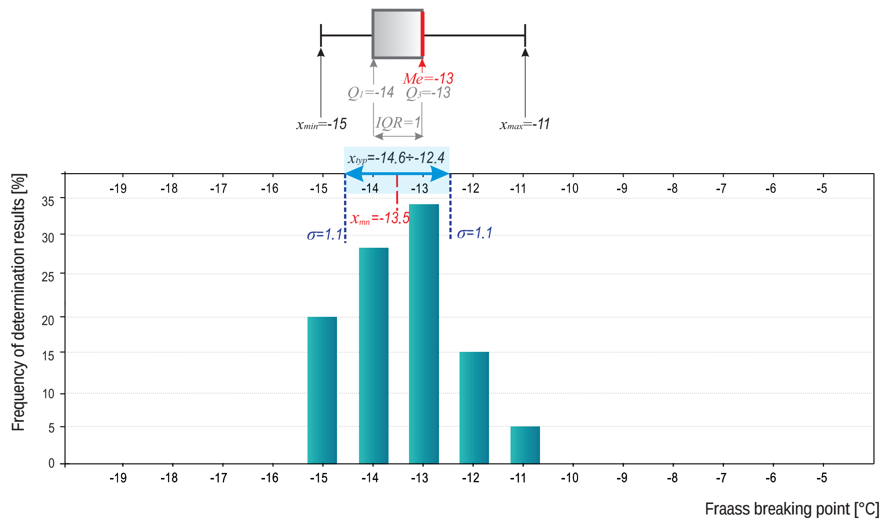


*Fig. 1.30. Histogram and box plot presenting the results of Fraass breaking point determinations for **paving grade bitumen 35/50** produced in the 2020 – 2022 period (standard range: ≤ -5 [°C])*

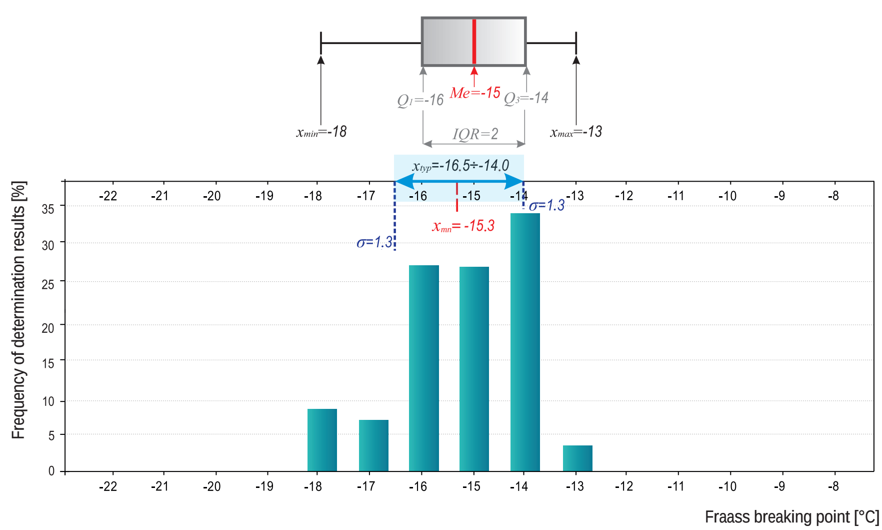


*Fig. 1.31. Histogram and box plot presenting the results of Fraass breaking point determinations for **paving grade bitumen 50/70** produced in the 2020 – 2022 period (standard range: ≤ -8 [°C])*

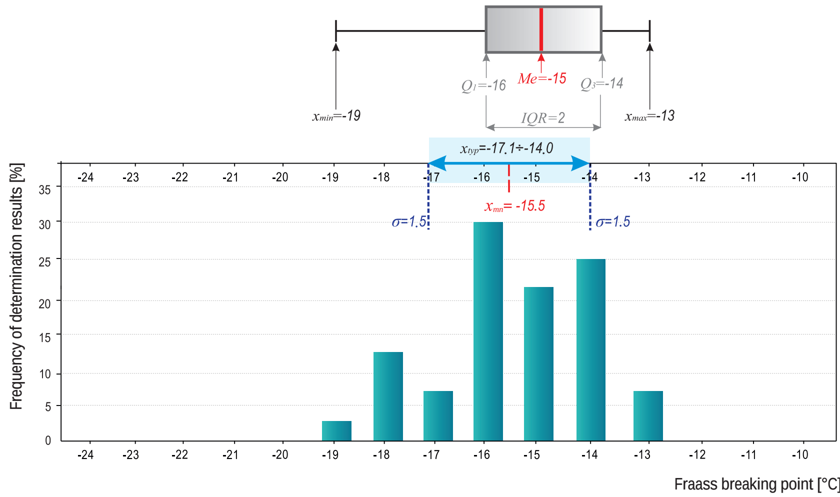


Fig. 1.32. *Histogram and box plot presenting the results of Fraass breaking point determinations for* ***ORBITON 25/55-60*** *binder produced in the 2020 – 2022 period (standard range: ≤ -10 [°C])*

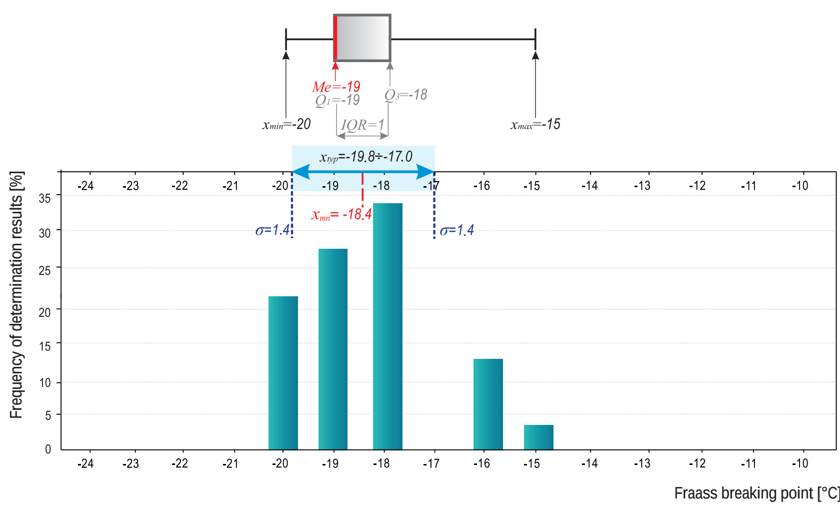


Fig. 1.33. *Histogram and box plot presenting the results of Fraass breaking point determinations for* ***ORBITON 45/80-55*** *binder produced in the 2020 – 2022 period (standard range: ≤ -15 [°C])*

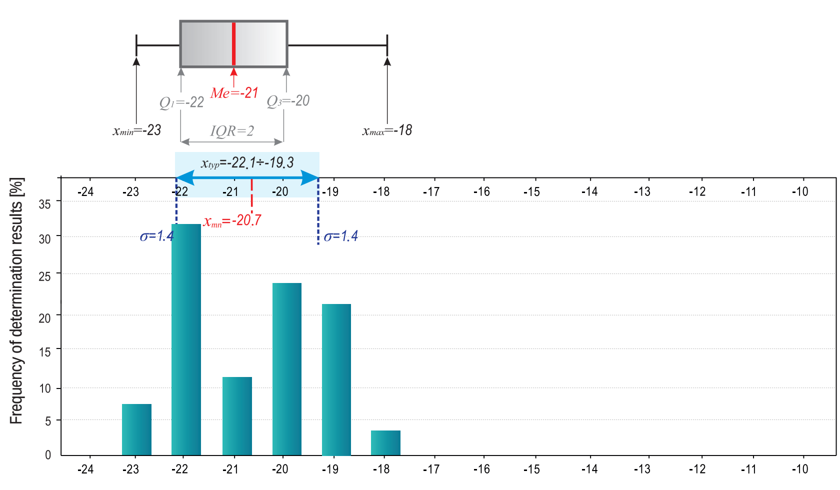


Fig. 1.34. *Histogram and box plot presenting the results of Fraass breaking point determinations for* ***ORBITON 45/80-80 HiMA*** *binder produced in the 2020 – 2022 period (standard range: ≤ -18 [°C])*

1.5.2.4. Viscosity

Viscosity is one of the key technological and functional parameters of bituminous binders. There are several definitions and test methods regarding viscosity. In relation to bitumen, the concept of viscosity can be defined as the internal friction occurring between the particles when one layer of bitumen is displaced relative to another [23].

Bitumens are treated as liquids with complex rheological characteristics. Their viscosity can vary depending on: temperature, shear rate, test duration, type of measurement method or system used in a given method. In other words, this means that **comparability of viscosity results obtained with different methods can only be maintained if strictly defined measuring conditions are met (correct temperature, measuring systems, shear rate, testing time, etc.).** In other cases, comparison and substitution of viscosity results is incorrect and may lead to erroneous conclusions.

The higher the temperature of the bitumen, the lower the viscosity [23]. This relation can be used to establish viscosity-temperature characteristics and determine the temperature of pumping of the bitumen, coating the aggregate and compacting the pavement. However, in the case of polymer modified bitumen and highly modified bitumen, taking into account their atypical features resulting from the specific properties of the used polymer, adopting the viscosity-temperature relation for precise determination of technological temperature does not seem appropriate. The temperature values determined in this way are largely approximate.

Process temperature values for bitumens offered by ORLEN Asfalt are available at:

SCAN ME!

Dynamic viscosity testing can be performed using:

- Cannon-Manning vacuum capillary method, acc. to EN 12596;
- Rheometer, by cone and plate method, acc. to EN 13702-1;
- Brookfield's rotational viscometer, acc. to EN 13302 or ASTM D 4402.

The kinematic viscosity test is performed with a BS/IP/RF viscometer (Fig. 1.35.), acc. to EN 12595. The main purpose of the test is to determine the time for a given volume of liquid to flow through the glass capillary of a calibrated viscometer, at a fixed measurement temperature (outflow time) [4]. The measurement time determination method is presented in Figure 1.36.

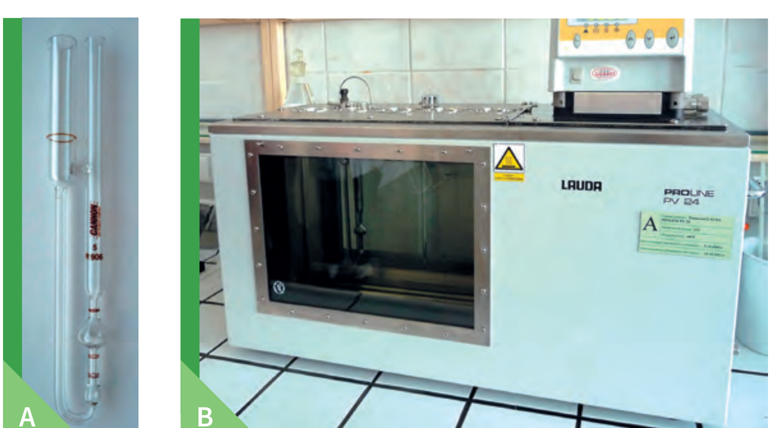


Fig. 1.35.
(A) View of a BS/IP/RF capillary viscometer and (B) apparatus used to perform the kinematic viscosity test (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium. S.A.)

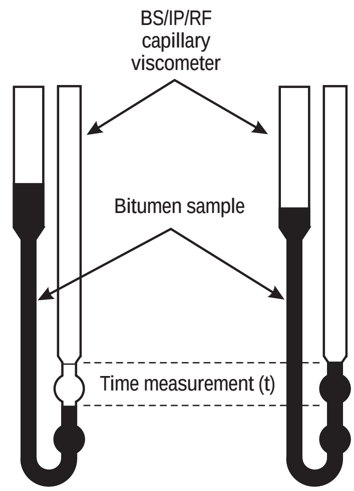


Fig. 1.36. Principle of measurement time determination in the BS/IP/RF capillary viscometer

As far as bituminous binders manufactured by the ORLEN Group are concerned, dynamic viscosity tests are performed mostly with Brookfield's rotational viscometers (Fig. 1.37.), acc. to EN 13302.

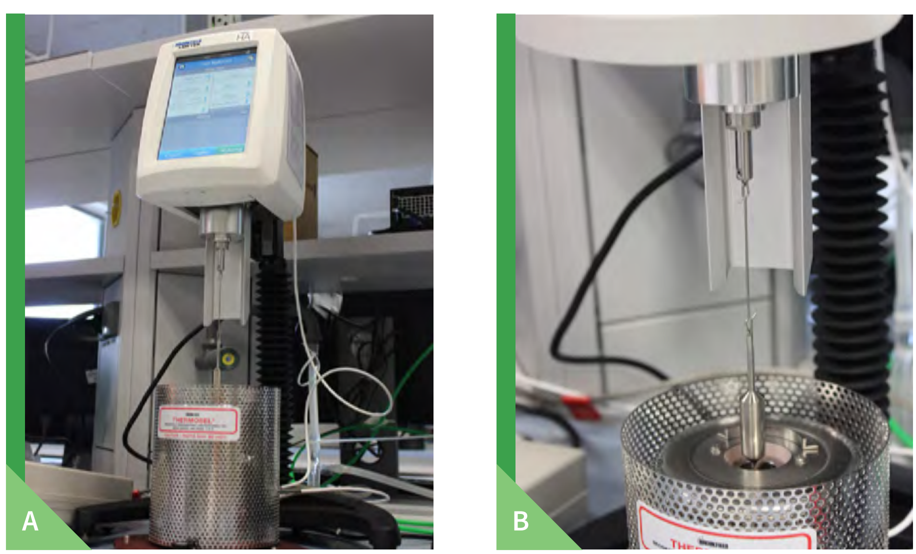


Fig. 1.37. *(A) General view of Brookfield's viscometer and (B) close-up of spindle and thermostated container for a bitumen sample (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

The main purpose of a Brookfield dynamic viscosity test is to determine the relative resistance to spindle rotations in a special container containing the test sample at a predetermined spindle speed. The dynamic viscosity value of the liquid under test is read out directly from the indication of the viscometer whose spindle torque must be set within a correct range. If this condition is not met, the spindle is changed to another one with a different characteristic form factor. The shape of the spindle used (spindle numbers are usually used to indicate it) must be specified with the viscosity test result in the Brookfield apparatus.

Fig. 1.38. presents the Brookfield viscometer diagram.

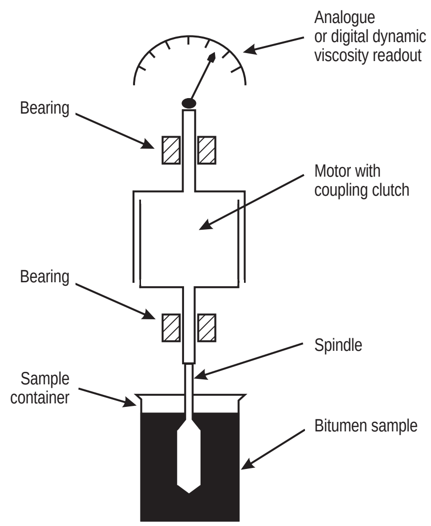


Fig. 1.38. *Brookfield viscometer configuration*

Table 1.18. shows examples of viscosity test results for bitumens produced in the 2020 – 2022 period. As for dynamic viscosity acc. to EN 13302, for soft paving grade bitumens used primarily for bitumen emulsion production ("cold mix" technology), viscosity values are given only before RTFOT ageing. For binders used in the "hot mix" technology, both values, i.e. before and after RTFOT ageing, are presented.

Table 1.18.
Example of viscosity test result values for bitumens produced in the 2020 – 2022 period

BINDER TYPE	DYNAMIC VISCOSITY ACC. TO EN 13302 [Pa·s]								KINEMATIC VISCOSITY ACC. TO EN 12595 [mm²/s]
	BEFORE RTFOT				*AFTER RTFOT*				
	60°C	90°C	135°C	160°C	60°C	90°C	135°C	160°C	
20/30	3,667.00	53.90	1.30	0.35	15,000.00	131.50	2.08	0.50	1 462
35/50	1,376.00	21.25	0.83	0.27	3,802.00	51.60	1.12	0.30	928
50/70	283.70	9.73	0.46	0.15	876.80	20.16	0.72	0.22	492
70/100	152.90	6.59	0.37	0.13	–	–	–	–	370
100/150	91.02	3.48	0.23	0.09	–	–	–	–	283
160/220	51.41	2.98	0.21	0.08	–	–	–	–	224
ORBITON 25/55-60	5,400.00	104.00	2.50	0.69	13,550.00	173.00	3.33	0.85	–
ORBITON 45/80-55	3,178.00	49.80	1.51	0.48	9,960.00	99.20	2.04	0.55	–
ORBITON 45/80-65	1,144.00	30.70	1.54	0.47	6,720.00	79.60	2.12	0.54	–
ORBITON 25/55-80 HiMA	–	1,330.00	3.74	0.75	–	1,590.00	5.04	0.96	–
ORBITON 45/80-80 HiMA	–	580.00	3.20	0.67	–	772.00	4.34	0.85	–
ORBITON 65/105-80 HiMA	–	274.00	2.82	0.59	–	680.00	4.01	0.80	–

1.5.2.5. Resistance to ageing

As a result of the ageing process, bituminous binder properties change in the following way:

- penetration reduction;
- softening point increase;
- increase (deterioration) of Fraass breaking point;
- viscosity increase;
- ductility reduction;
- several other chemical and mechanical changes.

The most intensive ageing of bitumen occurs when it is mixed with an aggregate in the asphalt mix plant, when the process temperature is the highest and the layer of bituminous binder on the aggregate is the thinnest.

It must be remembered that the bitumen built into the pavement is aged in a part of short-term ageing that is deemed to represent the ageing a bituminous binder undergoes during handling, storage, mixing, and laying of asphalt mixtures. From the perspective of pavement durability, it is therefore desirable to test to what extent the properties of a given bituminous binder have changed under the influence of high temperature, i.e. penetration, softening point, viscosity or elastic recovery in the case of polymer modified bitumens. Resistance to the short-term ageing by RTFOT is determined according to EN 12607-1.

Fig. 1.39. shows an oven for simulation of technological ageing using the RTFOT method.

Fig. 1.39. *Overview of an oven for simulation of short-term ageing using the RTFOT method (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Following the RTFOT test, a certain amount of aged bitumen is obtained. Next, tests are performed to determine to what extent the binder properties have changed as a result of short-term ageing at the reference temperature of 163°C.

1.5.2.6. Retained penetration after ageing

As a result of the ageing process, the bitumen penetration decreases, which means that the bitumen hardens. The result of the retained penetration after ageing is calculated as the percentage of penetration of the bitumen after RTFOT in relation to the original penetration value of the bitumen before ageing (assuming the penetration of unaged bitumen as 100%). Retained penetration data is provided in Table 1.19.

Table 1.19.
Statistical parameters of the determinations results for resistance to ageing – retained penetration [%], for bitumens produced in the 2020 – 2022 period

BINDER TYPE	REQUI-REMENT* [%]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
20/30	≥ 55	73.0	3.6	69.4 ÷ 76.6	72	70	76	67 ÷ 80
35/50	≥ 53	69.5	5.8	63.7 ÷ 75.3	69	67	72	61 ÷ 87
50/70	≥ 50	68.4	7.9	60.5 ÷ 76.3	66	63	70	56 ÷ 86
70/100	≥ 46	66.2	8.6	57.6 ÷ 74.8	64	61	69	54 ÷ 84
100/150	≥ 43	60.4	5.6	54.7 ÷ 66.0	59	56	64	52 ÷ 75
160/220	≥ 37	57.7	5.7	52.0 ÷ 63.3	58	52	62	48 ÷ 66
ORBITON 25/55-60	≥ 60	76.2	4.9	71.3 ÷ 81.2	76	73	78	67 ÷ 87
ORBITON 45/80-55	≥ 60	71.5	4.9	66.6 ÷ 76.4	71	68	75	62 ÷ 80
ORBITON 45/80-65	≥ 60	76.1	6.3	69.8 ÷ 82.4	76	72	82	64 ÷ 87
ORBITON 25/55-80 HiMA	≥ 60	75.8	2.9	72.8 ÷ 78.7	76	75	77	71 ÷ 80
ORBITON 45/80-80 HiMA	≥ 60	78.8	7.1	71.7 ÷ 85.9	78	74	84	65 ÷ 94
ORBITON 65/105-80 HiMA	≥ 60	75.3	**	**	75	**	**	75 ÷ 76

* for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** parameters not calculated, due to the insufficient number of results

1.5.2.7. Increase and drop in softening point after ageing

The bitumen softening point usually increases after short-term ageing. The bitumen sample after the RTFOT test is subjected to the softening point test according to EN 1427. Then, the result of the increase in the softening point after ageing is calculated in [°C] from the difference in the softening point obtained for the short-term aged (RTFOT) bitumen sample and the unaged bitumen sample, respectively. The requirements limiting the increase in softening point after ageing apply to each type of bitumen used in hot-mix technologies: paving grade, polymer modified, and highly modified bitumen. However, sometimes the RTFOT softening point after ageing decreases. This may be the case with some polymer modified and highly modified bitumens. The Polish requirement for a drop in softening point after RTFOT ageing is specified in National Annex (NA) to the amendment of PN-EN 14023:2011/Ap2, published in 2020, as a TBR value (to be reported).

Table 1.20 presents statistical data on the change in softening point (increase and decrease) under RTFOT ageing for the tested bituminous binders.

Table 1.20.
Statistical parameters of the determinations results for resistance to ageing – change in softening point R&B [°C], for bitumens produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT* [%]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
20/30	≤ 8	7.2	0.7	6.4 ÷ 7.9	7.4	6.6	7.8	5.4 ÷ 8.0
35/50	≤ 8	6.7	1.3	5.4 ÷ 8.0	6.8	6.0	7.8	1.4 ÷ 8.0
50/70	≤ 9	5.7	1.9	3.8 ÷ 7.6	6.0	4.6	7.2	1.6 ÷ 8.6
70/100	≤ 9	5.4	1.6	3.8 ÷ 7.0	5.9	4.4	6.5	1.6 ÷ 7.8
100/150	≤ 10	5.3	1.3	4.1 ÷ 6.6	5.6	5.0	6.0	1.0 ÷ 7.2
160/220	≤ 11	5.2	1.3	3.9 ÷ 6.5	5.0	4.2	6.2	3.0 ÷ 7.4
ORBITON 25/55-60	TBR**	5.9	1.2	4.6 ÷ 7.1	6.0	5.2	6.6	3.0 ÷ 8.0
ORBITON 45/80-55	TBR**	3.3	3.3	0.0 ÷ 6.6	4.2	0.2	6.0	-2.0 ÷ 8.0
ORBITON 45/80-65	TBR**	0.5	2.5	-2.0 ÷ 2.9	-0.3	-2.0	3.2	-2.0 ÷ 4.4
ORBITON 25/55-80 HiMA	TBR**	0.9	1.6	-0.7 ÷ 2.6	1.0	0.0	1.5	-2.0 ÷ 3.5
ORBITON 45/80-80 HiMA	TBR**	2.2	1.9	0.3 ÷ 4.1	2.0	0.5	3.5	-2.0 ÷ 7.0
ORBITON 65/105-80 HiMA	TBR**	1.8	**	**	1.8	**	**	0.5 ÷ 3.0

* **increase in R&B** for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** TBR (To Be Reported) applies **to a drop in softening point R&B** for ORBITON and ORBITON HiMA acc. to EN 14023 (National Annex)
*** parameters not calculated, due to the insufficient number of results

1.5.2.8. Change of mass after ageing

As a result of the ageing process, the bitumen mass may change (increase or decrease). The change of mass after ageing is determined according to EN 12607-1. It is the absolute value of the percentage difference between the mass of a unaged bitumen sample and the mass of the same sample after the RTFOT ageing.

Data on the change of mass after ageing for the tested bitumens are shown in Table 1.21. The table takes into account that the value of mass change can be a positive or a negative value.

Table 1.21.
Statistical parameters for ageing resistance determination results – change of mass [%] resulting from the short-term ageing using RTFOT method, for bitumens produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT* [%]	MEAN VALUE x_{mn}	STANDARD DEVIATION σ	TYPICAL RANGE x_{typ}	MEDIAN Me, Q_2	FIRST QUARTILE Q_1	THIRD QUARTILE Q_3	MIN-MAX VALUE $x_{min} - x_{max}$
20/30	≤ 0.5	-0.02	0.04	-0.06 ÷ 0.02	-0.01	-0.03	0.01	-0.16 ÷ 0.03
35/50	≤ 0.5	-0.02	0.04	-0.06 ÷ 0.02	-0.02	-0.04	-0.01	-0.10 ÷ 0.04
50/70	≤ 0.5	0.00	0.05	-0.06 ÷ 0.05	-0.01	-0.04	0.04	-0.12 ÷ 0.09
70/100	≤ 0.8	-0.01	0.06	-0.06 ÷ 0.05	-0.01	-0.04	0.05	-0.15 ÷ 0.09
100/150	≤ 0.8	-0.01	0.05	-0.06 ÷ 0.03	-0.01	-0.05	0.02	-0.10 ÷ 0.09
160/220	≤ 1.0	-0.02	0.05	-0.07 ÷ 0.04	-0.01	-0.03	0.02	-0.18 ÷ 0.04
ORBITON 25/55-60	≤ 0.5	-0.02	0.04	-0.06 ÷ 0.02	-0.02	-0.04	-0.01	-0.10 ÷ 0.08
ORBITON 45/80-55	≤ 0.5	0.00	0.04	-0.03 ÷ 0.04	0.00	-0.02	0.02	-0.06 ÷ 0.09
ORBITON 45/80-65	≤ 0.5	0.00	0.05	-0.05 ÷ 0.05	0.00	-0.04	0.04	-0.08 ÷ 0.10
ORBITON 25/55-80 HiMA	≤ 0.5	0.01	0.06	-0.05 ÷ 0.07	0.01	-0.02	0.07	-0.10 ÷ 0.08
ORBITON 45/80-80 HiMA	≤ 0.5	0.01	0.06	-0.05 ÷ 0.07	0.01	-0.04	0.06	-0.09 ÷ 0.10
ORBITON 65/105-80 HiMA	≤ 0.5	0.06	**	**	0.06	**	**	0.04 ÷ 0.07

* for paving grade bitumen acc. to EN 12591; for ORBITON and ORBITON HiMA acc. to EN 14023
** parameters not calculated, due to the insufficient number of results

1.5.2.9. Bitumen density

Bitumen density tests are performed in accordance with EN 15326. The goal of the test is to determine the ratio of the density of the tested bituminous binder to the density of the test fluid, determined under the same temperature conditions.

Bitumen density values are necessary for calculations of volume parameters of bituminous mixes according to EN 12697-8. The bituminous binder densities shown in Table 1.22 can be used in the design of asphalt mixes.

As a standard, in laboratories cooperating with ORLEN Asfalt, densities of all bituminous binders are determined at the temperature of 15°C (twice a year). Table 1.22 below presents the average results of density testing for bitumens produced in the 2020 − 2022 period. The test was performed according to the method using a pycnometer with a capillary plug, at 15°C.

Table 1.22.
Average results of the density of bituminous binders produced in the 2020–2022 period

BINDER TYPE	DENSITY AT 15°C ACC. TO EN 15326 [kg/m^3]
Paving grade 20/30	1,027
Paving grade 35/50	1,026
Paving grade 50/70	1,024
Paving grade 70/100	1,022
Paving grade 100/150	1,020
Paving grade 160/220	1,018
Modified ORBITON 25/55-60	1,023
Modified ORBITON 45/80-55	1,021
Modified ORBITON 45/80-65	1,021
Highly modified bitumen ORBITON 25/55-80 HiMA	1,021
Highly modified bitumen ORBITON 45/80-80 HiMA	1,020
Highly modified bitumen ORBITON 65/105-80 HiMA	1,016

The density values of bitumen given in Table 1.22. refer to measurements conducted at 15°C. If bitumens are used at other temperatures, the given density at 15°C can be converted into the density at the application temperature by using a conversion factor in the form of a bitumen volume expansion coefficient of 0.00061°C^{-1} [25]. To simplify the calculations, the following equation can be used:

$$\rho_x = \rho_{15} - (0.00061 \cdot \Delta t)$$

where:

ρ_x – density at the calculated temperature X

ρ_{15} – density at 15°C in Mg/m^3

Δt – temperature difference (X – 15), X ∈ <15,16…200>

The calculated density values are obviously approximations and not exact values.

1.5.3. RESULTS FOR ADDITIONAL POLYMER MODIFIED BITUMEN PROPERTIES

1.5.3.1. Elastic recovery at 25°C before and after RTFOT ageing

The elastic recovery test both before and after the RTFOT ageing is performed according to EN 13398. The objective of the test is to determine the conventional elasticity of bitumen by measuring the distance between the ends of a stretched and cut sample under specified conditions, Fig. 1.40.

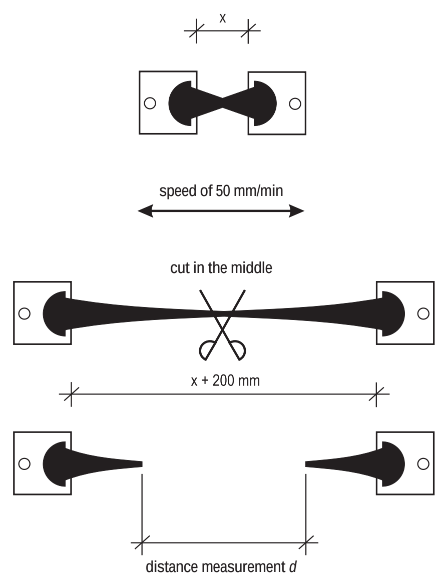


Fig. 1.40. *Elastic recovery test performance principle*

A bitumen sample is stretched at a predetermined temperature (usually 25°C or 10°C), at the constant speed of 50 mm/min, until 200 mm elongation is achieved. A bitumen "thread" achieved in this manner is cut in the middle to obtain two equally long sections. After 30 minutes, the distance between two ends of the cut sample is measured. Next, the elastic recovery value expressed as percentage in relation to the elongation [%] is calculated.

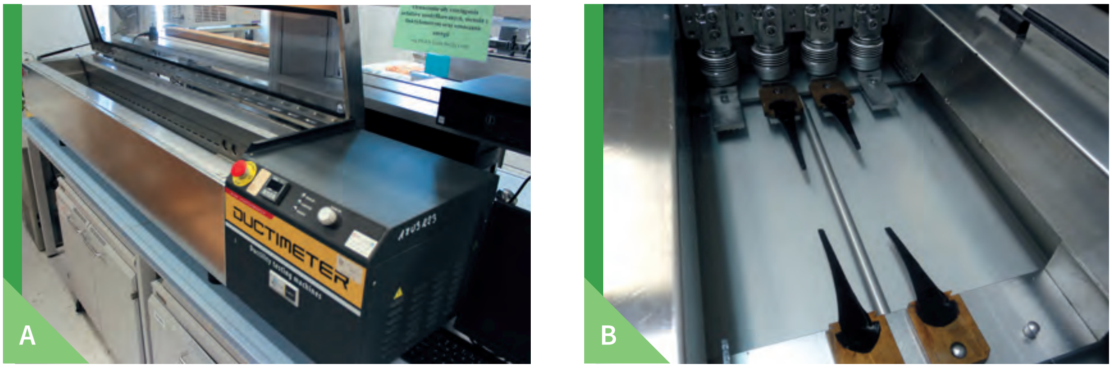


Fig. 1.41.*(A) General view of the apparatus for testing elastic recovery, and (B) view of a bitumen sample during a test (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

In the case of testing bitumens after the RTFOT ageing, the result makes it possible to determine to what extent the polymer (elastomer) remains effective after ageing, and thus, how effectively the polymer network can act in the asphalt pavement.

Tables 1.23. and 1.24. contain statistical parameters for the elastic recovery determination results at 25°C for ORBITON and ORBITON HiMA binders produced in the 2020 – 2022 period, before and after the RTFOT ageing, respectively.

Table 1.23.
Statistical parameters for elastic recovery determination results at 25°C before the RTFOT ageing for ORBITON and ORBITON HiMA binders produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT EN 14023 [%]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
ORBITON 25/55-60	≥ 60	80.6	4.2	76.4 ÷ 84.7	80	79	83	70 ÷ 90
ORBITON 45/80-55	≥ 70	85.6	4.8	80.8 ÷ 90.3	87	83	89	72 ÷ 90
ORBITON 45/80-65	≥ 80	90.4	3.1	87.3 ÷ 93.5	91	89	92	83 ÷ 96
ORBITON 25/55-80 HiMA	≥ 80	91.9	3.5	88.4 ÷ 95.4	93	90	95	86 ÷ 96
ORBITON 45/80-80 HiMA	≥ 80	94.2	4.0	90.2 ÷ 98.1	95	93	97	82 ÷ 99
ORBITON 65/105-80 HiMA	≥ 80	90.0	**	**	90	**	**	85 ÷ 95

* parameters not calculated, due to the insufficient number of results

Table 1.24.
Statistical parameters for elastic recovery determination results at 25°C after ageing by the RTFOT method for ORBITON and ORBITON HiMA binders produced by ORLEN Asfalt in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT EN 14023 [%]	MEAN VALUE	STANDARD DEVIATION	TYPICAL RANGE	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
ORBITON 25/55-60	≥ 50	74.8	5.0	69.8 ÷ 79.9	75	71	78	65 ÷ 90
ORBITON 45/80-55	≥ 50	83.4	3.6	79.7 ÷ 87.0	84	82	86	74 ÷ 88
ORBITON 45/80-65	≥ 60	85.3	3.3	82.0 ÷ 88.7	86	83	88	77 ÷ 90
ORBITON 25/55-80 HiMA	≥ 50	89.7	3.5	86.2 ÷ 93.2	90	88	91	84 ÷ 95
ORBITON 45/80-80 HiMA	≥ 60	91.3	3.2	88.1 ÷ 94.6	92	90	93	82 ÷ 98
ORBITON 65/105-80 HiMA	≥ 70	88.0	**	**	88	**	**	86 ÷ 90

* parameters not calculated, due to the insufficient number of results

Additionally, Figures 1.42. ÷ 1.44. present histograms and box plots for the elastic recovery results for selected polymer modified and highly modified bitumens produced in the 2020 – 2022 period.

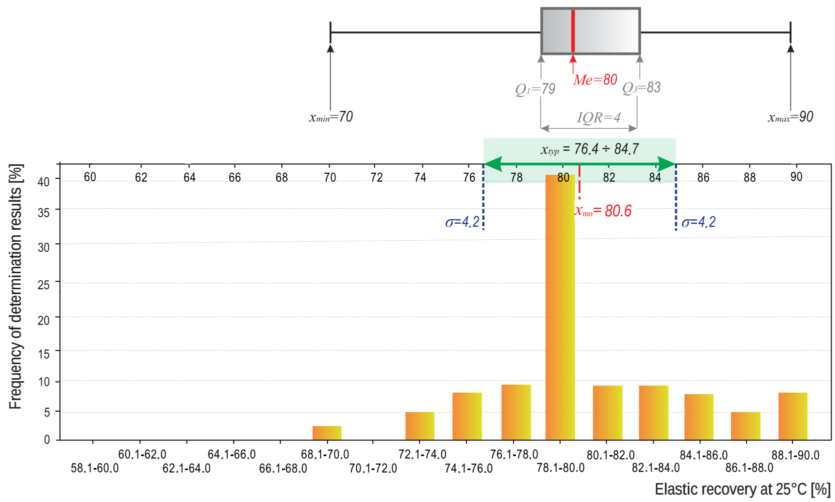


Fig. 1.42. *Histogram and box plot presenting the results of elastic recovery at 25°C of* **ORBITON 25/55-60** *binder produced in the 2020 – 2022 period, before ageing (standard range: ≥ 60 [%])*

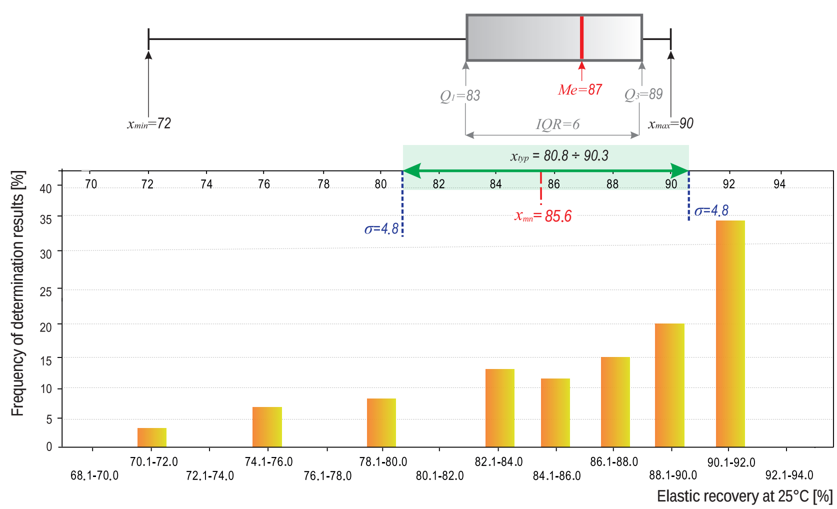


Fig. 1.43. *Histogram and box plot presenting the results of elastic recovery at 25°C of* **ORBITON 45/80-55** *binder produced in the 2020 – 2022 period, before ageing (standard range: ≥ 70 [%])*

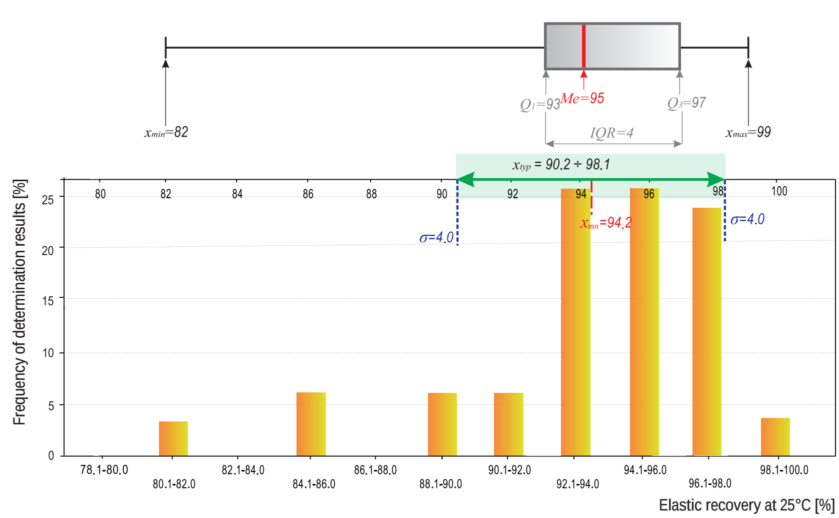


Fig. 1.44. *Histogram and box plot presenting the results of elastic recovery at 25°C of* **ORBITON 45/80-80 HiMA** *binder produced in the 2020 – 2022 period, before ageing (standard range: ≥ 80 [%])*

1.5.3.2. Plasticity range

The plasticity range is the difference between the softening point and the Fraass breaking point. It is therefore the temperature range over which a bituminous binder retains its viscoelastic properties. From the point of view of a binder user, the classic bitumen theory emphasises the greatest possible value for this range, i.e. the lowest possible breaking point and the highest possible softening point. The average plasticity ranges of polymer modified bitumens produced in the 2020 – 2022 period are presented in Table 1.25.

Table 1.22.
Average plasticity ranges of bituminous binders produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT EN 14023	PLASTICITY RANGE [°C]
Modified ORBITON 25/55-60	NR	80.3
Modified ORBITON 45/80-55	NR	83.7
Modified ORBITON 45/80-65	NR	99.0
Highly modified ORBITON 25/55-80 HiMA	NR	116.5
Highly modified ORBITON 45/80-80 HiMA	NR	114.3
Highly modified ORBITON 65/105-80 HiMA	NR	113.5

NR – No Requirement

1.5.3.3. Microstructure

One of the methods enabling observation of the polymer microstructure of bitumens is fluorescence microscopy. The test is performed (acc. to EN 13632) on a fresh fracture of a frozen modified bitumen sample, using a fluorescence microscope with a UV lamp (Fig. 1.45.) and analysing the image in reflected light.

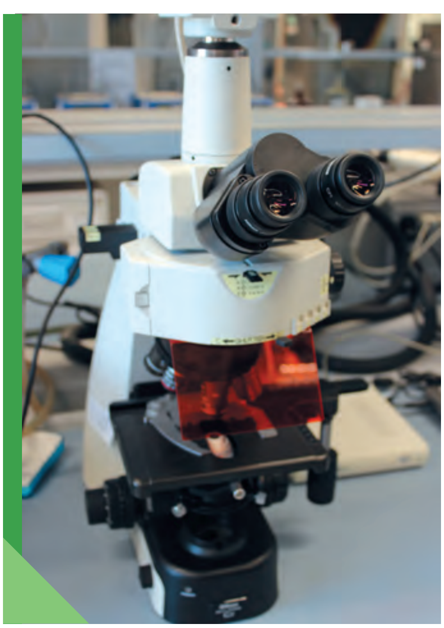


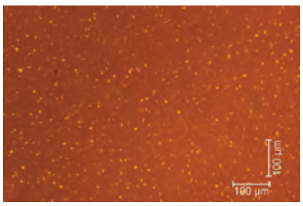
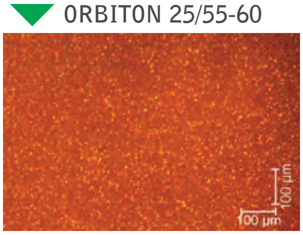
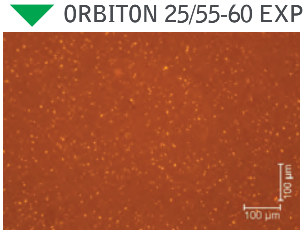
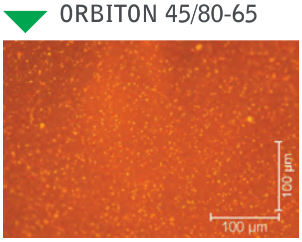
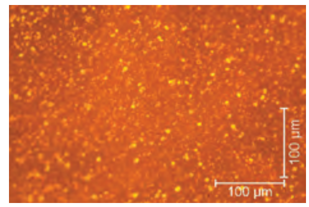
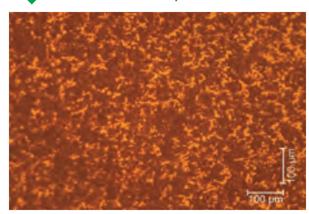
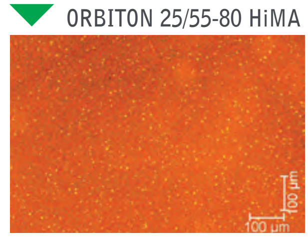
Fig. 1.45. *Overview of a fluorescence microscope with a UV lamp (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

On the basis of Annex A.3 of EN 13632 the structure of polymer modified bitumens can be described according to the letter markings characterising the polymer-bitumen dispersion system:

1. PHASE CONTINUITY:	P: CONTINUOUS POLYMER PHASE B: CONTINUOUS BITUMEN PHASE X: CONTINUITY OF BOTH PHASES
2. PHASE DESCRIPTION:	H: HOMOGENEOUS I: INHOMOGENEOUS
3. SIZE DESCRIPTION:	S: SMALL (< 10 μm) M: MEDIUM (10 – 100 μm) L: LARGE (> 100 μm)
4. SHAPE DESCRIPTION:	r: ROUNDISH, OVAL s: STRIPES o: OTHER

An example of the microstructure of polymer modified bitumens, acc. to EN 13632, produced by the ORLEN Group is presented in Table 1.26.

Table 1.26.
Microstructure of polymer modified bitumens according to EN 13632

POLYMER MODIFIED BITUMEN TYPE	PHOTOGRAPH	POLYMER DISPERSION CODE: PHASE CONTINUITY	PHASE DESCRIPTION	SIZE DESCRIPTION	SHAPE DESCRIPTION
ORBITON 10/40-65		B	H	S	r/o
ORBITON 25/55-60		B	H	S	r/o
ORBITON 25/55-60 EXP		B	H	S	r/o
ORBITON 25/55-65 EXP		B	H	S	r/o
ORBITON 45/80-65		B	H	S	r/o
ORBITON 45/80-55		B	H	S	r/o
OBITON 65/105-60		B	H	S/M	r/o
ORBITON 25/55-80 HiMA		P	H	S	r/o
ORBITON 45/80-80 HiMA		P	H	S	r/o
ORBITON 65/105-80 HiMA		P	H	S	r/o

1.5.3.4. Force ductility (cohesion)

Cohesion describes the mutual attraction of particles of the same material due to intermolecular forces. For bitumens, a sufficiently high value of cohesion enables the bituminous binder to transmit tensile stress in the road pavement. It is assumed that it makes it more resistant to craking and fatigue.

The tensile force test (at a low tensile rate) is performed in accordance with EN 13589 (revision published in 2019). The main purpose of this test is to determine the force required to stretch the sample at a specified temperature.

A correctly formed sample is placed in a ductilometer, in a water bath at a correct (determined for each type of modified bitumen) temperature. The sample is then subjected to uniform tension at the rate of 50 mm/min until it breaks or reaches a minimum elongation of 1,333%, i.e. 400 mm. The force is recorded throughout the tensile process using sensors. According to the revised standard, the final result of cohesion is calculated as the difference between the cohesion energy at breaking or at the elongation of 1,333% (400 mm) and the cohesion energy at the elongation of 667% (200 mm). **To determine the compliance with the specification, the cohesion energy at 200 – 400 mm elongation is adopted**.

Figure 1.46. presents the general method of force ductility test performance aimed at confirming compliance with specifications – force ductility-elongation relationship chart. Figure 1.47. presents the view of bitumen before and after the force ductility test, respectively.

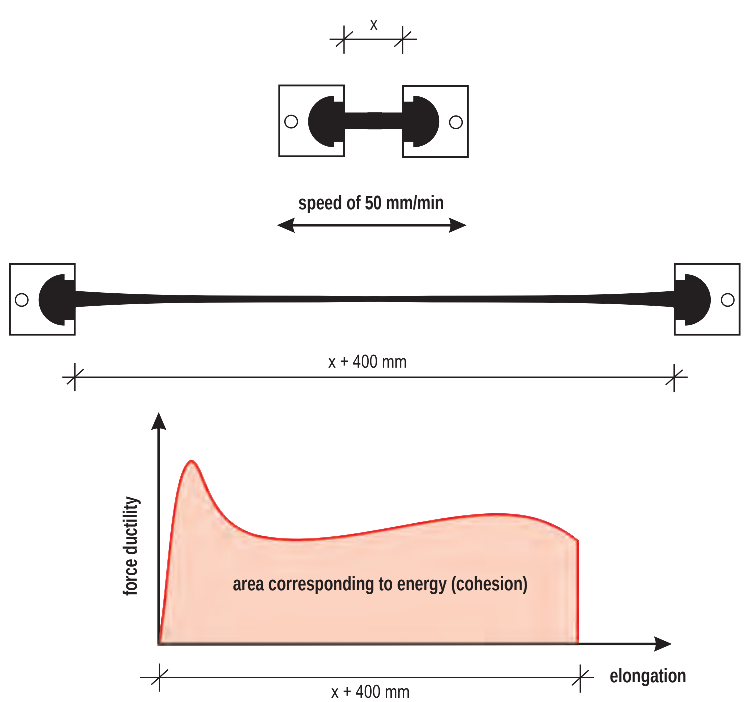


Fig. 1.46. *Method of force ductility test performance aimed at confirming compliance with specifications – force ductility-elongation relationship chart*

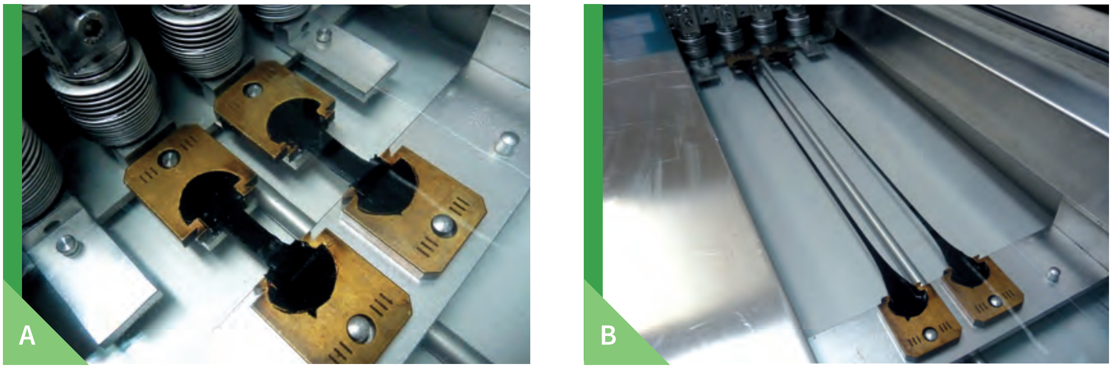


Fig. 1.47. *Bitumen sample (A) before testing and (B) after testing (stretched to 400 mm) in a ductilometer (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Table 1.27. presents statistical parameters for cohesion determination results for ORBITON and ORBITON HiMA produced in the 2020 – 2022 period.

Table 1.27.
Statistical parameters for cohesion determination results for ORBITON and ORBITON HiMA binder produced in the 2020 – 2022 period

BINDER TYPE	REQUIREMENT PN-EN 14023 [J/cm²]	MEAN VALUE	STANDARD DEVIATION	TYPICAL INTERVAL	MEDIAN	FIRST QUARTILE	THIRD QUARTILE	MIN-MAX VALUE
		x_{mn}	σ	x_{typ}	Me, Q_2	Q_1	Q_3	$x_{min} - x_{max}$
ORBITON 25/55-60	≥ 2 (at 10°C)	5.0	0.9	4.0 ÷ 5.9	4.9	4.6	5.7	2.9 ÷ 6.5
ORBITON 45/80-55	≥ 3 (at 5°C)	7.8	0.8	7.0 ÷ 8.6	7.8	7.5	8.2	5.7 ÷ 9.8
ORBITON 45/80-65	≥ 2 (at 10°C)	4.5	0.6	3.9 ÷ 5.1	4.6	4.0	4.9	3.3 ÷ 5.6
ORBITON 25/55-80 HiMA	≥ 0.5* (at 15°C)	3.6	0.6	3.0 ÷ 4.3	3.6	3.5	3.6	2.6 ÷ 5.1
ORBITON 45/80-80 HiMA	≥ 2* (at 10°C)	4.4	1.3	3.1 ÷ 5.7	4.2	3.6	4.9	2.4 ÷ 7.6
ORBITON 65/105-80 HiMA	≥ 1.0* (at 5°C)	6.8	**	**	6.8	**	**	3.6 ÷ 9.9

* requirements specified in PN-EN 14023:2011/Ap2:2020-02
** parameters not calculated, due to the insufficient number of results

II. ENERGY EFFICIENCY AND CARBON FOOTPRINT

#carbon foot print, #energy, #The Green Deal, #Fitfor55, #asphalt mix plant, #HMA production

2.1. INTRODUCTION

The ever-changing macroeconomic environment forces all of us to take action to limit the impact exerted by individuals, organisations, processes or products on the environment. As Poland is a Member of the European Union, it must also adapt to the changing reality.

This chapter is in a way an introduction to the following ones and provides the definition of the "carbon footprint", and also discusses various aspects of energy efficiency in the asphalt mix production.

The European Union has implemented numerous environment and climate protection programmes; however, the Green Deal and Fit for 55 are its most recognisable initiatives.

The Green Deal was published by the European Commission in December 2019 and consists of a series of actions and targets aimed at reducing greenhouse gas emissions, increasing energy efficiency and promoting a sustainable economy. The programme assumes achieving climate neutrality across all industry sectors by 2050, and one of its key targets is to reduce greenhouse gas emissions by at least 50-55% by 2030, as compared to the levels recorded in 1990.

Fit for 55 is a package of ten climate-related acts and policies published by the European Commission in July 2021, which aims at accelerating EU-wide actions taken with the view of achieving climate neutrality. It includes a number of measures and proposals, such as detailing targets related to the share of renewable energy, introducing a tax on fossil fuels (primarily coal), tightening CO_2 emission standards for cars and lorries, creating an additional European system for greenhouse gas emission allowance trading (ETS2) for the road transport and building sectors, and introducing a "social adjustment mechanism" to ensure that the climate transition is socially fair and does not expose the poorest society sections to additional costs.

Relating the road construction sector to the *Green Deal* and *Fit for 55* programmes, it can be assumed that, as one of the largest economy sectors, it exerts impact on greenhouse gas emissions and the environment. The factors determining the road construction sector impact on the environment are related to:

- material manufacturing: road construction requires a large quantity of materials such as bitumen, concrete, aggregates or steel; their production involve CO_2 emissions resulting from the energy required to produce them;
- high energy intensity: road construction is a very energy-intensive endeavour, involving processes such as heating, crushing and mixing materials together, and requiring the use of machinery and equipment which, as a rule, are powered with fossil fuels, so the resulting CO_2 emissions exert a considerable environmental impact;
- material transport: road construction processes often require transporting materials and machinery to a construction site; related CO_2 emissions depend on the distance, amount of materials transported and transport vehicle efficiency.

It can be assumed that even if today, i.e. in 2024, no restrictions and regulations are imposed on the use of energy-intensive and CO_2 – generating materials and technologies, such measures will be implemented in the future, either directly or indirectly. Therefore, the main objectives of the road construction industry in terms of reducing the environmental impact should be to strive towards designing technologies that will reduce emissions and limit consumption of natural resources and energy. To this end, such actions can be taken:

- using recycled raw materials (including asphalt mixes), i.e. increasing the reclaimed asphalt pavement in newly-built roads;
- implementing technologies making it possible to build pavements at reduced temperatures as compared with standard hot asphalt mixtures, i.e. using 'cold', 'half-warm' and 'warm' mixtures technologies (fuel efficiency and reduced emissions);
- employing materials with improved durability, which will significantly extend the service life of the pavement to reduce the amount of natural resources (aggregates, bituminous binders); decrease in the number of necessary overhauls also translates into smaller time losses resulting from congestion and lower emissions when driving at low speeds;
- modifying the pavement structure schemes by taking advantage of hi-tech material properties, with the final increase in the efficiency of their use, which also reduces the amount of road construction materials that need to be transported from refineries and quarries to asphalt mix plants and then, in the form of asphalt mix, to a construction site, thus generating savings in terms of transport (fuel, emissions);
- modifying the asphalt mix plant equipment, its management methods, types of fuel and power supply.

The issues enumerate above are discussed in detail in this and consecutive chapters of this Handbook.

2.2. CARBON FOOTPRINT

2.2.1. INTRODUCTION AND DEFINITIONS

The term “carbon footprint” was initially used in 2004, when a BP’s campaign demonstrated humans’ impact on the environment [1]. So, what is the carbon footprint? There are several definitions. Generally, **the carbon footprint is the total sum of greenhouse gas emissions[1] caused directly or indirectly by a person, organisation, event, process or product**.

The concept of a carbon footprint is related to the earlier ecological footprint concept developed in the early 1990s in Canada by William Rees and Mathis Wackernagel [5].

The carbon footprint measurement unit is **tCO_2e, i.e. a tonne of carbon dioxide equivalent**. It results from the fact that various greenhouse gasses exert different impact on the climate warming process. The main greenhouse gases include carbon dioxide (CO_2), methane (CH_4), dinitrogen oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFC) and perfluorocarbons (PFC). Using a single measurement unit, i.e. the (CO_2e) equivalent, facilitates comparing emissions of various gases – see Table 2.1. [3, 15].

Table 2.1.
Greenhouse gasses and their share in the greenhouse effect [15]

GREENHOUSE GAS	CHEMICAL FORMULA	EMISSION SOURCE	GWP *
Carbon dioxide	CO_2	• Combustion in stationary sources • Combustion in mobile sources • Process-related emissions, e.g. during material production	1
Methane	CH_4	• Combustion of fuels • Fugitive emissions - landfill sites, leakages from installations or tanks (natural gas), emissions from mines • Natural emissions	28 - 36
Dinitrogen oxide	N_2O	• Combustion • Fertilisers	265 - 298
Hydrofluorocarbons (HFC)	$C_XH_XF_X$	• Refrigerants • Fugitive emissions	4 - 12,400
Perfluorocarbons (PFC)	C_XF_X	• Refrigerants • Fugitive emissions	6,630 - 11,100
Sulphur hexafluoride	SF_6	• Electric energy transmission and distribution equipment	22,800

* **GWP** – Global Warming Potential, e.g. GWP for methane equal to 28 means that emission of 1 tonne of CH_4 = emission of 28 tonnes of CO_2e

Greenhouse gases are directly related to the carbon footprint, which refers to the total amount of greenhouse gas emissions generated as a result of an activity of humans, organisations, products, services or processes. The impact of individual greenhouse gases on the carbon footprint is related to their potential, in particular their GWP (Global Warming Potential) values used to determine the carbon footprint. GWP is a measure that determines the ability

1) Greenhouse gases are the gases present in the atmosphere that contribute to global warming. They are responsible for trapping heat in the atmosphere and maintaining the correct temperature on our planet. Greenhouse gas emissions are a major contributor to climate change and global warming.

of a given gas to impact global warming as compared to CO_2. The GWP value for carbon dioxide is assumed as 1, and other greenhouse gases are assigned GWP values relative to CO_2. For example, methane (CH_4) GWP value is 28 – 36, meaning that over a period of 100 years its ability to retain heat is 28 – 36 times greater than that of CO_2. Dinitrogen oxide (N_2O) GWP value is around 265 – 298 and hydrofluorocarbons (HFCs) have GWPs in the range from tens to thousands, depending on the specific compound (Table 2.1).

Introducing the GWP factor facilitates considering various greenhouse gases in the context of their impact on global warming.

Share of all greenhouse gases in total global emissions, based on data published in 2019[2]:

- Carbon dioxide – 80%
- Methane – 11%
- Dinitrogen oxide – 6%
- Hydrofluorocarbons (HFC) – 2%

Carbon dioxide (CO_2) is the major greenhouse gas exerting the most significant impact on the carbon footprint. CO_2 emissions generated by fossil fuel combustion, industrial processes and other activities account for a significant part of total global greenhouse gas emissions. Other greenhouse gases such as methane (CH_4), dinitrogen oxide (N_2O) and hydrofluorocarbons (HFCs), although emitted in smaller quantities, are highly capable of trapping heat in the atmosphere, as compared to CO_2. The effect of these gases on the carbon footprint is usually expressed as the CO_2 equivalent, taking into account their greenhouse potential and atmospheric life cycle.

Various economy sectors contribute differently to greenhouse gas emissions generated in the EU. The energy generation sector is responsible for about 77% of EU-wide GHG emissions (of which about 1/3 is transport), agriculture for about 10%, industrial processes and product use for 9% and waste management for about 3.5%.

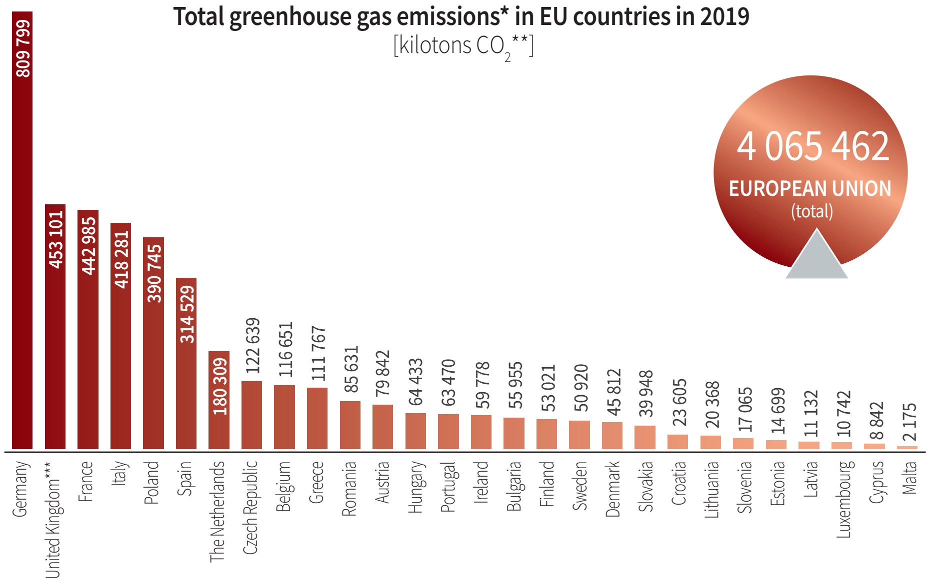
According to the 6th report of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas emissions related to human activity have contributed to climate warming by approximately 1.1°C since the beginning of the 20th century [28]. It has mainly resulted from combustion of fossil fuels such as coal, petroleum and natural gas used in such fields as energy generation, transport and industry. Other factors contributing to greenhouse gas emissions include deforestation and agriculture.

Learn more about climate change

SCAN ME!

2) All data available on official websites or in official reports published by the European Parliament.
[source: https://www.europarl.europa.eu/resources/library/images/20211026PHT15896/20211026PHT15896_original.jpg]

Figure 2.1. presents greenhouse gas emissions generated by individual EU countries. Figure 2.2. presents the largest global CO2 generators.



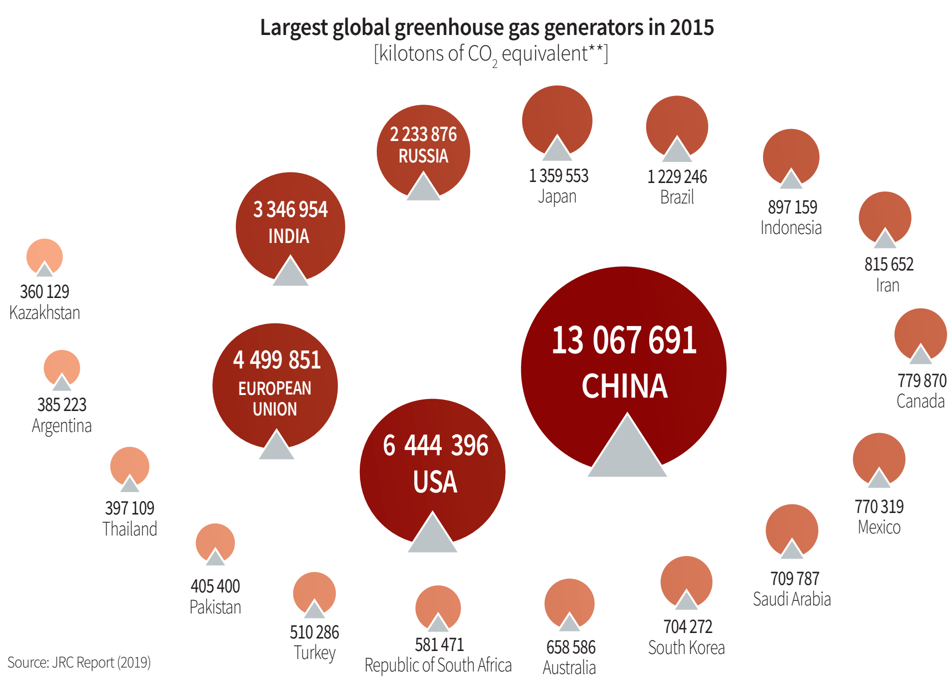
* All sectors excluding land use, land-use change and forestry (LULUCF)

** CO_2 and N_2O, CH_4, HFC, PFC, SF_6, NF_3 expressed as CO_2 equivalent

*** In 2019, United Kingdom was still part of the EU.

Source: United Nations Framework Convention on Climate Change (UNFCCC)

Fig.2.1. *Greenhouse gas emissions in individual EU countries (2019), [proprietary figure based on (29)]*



Source: JRC Report (2019)

Fig. 2.2. *Countries emitting the largest amounts of greenhouse gases in the world in 2015 [proprietary figure based on (30)]*

In Poland, data concerning emissions of carbon dioxide and other greenhouse gases is collected and analysed by KOBiZE.[3]

Learn more about CO_2 concentration level changes in the atmosphere: The American *National Oceanic and Atmospheric Administration* (NOAA) monitors greenhouse gas concentration levels in the atmosphere. NOAA has developed historical data on carbon dioxide emissions in the period from 800,000 years ago up to now.

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In line with the applicable definition, the carbon footprint can be calculated in relation to a product, service, process, company or person.

A product's **carbon footprint** describes the total greenhouse gas emissions generated during its full life cycle, expressed as the carbon dioxide equivalent per a functional unit of the product (CO_2e/functional unit), e.g. for bitumen, it could be kg CO_2e per 1 tonne of binder. **A company's carbon footprint** can also be determined as a numerical expression specifying the number of kilograms of greenhouse gases generated by a business or its activities. Such calculations usually take into account emissions of carbon dioxide, methane, dinitrogen oxide and other harmful gases, and the result is presented as a CO_2 equivalent. Obviously, **a person's carbon footprint** can also be calculated, taking into account the range of their activities, e.g. diet, electronic equipment use, travelling, etc. It is estimated that the carbon footprint of an average Pole is around 10 tonnes per year [2], an average American generates a carbon footprint amounting to 16 tonnes [6], and the global average value is approximately 4-5 tonnes [6].

Therefore, it can be concluded that the carbon footprint is a relatively broadly-defined notion. Its application is directly linked to the assumption stating that human activity (people, organisations, processes, services or manufactured products) causes climate change. Consequently, demonstrating the size of the carbon footprint associated with each of these elements is to ensure its conscious reduction.

Examples of methods to reduce the carbon footprint include buying long-lasting and reusable consumer items, repairing damaged items instead of replacing them with new ones, eating locally produced food, saving electricity, water, etc. Companies, in turn, may reduce the carbon footprint resulting from their operations by shortening supply chains, using local sub-suppliers and/or organic product manufacturers. Ultimately, implementation of the Green Deal aims to reduce the amount of greenhouse gas emissions within the European Union countries, until we achieve complete climate neutrality in 2050.

Several organisations have created on-line carbon dioxide emission calculators. They enable people to compare their own estimated carbon footprints with national and global averages.

Would you like to calculate your carbon footprint? Use the on-line calculator.

SCAN ME!

3) KOBiZE – National Centre for Emissions Management. This centre is a part of the Environmental Protection Institute – National Research Institute. Among others, KOBiZE is responsible for administering the greenhouse gas emission allowance trading system in Poland. KOBiZE also maintains a national database to collect data regarding emissions of greenhouse gases and other substances, as well as related parameters. It is responsible for conducting annual, national stock-taking activities related to emissions of greenhouse gases and other substances, and also developing reports within the framework of UNFCCC, in line with the Kioto Protocol requirements. KOBiZE is supervised by the Minister of Climate and Enviroment and is financed from the National Fund for Environmental Protection and Water Management.

2.2.2. CARBON FOOTPRINT CALCULATION

Various methodologies are adopted to calculate the carbon footprint, depending on whether they apply to carbon footprints generated by organisations, products, services or projects.

Table 2.2. presents a summary of carbon footprint calculation methods.

Table 2.2.
Standards defining carbon footprint calculation methodologies

CARBON FOOTPRINT OF ORGANISATION/PROJECT		CARBON FOOTPRINT OF PRODUCTS
GHG Protocol (GHG *GreenHouse Gas*)	• GHG Protocol A Corporate Accounting and Reporting Standard • GHG Protocol Scope 2 Guidance – An Amendment to the GHG Protocol • Corporate Value Chain (Scope 3) Accounting and Reporting Standard Supplement to the GHG Protocol Corporate Accounting and Reporting Standard	Product Life Cycle Accounting and Reporting Standard
ISO	• ISO 14064-1:2018 Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals • ISO 14064-2:2019 Greenhouse gases – Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements • ISO 14064-3:2019 Greenhouse gases – Part 3: Specification with guidance for the verification and validation of greenhouse gas statements	ISO 14067:2018 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification

Carbon footprint of organisations

The Greenhouse Gas Protocol is a global standard developed by the *World Resources Institute* (WRI) and *World Business Council for Sustainable Developmen*t (WBCSD) for organisations to measure, manage and report greenhouse gas emissions. It comprises three standards, the application of which is related to organisation's decisions and approach to the method of its carbon footprint calculation (Table 2.2). This protocol provides comprehensive guidance on identifying, measuring and reporting greenhouse gas emissions, enabling companies and other organisations to monitor and assess their impact on climate change.

The Greenhouse Gas Protocol is widely used by companies, financial institutions, non-profit organisations and other entities around the world as a standard for greenhouse gas emission monitoring and reporting. It enables organisations to accurately track their emissions, define reduction targets, identify areas of greatest impact and develop actions and strategies aimed at reducing their climate impact.

The ISO 14064 standard series also applies to greenhouse gas management, and specifically to quantifying and reporting greenhouse gas emissions and absorption. The ISO 14064 standard provides comprehensive guidance on greenhouse gas management at an organisation's level. It helps business entities to identify, quantify, monitor and report their greenhouse gas emission and absorption levels, facilitating effective management of their climate change impact. Complying with these standards helps organisations enhance their credibility, transparency and compliance with international greenhouse gas management standards.

Carbon footprint of products

A carbon footprint of products reflects the total greenhouse gas emissions during each product life cycle stage, from raw material procurement, through production, transport, utilisation, to disposal.

One of the standards used to calculate the carbon footprint is the *Product Life Cycle Accounting and Reporting Standard* developed by the *Greenhouse Gas Protocol* (GHG Protocol). This standard enables organisations to comprehensively assess the impact of their products on the climate change, taking into account emissions generated both during production processes and other product life cycle stages, e.g. delivery, use, repair or disposal.

The standard ISO 14067:2018 *(Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification)* also belongs to the group of international standards dealing with assessment and reporting of the product impact on climate change. This standard concentrates on methods for calculating product life cycle greenhouse gas emissions and specifies requirements and guidelines for declaring and reporting the results obtained.

Calculations related to product carbon footprint involve several different approaches to determining different product life cycle stages (Fig. 2.3). Correct carbon footprint calculation range selection depends on the analysis objective and data availability. In order to obtain a comprehensive overview of a product impact on greenhouse gas emissions and the environment, its full life cycle must be taken into account.

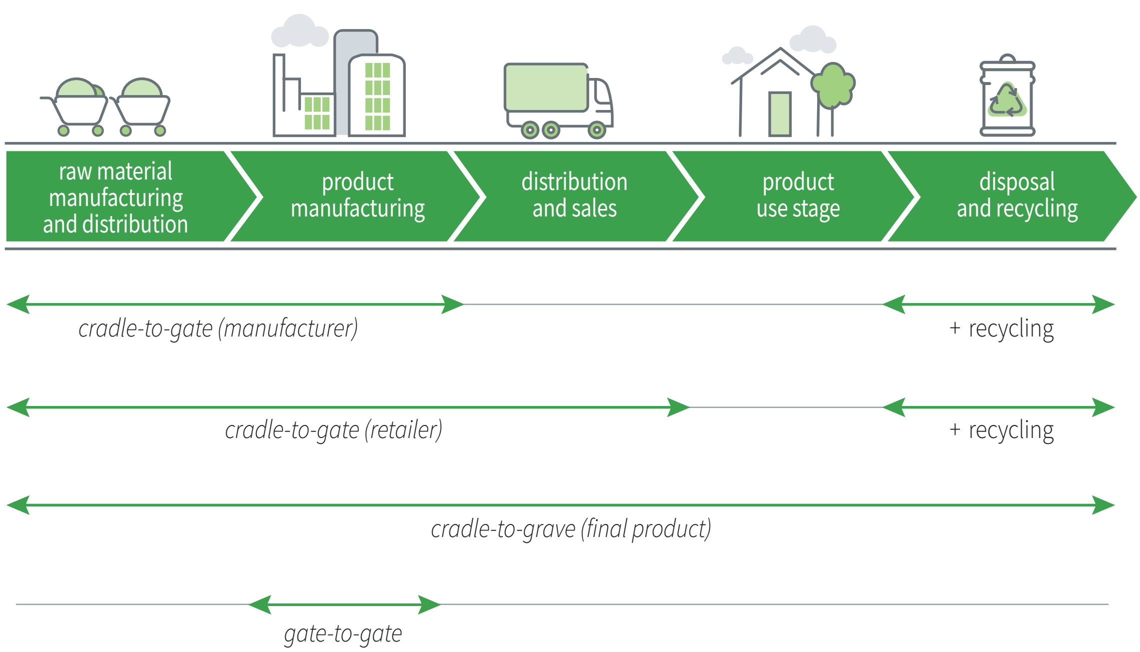

Fig. 2.3. *Stages taken into account in carbon footprint calculations [4]*

See below for a few examples of most popular product carbon footprint calculation ranges:

- cradle-to-gate – a range including greenhouse gas emission from the stage of raw material sourcing to the stage during which a product leaves a factory or manufacturing site. It does not take the product transport, use or disposal stages into account.
- cradle-to-grave – a range including all product life cycle stages, starting from raw material sourcing, through production, transport and use, to disposal or recycling. It includes both emissions directly related to a product and indirect emissions, e.g. resulting from raw material and energy supply.
- cradle-to-cradle – a range including the full product life cycle, but also concentrated on recyclability or recoverability of materials at the end of this life cycle. It includes emissions related to raw material sourcing, production, transport, use, recycling and reuse of materials.
- gate-to-gate – a range concerning only the production stage, i.e. from the moment a product leaves a factory, up to the moment it is delivered to another factory or manufacturing site. Here, other product life cycle stages are not taken into account.

For example, the cradle-to-gate variant is commonly used for B2B products, and includes the stages from raw material extraction up to the product delivery to a customer. On the other hand, the cradle-to-grave variant is the broadest range concerning B2C products, i.e. from the beginning (raw material extraction) to the end (recycling/disposal) of the product life cycle [4].

2.2.3. CARBON FOOTPRINT OF BITUMENS AND APSHALT MIXES

As we have mentioned above, depending on the life cycle range assumed for a given product, a different carbon footprint value can be obtained.

In the case of refinery manufactured products such as bitumen, their carbon footprint is relatively difficult to calculate, as the refinery is a production facility with dozens of chemical processes operated, each of which exerts an impact on the final result value.

Organisations such as *Eurobitume* periodically publish updated data regarding the bituminous binder carbon footprint. The first *Eurobitume* report containing data on bitumen manufacturing process environmental impact was published in 2012. Its latest update was published in May 2022 [27].

In order to discuss the carbon footprint of a given product, the following factors must be precisely defined: which life cycle stages will be analysed, where the analysis start and end points will be determined, which processes will be taken into account, and which of the available standards will be used to conduct calculations (Table 2.2).

The latest *Eurobitume* analysis encompasses four life cycle stages of the product, i.e. paving grade bitumen:

- petroleum mining;
- petroleum transport from a country or region where it is mined;
- bitumen production;
- bitumen storage in refinery facilities.

The calculations were conducted in the cradle-to-gate mode and the system boundaries are presented in Fig. 2.4. The research concentrates on production of 1 tonne of a bituminous binder. The LCI (Life Cycle Inventory) analysis was conducted as per ISO 14040 and ISO 14044. All calculations were conducted using the SimaPro software.

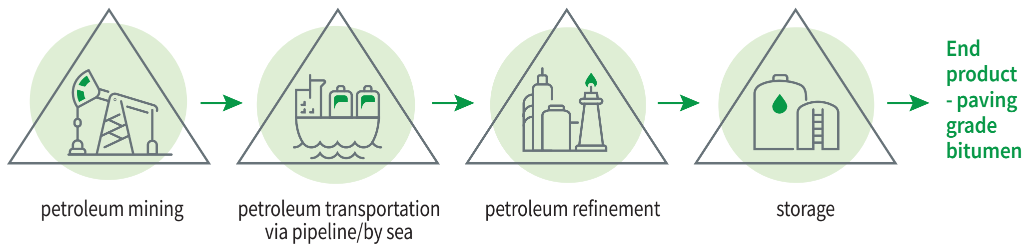

Fig.2.4. *System boundaries – cradle-to-gate approach*

Table 2.3. presents the effect of all paving grade bitumen production process stages on the end result, i.e. the environmental impact.

Table 2.3.
Potential environmental impact for the production of 1 tonne of paving grade bitumen – with infrastucture [27]

IMPACT CATEGORY	UNIT	PETROLEUM PRODUCTION	TRANSPORT-ATION	REFINERY STEP	STORAGE	TOTAL
Climate change – IPCC 2013	kg CO_2 eq	153	33.8	22.6	6.49	216
Ozone layer depletion	kg CFC^{-11}_{eq}	$8.43 \cdot 10^{-6}$	$6.48 \cdot 10^{-6}$	$5.69 \cdot 10^{-7}$	$3.08 \cdot 10^{-7}$	$2.09 \cdot 10^{-5}$
Acidification	mol H^+_{eq}	1.09	0.638	0.116	0.0266	1.87
Exploitation of resources, energy media	MJ	45,034	512	353	35.7	45,934
Photochemical ozone generation	kg $NMVOC_{eq}$	1.02	0.700	0.0492	$9,65 \cdot 10^{-3}$	1.78

As the presented data shows, in refineries, the stage related to petroleum mining and transport exerts the most considerable on the size of the carbon footprint generated by bituminous binders. However, the petroleum refinement process aimed at manufacturing bituminous binders does not impose any major environmental strain. **The total carbon footprint value calculated in line with the analysis assumptions is 208 kg CO_2 eq/1 tonne of bitumen**.

Note, however, that the values specified in Table 2.3. are not always constant and unambiguous. The carbon footprint size is influenced considerably by the assumptions made, such as how petroleum is extracted and transported to a refinery, what heating sources (fuel type, share of renewable energy sources, etc.), types of transport are used, etc. It is a very complex analysis, that can vary from one production facility to another.

On the other hand, if the entire life cycle of bitumen is considered, i.e. from the production process at the refinery, through the asphalt mix production, to recycling – the carbon footprint size is determined by subsequent processes. Figure 2.5. presents an example diagram describing individual process stages.

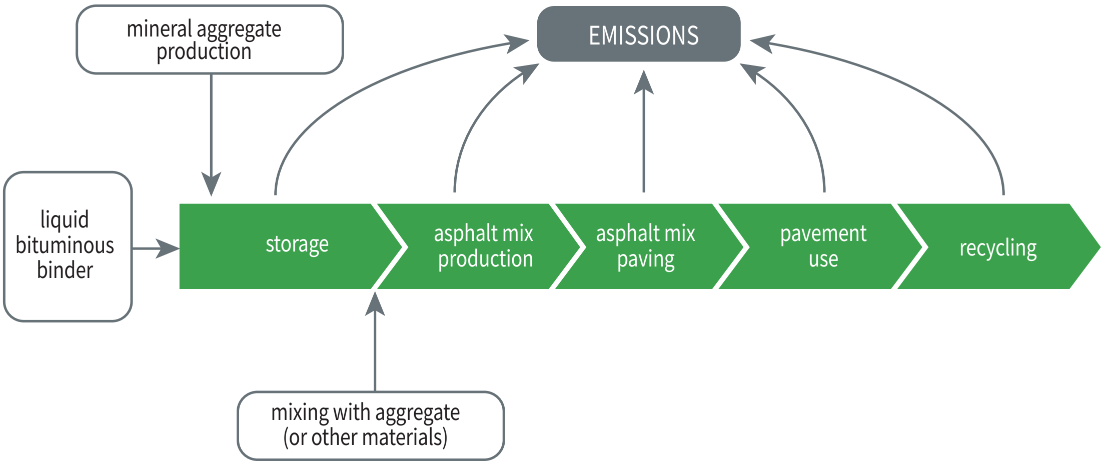

Fig. 2.5. *Stages of emissions generated by bituminous binders and asphalt mixes during life cycle [16]*

The carbon footprint is generated during each stage of the asphalt pavement construction process, i.e. raw material production (aggregate production at a quarry, bituminous binder production at a refinery, asphalt mixture's additives production), transport of materials to an asphalt mix plant, their storage prior to asphalt mix production, transport to a construction site, paving, operation, repairs and finally replacement and reuse. Therefore, these processes are very broadly-defined and each of them can be treated as a potential source of energy consumption reductions resulting in a CO_2 emission decrease.

2.3. ENERGY EFFICIENCY DURING ASPHALT MIX PRODUCTION

Production of asphalt mixes in an asphalt mix plant currently combining two elements, i.e. issues related to CO_2 emission reduction (see 2.2) and a number of actions taken to decrease energy consumption per 1 tonne of asphalt mix produced. The former element is related to the environmental impact, and the latter one is also strongly linked with economic issues.

In this chapter, mostly classic hot mix technologies are discussed, since other process solutions designed to reduce emissions and energy consumption are described in further chapters of this Handbook.

Watch the video:
"How does the Asphalt Mix Plant Work?"
(English version)

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2.3.1. ENERGY CONSUMPTION IN ASPHALT MIX PLANTS

Energy consumption during asphalt mix production generates a large part of the production costs. In addition to the asphalt mix ingredients themselves, i.e. bitumen, aggregate and additives, the energy required to heat up the ingredients, both during the temperature maintenance stage (bitumen storage in the tank) and the aggregate heating and drying stage, generates significant costs. It can be said that all methods that contribute to reducing energy requirements are worth considering.

Figure 2.6. presents a general diagram of material circulation and energy consumption during asphalt mix production in an asphalt mix plant.

The most energy-intensive processes related to asphalt mix production include:

- asphalt mix production target temperature;
- aggregate drying and heating.

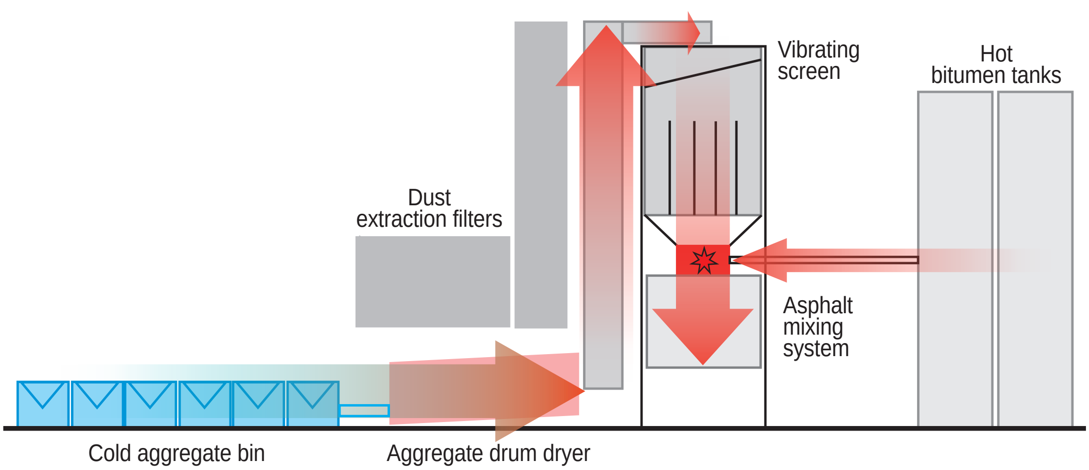

Fig. 2.6. *General diagram of material circulation in an asphalt mix plant*

See the National Asphalt Pavement Association publication discussing various aspects contributing to emission reduction in the asphalt pavement sector (English version).

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2.3.2. TEMPERATURE OF READY-MADE ASPHALT MIX

The temperature of a ready-made asphalt mix is determined either by the bitumen viscosity characteristics or, in specific cases, by the mix type, e.g. mastic asphalt (MA).

For classic bitumen, the rule of thumb is that the harder the binder, the higher the asphalt mix production temperature. It applies to paving grade bitumens and polymer modified bitumens. In the case of highly modified bitumens (HiMA) and special bitumens, the ready-made asphalt mix temperature should be adopted individually on the basis of the bitumen manufacturer's recommendations.

Various methods of specifying (testing and calculating) correct process temperatures are discussed in the Bitumen Handbook 2021 (published by ORLEN Asfalt).

Download a free copy
of the Bitumen Handbook 2021.

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While analysing the chart of energy consumption during the asphalt mix production using various technologies (from the cold-mix technology to the hot-mix technology), the economic and environmental significance of the mix temperature can be easily noticed. Note also (Fig. 2.7.) that exceeding the temperature limit of 100°C results in an abrupt increase in energy consumption related to the water evaporation process, which is accompanied by increase in CO_2 emissions. The energy demand results from latent evaporation heat, which is higher than the energy required to increase water temperature from 0 to 100°C. Therefore, exceeding the 100°C limit results in a considerable increase in energy expenditure [23].

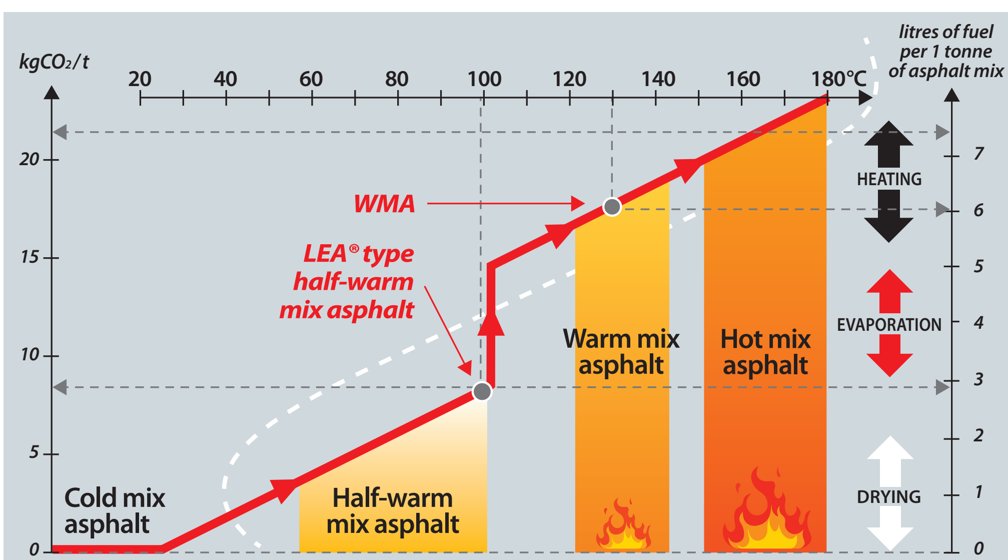

Fig. 2.7. *Final asphalt mix temperature in relation to fuel consumption and CO_2 emissions per 1 tonne of damp aggregate [23, 24]*

Due to the characteristics presented in Fig. 2.7., decreasing the asphalt mix temperature from 180°C to 115°C results in decreasing fuel consumption by 1.5 – 2.0 kg per 1 tonne of asphalt mix [9, 23]. Additionally, note that energy consumption also depends on the asphalt mix plant type. Batch type plants (most popular in Poland) consumed more energy than drum type plants.

This is because, in drum type plants, aggregate is dried and heated in the same drum where it will also be surrounded by bitumen. On the other hand, the popularity of batch type asphalt mix plants results from better production quality control and their versatility [7].

The electricity consumption (research conducted in Turkey) for the assumed asphalt mix production temperature of 160 − 165°C and annual production of 100,000 tonnes of asphalt mix (as described in the publication [25]) was 3.24 kWh/tonne of asphalt mix. In contrast, it was found that increasing the asphalt mix production temperature by 5°C results in increasing the electricity consumption by 11% [11]. Exhaust and combustion blowers in an asphalt mix plant are usually the largest electricity consumers [22].

The asphalt mix production temperature in relation to natural gas consumption can be described by the following equation [12]:

Gas consumption (m³/tonne) = 0.0935x mixing temperature (°C) - 7.6635

The summary of the presented energy savings associated with decreasing the asphalt mix production temperature, based on an analysis of various research works, leads to the conclusion that, in general, **energy savings amounting to 5.9% per each decrease in the aggregate and bitumen mixing temperature by 10°C [24] can be achieved**.

The asphalt mix production temperature is also related to the CO_2 emission value which can be estimated for various temperature values, e.g. using the equation presented in [13]:

$$C_{CO2} = 2.175\, e^{0.039\, T}$$

Where: C_{CO2} – defined as carbon dioxide concentration (in ppm) measured over 200 g of asphalt mix contained in a 200 ml flask heated to temperature T.

This equation makes it possible to estimate the reduction in CO_2 emissions resulting from decreasing the asphalt mix production temperature, as shown in Fig. 2.8.

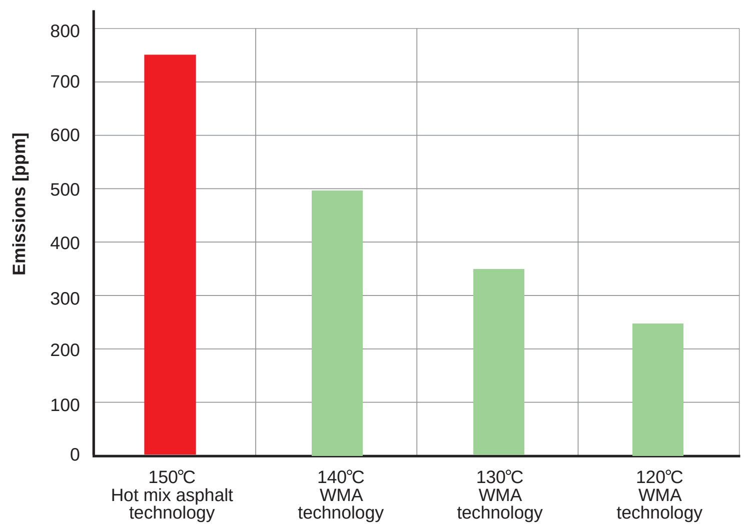

Fig. 2.8. *CO_2 emission reduction resulting from decrease in asphalt mix production temperature – comparison of standard temperatures for paving grade bitumen, i.e. 150°C and emissions resulting from a temperature decrease achieved by the application of WMA technology [13]*

2.3.3. AGGREGATE HEATING AND DRYING

Aggregate moisture is the second key factor of energy intensity for asphalt mix production (apart from the production temperature). As it has been mentioned while discussing the data presented in Fig. 2.7., the energy necessary to remove water from aggregate is quite considerable.

The water contained in the aggregate comes largely from rainfall. We have no control over the weather, but we can protect stored aggregate from rain by planning the locations of various asphalt mix plant areas, including the aggregate storage bunkers, in a way minimising the rainfall impact on aggregate moisture. It is therefore worth considering providing aggregate storage bunkers with canopies. Similarly, reclaimed asphalt (RA) should be protected as well.

Note that, as a general rule, fine aggregate has a higher moisture content than coarse aggregate (obviously, the type of rock and, more specifically, the volume of the external pores accessible to water must also be taken into account). According to that fact, if one already decides to install a canopy over a bunker, the finest fractions (below 11 mm) should be protected first. While the fine sand moisture content is 0 – 16% and 0 – 12% for coarse sand, this value for various fractions of coarse aggregate ranges from 0 to 2% (for fractions up to 20 mm). On the other hand, RA demonstrates a moisture content of around 7% [19].

As it has been mentioned earlier, the storage of aggregates on heaps, especially without canopies, results in the material soaking up water. In such cases, the ground beneath a heap must be hardened and sloped to facilitate rainwater drainage in the direction "away" from an aggregate loader (Fig. 2.9.).

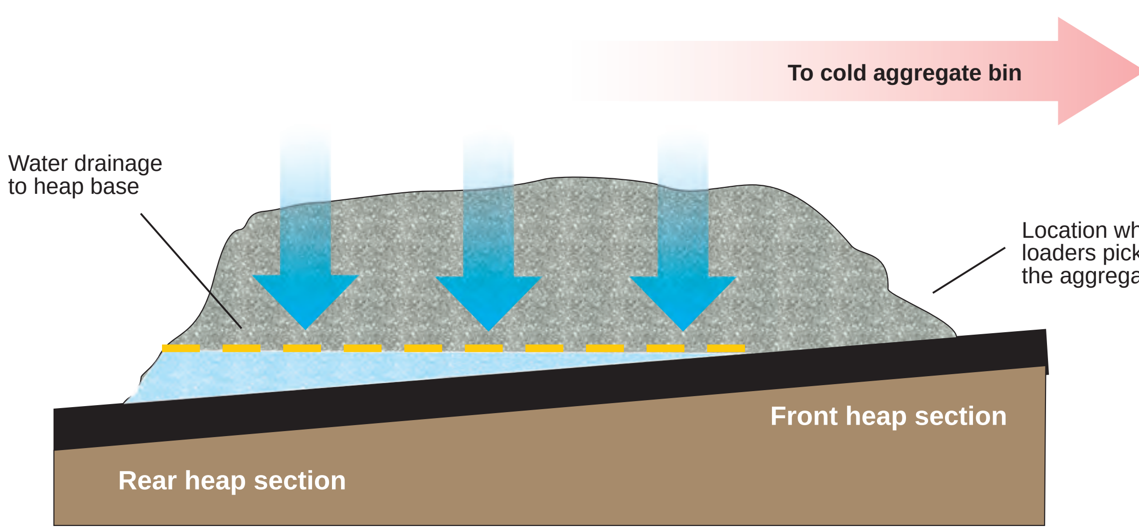

Fig. 2.9. *Correct aggregate heap drainage in the direction "away" from an aggregate loading location [20]*

Table 2.4. presents NAPA's *(National Asphalt Pavement Association)* [18] factors regarding possible energy savings resulting in decrease in aggregate moisture content.

Table 2.4.
Energy savings resulting in aggregate moisture content decrease [18]

MOISTURE CONTENT [%] BEFORE CHANGING	MOISTURE CONTENT [%] AFTER CHANGING								
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1.0	0%								
1.5	8%	0%							
2.0	15%	7%	0%						
2.5	21%	14%	7%	0%					
3.0	26%	19%	13%	6%	0%				
3.5	30%	24%	18%	12%	6%	0%			
4.0	34%	29%	23%	17%	11%	6%	0%		
4.5	38%	33%	27%	22%	16%	11%	5%	0%	
5.0	41%	36%	31%	26%	21%	15%	10%	5%	0%

Taking into account the importance of aggregate moisture content in an asphalt mix plant, it can be concluded that **lowering the aggregate moisture content by 3% results in energy savings amounting to 55 – 60% [7] or (according to another rule) increase in aggregate moisture content by 1% results in fuel consumption increase by 10% [14]. Interestingly, it can be assumed that, for an aggregate moisture content of 6%, more energy can be used to dry the aggregate than to heat it up to the paving temperature** (150°C) [19].

A few observations regarding moist aggregate:

- It is a good practice to install aggregate moisture measurement sensors that monitor this property in real time, e.g. when feeding the material from cold aggregate bin to a conveyor belt (installed at the aggregate chute from the cold aggregate bins) and provide up-to-date information to the operator.
- A typical (reference) aggregate moisture value is assumed for each asphalt mix plant to determine its nominal capacity (e.g. 160 tonnes/h). Any increase in the aggregate moisture content above the typical value results in asphalt mix plant nominal capacity reduction to the necessity to extend the time during which the aggregate passes through a drum dryer. Ultimately, this obviously results in increasing fuel consumption for aggregate drying purposes.
- Conveyor belts with aggregate collected from cold aggregate bins routed to the dryer should be covered to protect the aggregate from moisture.
- Extensive aggregate moisture fluctuations in a cold fed material can lead to variations in the asphalt mix moisture. Additionally, variations in the moisture of equal aggregate fractions can result in different temperatures of the aggregate leaving the drum dryer. That can lead to incorrect material temperatures in the mixer. Moreover, varying aggregate moisture content may result in inefficient dryer operation, e.g. over-drying already dry aggregate or under-drying another material [19].
- In the case of the RA, 3% should be the target moisture value [14].

In conclusion with combine the above-mentioned factors, i.e. asphalt mix temperature and aggregate moisture content, the research [9] has shown that decreasing the mixing temperature from 165°C to 115°C and reducing the aggregate moisture from 4% to 2% results in saving approx. 2.5 kg of fuel per 1 tonne of asphalt mix.

2.3.4. OTHER FACTORS RELATED TO ENERGY EFFICIENCY

- Dryers should be insulated. The same applies to the pipeline and bitumen tanks. No expense should be spared on providing necessary bitumen tank insulation. It can be regularly inspected with an IR camera to detect thermal bridges.

- It is good practice to paint bitumen tanks black, which improves the bitumen temperature maintenance efficiency.

- Additional bitumen tank insulation should be considered, so that, during asphalt mix plant standstills, as little energy as possible is consumed to maintain the bitumen operating temperature.

- Care should be taken to ensure that the dryer burner is correctly positioned and selected, and that the combustion zone is properly sized.

- Adequate air flow in the burner is important for dryer energy consumption efficiency, as it ensures complete fuel combustion. An excessive air flow results in increased smoking and heat escape. Conversely, an insufficient air flow prevents full fuel combustion, which results in low fuel efficiency.

- Preliminary aggregate bins feed cold and wet fractions, and the energy consumption for drying and heating is strongly dependent on precipitation and ambient temperature.

- A waste gas flue discharges significant amounts of thermal energy. The waste gas flow contains a considerable energy potential that can, and should be exploited.

- Any standstill and necessity to restart a plant generates additional energy consumption amounting to 20% – 35% [8] plus additional CO_2 emissions.

- Technical condition inspections of the burners, parallel drum and gas ducts during operation, as well as cleaning of the gas ducts, the outlet area in front of the burner and scraper blades in the parallel drum, will certainly contribute to enhancing asphalt mix plant performance [14].

Watch the National Asphalt Pavements Association video on sustainable asphalt pavements (English version).

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Finally, see below for 10 guidelines ensuring asphalt mix plant performance and effectiveness enhancement [26]:

1. Keep the facility, equipment and fuel clean.
2. Make sure that the plant and equipment are insulated.
3. Provide guards and ensure storage site sloping to keep the aggregate dry.
4. Consider replacing obsolete, less efficient equipment with new machinery.
5. Plan regular equipment maintenance intervals.
6. Hold regular, formal and informal, conversations with the personnel (operators).
7. Develop a safety plan and train the personnel on safety procedures.
8. Provide the personnel with high-quality personal protective equipment.
9. Plan strategically.
10. Consider organising a professional audit to identify areas where asphalt mix plant performance can be improved.

III. WMA BITUMENS

#WMA, #Warm Mix Asphalt

3.1. INTRODUCTION

Currently, there are no formal limits imposed in the European Union concerning the application of hot mix asphalt technology, but numerous countries voluntarily take actions aimed at increasing the share of warm-mix and half-warm-mix technologies in the total asphalt mix production. Norway is a good example, as it has introduced bonuses for companies constructing pavements using asphalt mixes manufactured at a temperature reduced by at least 25°C in comparison with the hot mix asphalt technology. As a result, since 2013, the production volume for WMA asphalt mixes has increased almost fivefold [1].

According to the 2021 data published by EAPA (European Asphalt Pavement Association), USA is still the global leader in WMA technology application. Almost 50% asphalt mixes generated in the USA are manufactured using the WMA technology. In Europe, the WMA technology is becoming increasingly popular with the largest share of its application in France, the Netherlands and Norway, as well as Belgium (since 2021) [1]. In Poland, however, this technology is not currently popular.

The ever-changing macroeconomic environment and new EU regulations stimulate the entire road construction industry to look for solutions that will reduce the environmental impact exerted by this industry. The very process of asphalt mix production shows great potential to reduce energy consumption and emissions of harmful compounds into the atmosphere. This chapter contains information regarding the WMA technology being one of the ORLEN Asfalt responses to evolving economic requirements connected with road pavement construction.

3.2. WMA TECHNOLOGY

The WMA (***W****arm* ***M****ix* ***A****sphalt*) technology encompasses a series of solutions ensuring decrease in temperatures during such processes as asphalt mix production, paving and compaction.

During the standard hot mix asphalt production process, it is necessary to heat up the mix components, i.e. aggregate and bitumen, to a sufficiently high temperature, generally ranging from 160 to 180°C. The aggregate must be heated up to remove water and ensure better bitumen adhesion to the aggregate; on the other hand, heating up the bitumen is aimed at lowering its viscosity, which ensures improved adhesion and correct coverage of aggregate grains with bitumen. However, water contained in the aggregate can be evaporated already at temperatures exceeding 100°C (Fig. 2.7). Heating up the aggregate above 150°C is only intended to adjust its temperature to the bitumen operating temperature. High bitumen temperature is in turn related to its viscosity. Therefore, if we are able to use a lower viscosity bituminous binder at a lower temperature, then we can simultaneously lower the aggregate temperature. This would result in saving the energy required to heat up the mix components.

In order to better understand how WMA mixes operate, it is necessary to analyse the entire process of asphalt mix producing, paving and compacting, and to consider the bitumen role in each of these stages.

Basically, a bitumen has three main functions in an asphalt mix. Firstly, there is the "liquid" function, which means that, at the initial stage of the asphalt mix production process, a bituminous binder must demonstrate sufficiently low viscosity to be able to coat the aggregate. It is assumed that bitumen viscosity during the aggregate coating process should be approximately 0.2 Pa·s [3]. It ensures efficient coverage of all the aggregate in an asphalt mix plant mixer with bitumen. Subsequently, transporting the produced asphalt mix to paving site results in a temperature drop and increase in bitumen viscosity. On a paving site, the second bituminous binder function in an asphalt mix begins. This is the "lubricant" function, which means that bitumen viscosity should be at such a level that it is possible for a spreader to spread the asphalt mix without any problems, i.e. the viscosity level guarantees the mix cohesion. On the other hand, the final asphalt mix compaction on the road requires the binder to allow aggregate to slip and to be laid under a roller. It is assumed that the maximum bitumen viscosity level at which effective asphalt mix compaction is competed is approximately 20 Pa·s [3]. Finally, the bitumen in a mix acts as an "adhesive". Therefore, once the mix has been compacted on the road, the bitumen should effectively bond aggregate to avoid various types of damage during the pavement life cycle.

Fig. 3.1 presents a diagram describing bitumen functions in an asphalt mix.

Fig. 3.1. *Bitumen's role in asphalt mix*

The role of bitumen in asphalt mix depends on its viscosity, which in turn varies along with the temperature. The lower the bituminous binder temperature that can be achieved at the very beginning of the process (aggregate and bitumen mixing in an asphalt mix plant), the lower the temperature of the entire process will be, which directly translates into higher energy savings.

Fig. 3.2. presents an example of bitumen viscosity change in relation to the temperature. Note also that, in order to mix bitumen with aggregate, the bitumen viscosity tested before ageing (RTFOT) must be taken into account, and to assess the beginning and end of the asphalt mix compaction process, the viscosity tested after ageing (RTFOT) must be considered.

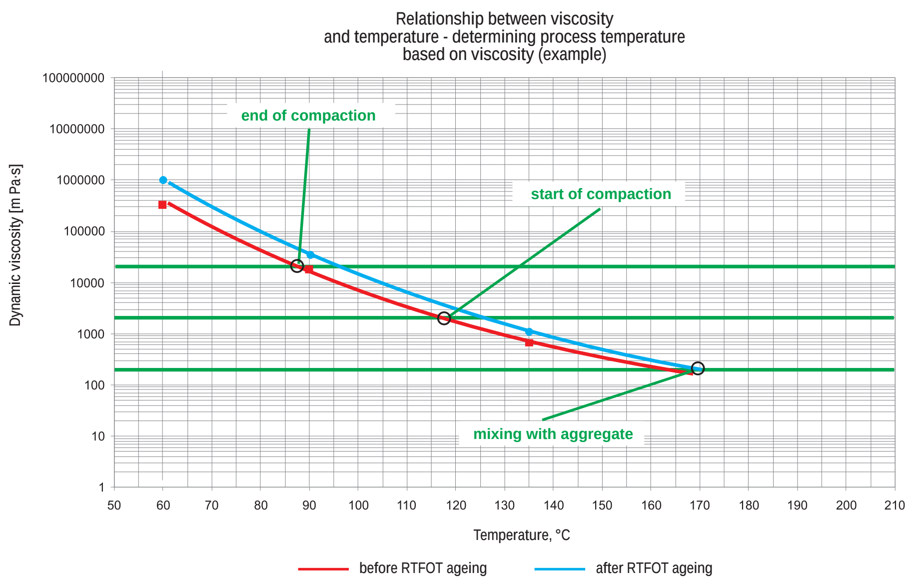

Fig. 3.2. *Relationship between viscosity and temperature for bitumen (example)*

In the road construction industry, different technologies for producing asphalt mixes depending on the temperature (Fig. 3.3) are employed. The cold-mixes (Cold Asphalt) depicted in the chart are most often produced from bitumen emulsions (see Chapter 5 for more details on the cold-mix technology).

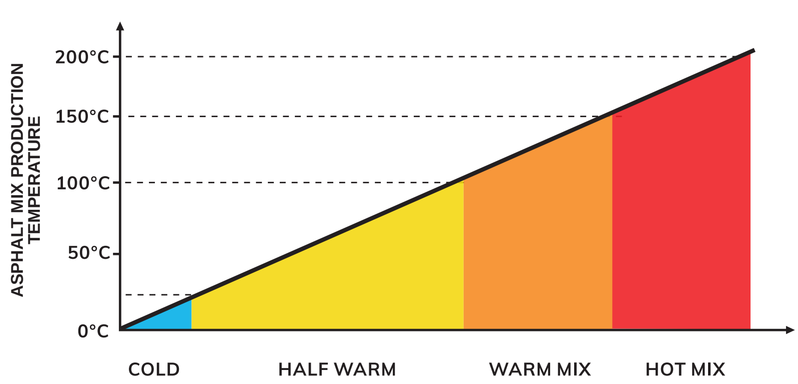

Fig.3.3. *Temperature ranges for production of various types of asphalt mixes*

HMA (**H***ot* **M***ix* **A***sphalt*) is the most popular, but the most energy-intensive, asphalt mix. The hot mix asphalt temperature usually is approximately 160 ÷ 180°C. Fig. 3.3. shows that it is possible to manufacture a WMA at temperatures lower by approximately 10 − 30°C than standard hot-mixes. One of the main advantages of WMA is the possibility of decreasing the consumption of energy necessary to heat up its main components, i.e. aggregate and binder.

3.3. WMA APPLICATION VARIANTS

When discussing the WMA technology, the benefits of decreasing the temperature of an asphalt mix production and the pavement construction process are most often pointed out. There is also another variant concerning the use of mixes with WMA additives produced at a standard, unchanged temperature, as for the hot mixes. Here, asphalt mix workability and compactability is improved, which makes it possible to extend the road construction period into the autumn and winter months when weather conditions are quite adverse.

Fig. 3.4. presents different variants of the WMA technology.

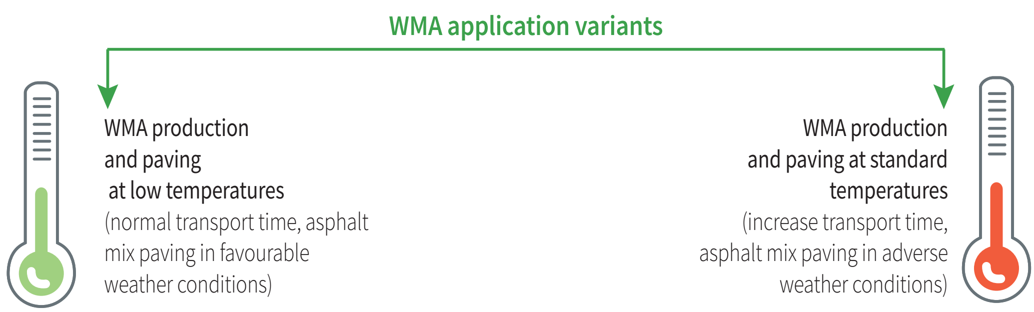

Fig. 3.4. *WMA technology variants*

WMA technology variants are associated with specific functionalities and limitations defined for each variant application. For example, standard WMA produced at reduced temperatures ensure reductions in energy consumption, emissions or bitumen short-term ageing. Not, however, that such mixes should be paved in good weather conditions and the construction site should be at a suitable distance from a paving plant.

Conversely, mixes with WMA additives produced at standard temperatures demonstrate improved workability and compactability as compared to standard hot mixes (without WMA additives), so they can be paved during adverse weather conditions. They can also be transported over longer distances as compared to mixes without WMA additives. In this case, we no longer consider improving the environmental aspects of using WMA technology, but only their process-related and quality aspects.

Note also that the presented WMA technology application variants should not be combined with each other. It means that it is quite unreasonable produce an asphalt mix at 130°C and pave it under adverse weather conditions, e.g. at temperatures below 0°C, which may even result in serious problems at a construction site.

See Table 3.1. for a summary of two WMA technology application variants and requirements related to each variant.

Table 3.1.
WMA technology variants

WMA PRODUCTION AND PAVING AT LOW TEMPERATURES	WMA PRODUCTION AND PAVING AT STANDARD TEMPERATURES
• asphalt mix paving in favourable weather conditions • normal transport time • lower energy consumption (by approx.20 – 30%) • emission reduction by up to 90% • carbon footprint reduction • personnel work comfort improvement • bitumen short-term ageing reduction	• asphalt mix workability and compactability improvement • asphalt mix paving in adverse weather conditions • asphalt mix transport over longer distances • no effect related to reduction of energy consumption, emissions and carbon footprint • standard bitumen ageing process

So far, WMA type binders have mainly been used during the cold months to improve asphalt mix workability facilitate compaction at low ambient temperatures. The option to decrease asphalt mix production temperature in favourable weather conditions has not been exploited, because the gain associated with reduced energy consumption was not as significant as compared to the WMA additive costs. However, the change in energy prices makes the process more cost-effective. It has already been determined that a temperature reduction by 30°C can significantly reduce fuel consumption (see section 2.3). Taking into account the current energy prices, it is worth considering using the WMA technology, as the cost of WMA additives may be lower than the cost of heating up a mix by another 10 – 30°C.

The WMA technology is particularly suitable:

- when asphalt mixes in **unfavourable weather conditions** or in locations where air circulation is limited;
- in case an asphalt **mix must be transported over longer distances**;
- in case of a reduction in **energy consumption** as well as in gas and dust emissions;
- in case of the necessity of improvement of asphalt mix **workability and compactability**.

3.4. METHODS TO DECREASE ASPHALT MIX PRODUCTION TEMPERATURE

The asphalt mix production temperature reduction can be achieved in the following manner:

- by using bitumen additives (WMA additives);
- by foaming the bitumen in the presence of water.

Chemicals added to bituminous binders include:

- viscosity-reducing additives (over the entire or partial temperature range) – the largest group of bitumen viscosity modifiers are organic additives with long hydrocarbon chains. They include various types of waxes or compounds from the fatty acid amide group. When dissolved in the bitumen, such additives exhibit very low viscosity, thus reducing the overall mix viscosity;

- surfactants (improving aggregate wettability through the bitumen) – additives that act at the interface between the aggregate and bitumen. They reduce the surface tension at the bitumen-aggregate interface; such agents adjust the frictional force between the aggregate and bitumen; in other words, the aggregate moves more easily in the mix because these compounds act as a lubricant, making the process of aggregate coating with bitumen more efficient. They include such chemical compounds as phosphate esters, ethoxylated alcohols and polyethylamines. The surfactant effect (Fig. 3.4) consists in reducing the contact angle, i.e. the smaller the contact angle at the drop-surface interface, the better the coverage efficiency:

Fig. 3.5. *Surfactant effect [proprietary figure, based on (5)]*

There are two methods to batch WMA additives into bituminous binders:

- mixing bitumen with a WMA additive in a refinery, during the bitumen production process;
- mixing bitumen with a WMA additive in an asphalt mix plant, during the asphalt mix production process. Each of the above methods comes with certain pros and cons which are summarised in Table 3.2.

Table 3.2.
Summary of advantages and disadvantages of different WMA additive batching methods

	BATCHING A WMA ADDITIVE IN A REFINERY DURING THE BITUMEN PRODUCTION	BATCHING A WMA ADDITIVE IN AN ASPHALT MIX PLANT, DURING THE ASPHALT MIX PRODUCTION
Advan-tages	• homogeneous, well-mixed product • resulting WMA binder complies with the requirements of the relevant EN standard • no need to equip an asphalt mix plant with special batch meters	• WMA additive is batched during asphalt mix production; WMA is not stored in a tank, which results in no necessity to use it within a certain period of time
Disad-vantages	• bitumen must be used within a certain time after delivery[a]	• asphalt mix plant must be equipped with special batch meters • risk of inaccurate WMA mixing

a) – depending on the WMA additive used, its durability over time is determined by the manufacturer and is generally dependent on the storage time and WMA temperature in the asphalt mix plant tank.

The second method of producing a reduced-viscosity bitumen is the "foamed bitumen" technology based on the phenomenon of rapid hot bitumen foaming after adding water to it. This process creates bitumen foam with a very high volume and low viscosity, allowing aggregate to be coated at reduced temperatures. Note, however, that adapting an existing asphalt mix plant to producing foamed bitumen involves purchasing specific components that will allow water to be added to the asphalt mix. Ready-made technologies, such as ASTEC Double Barel Green or LEA (Low Energy Asphalt) can also be employed.

The foamed bitumen technology is not discussed further in this study. Readers interested in this subject should refer to applicable technical publications.

3.5. WMA BITUMEN PROPERTIES

WMA – these are bitumens with special additives batched during the production stage in a refinery, which facilitate **asphalt mix production at reduced temperatures** (first variant) in comparison with the hot mix asphalt, or **improve asphalt mix workability and compactability** during placement, when the asphalt mix is produced at standard, not reduced, temperatures (second variant).

The ORLEN Asfalt currently offers:
- paving grade bitumen WMA (35/50 WMA, 50/70 WMA);
- highly modified bitumen ORBITON HiMA WMA (ORBITON 25/55-80 HiMA WMA, ORBITON 45/80-80 HiMA WMA).

The modified bitumen ORBITON PMB WMA will be available shortly.

3.5.1. WMA PAVING GRADE BITUMEN

Paving grade bitumens 35/50 WMA and 50/70 WMA offered by ORLEN Asfalt are manufactured in accordance with the EN 12591 standard. Their standard properties are the same as for typical paving grade bitumens.

Table 3.3. presents requirements regarding paving grade bitumen WMA, according to information provided in the National Annex to PN-EN 12591:2010.

Table 3.3
Requirements for paving grade bitumen 35/50 and 50/70 in Poland, penetration values from 20 × 0.1 to 220 × 0.1 mm, acc. to the National Annex to the PN-EN 12591:2010 standard

PROPERTY		TEST METHOD	UNIT	PAVING GRADE BITUMEN TYPE	
				35/50 WMA	50/70 WMA
Properties applied to all paving grade bitumen types specified in this table	Penetration at 25°C	EN 1426	0.1 mm	35-50	50-70
	Softening point	EN 1427	°C	50-58	46-54
	Resistance to hardening at 163°C	EN 12607-1 (RTFOT method)			
	Retained penetration		%	≥ 53	≥ 50
	Increase in softening point		°C	≤ 8	≤ 9
	Change of mass* (absolute value)		%	≤ 0.5	≤ 0.5
	Flash point	ISO 2592	°C	≥ 240	≥ 230
	Solubility	EN 12592	% (m/m)	≥ 99.0	≥ 99.0
Properties associated with regulatory or other regional	Penetration index	EN 12591 Annex A	—	NR	NR
	Dynamic viscosity at 60°C	EN 12596	Pa · s	NR	NR
	Fraass breaking point	EN 12593	°C	≤ - 5	≤ - 8
	Kinematic viscosity at 135°C	EN 12595	mm²/s	NR	NR

* – change of mass may be a positive or negative value
NR (No Requirement) indicates that there are no requirements for a specific property.

The paving grade bitumen WMA is recommended for the same applications as their equivalents demonstrating the same hardness values. Due to the risk of rutting, the use of paving grade bitumen WMA should always be preceded by testing the mix resistance to rutting, according to EN 12697-22 (method B, small-size apparatus, in the air, temperature +60°C, 10,000 cycles). The above refers especially to road sections located within crossroad zones, slow traffic zones, parking zones, etc.

3.5.1.1. Asphalt mix test results

Fig. 3.6. presents the rutting resistance test results for paving grade bitumen WMA. The tests were performed using the AC 16 for the binder course. The results show that WMA bitumen retains good rutting resistance, but it is recommended that this test should be performed to verify this property, particularly for asphalt mix used for more heavily loaded pavements.

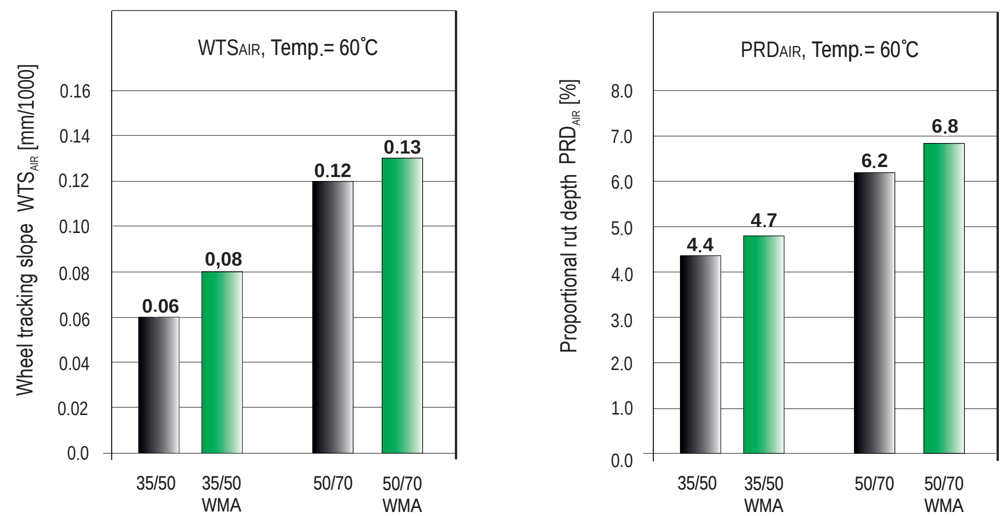

Fig. 3.6. *Rutting resistance test results for paving grade bitumens 35/50 WMA and 50/70 WMA, [proprietary tests, ORLEN S.A.]*

3.5.1.2. Paving grade WMA bitumen applications

See below for typical applications of paving grade bitumens: 35/50 WMA and 50/70 WMA.

Paving grade bitumen 35/50 WMA can be used to produce asphalt concrete (AC) for base and binder courses (medium to very heavy traffic load), or for wearing courses as mastic asphalt (MA) for roads designed to carry light and medium traffic load. Bitumen 35/50 WMA should not be used in wearing courses (except for the MA).

Paving grade bitumen 50/70 can be used primarily for asphalt concrete and SMA in wearing courses (light and medium traffic load), provided that the asphalt mixture complies with the requirements concerning rutting resistance. Using the bitumen 50/70 WMA to pave base and binder courses also requires verification the rutting resistance (medium traffic load). It is not recommended that bitumen 50/70 WMA should be used to produce any course of pavement designed to carry heavy and slow traffic load (slow lanes, approaches to crossroads, etc.).

3.5.1.3. Asphalt mix production temperatures

Table 3.4. presents suggested temperatures for production and compaction of asphalt mixes in which paving grade WMA bitumen was used.

Table 3.4.
Temperatures for production of asphalt mixes with paving grade WMA bitumen

TYPE OF PAVING GRADE WMA BITUMEN ACC. TO EN 12591	SAMPLE COMPACTION TEMPERATURE DURING TYPE TESTING 1) 2) 3) 4)	BITUMEN TEMPERATURE IN TANK IN ASPHLAT MIX PLANT 5) FOR ASPHALT MIX PRODUCTION	ASPHALT MIX TEMPERATURE DIRECTLY AFTER UNLOADING FROM MIXER 4) 6)	INITIAL ASPHALT MIX TEMPERATURE DURING COMPACTION 4) 6)	FINAL ASPHALT MIX COMPACTION TEMPERATURE
	[°C]	[°C]	[°C]	[°C]	[°C]
35/50 WMA	120÷125	160÷165	140-150 6)	135-140 6)	100
50/70 WMA	120÷125	155÷165	140-150 6)	135-140 6)	100

1) Temperatures recommended by the manufacturer can be adjusted according to the contractor's experience.
2) The specified temperature ranges for compaction of samples in the laboratory applies to the "warm-mix" technology.
3) Compaction of samples taken from coarse-grained asphalt mixes and asphalt mixes embedded in thick process courses with high heat capacity requires determination of the individual sample compaction temperature in the laboratory, on the basis of previous experience and anticipated placement conditions.
4) The specified process temperatures apply to rolled mixes (AC, SMA, BBTM, PA, etc.). For mastic asphalt (MA), the process temperatures should be applied on the basis of the asphalt mix workability test conducted in a laboratory.
5) The storage time at the process temperature should not exceed 7 days. In case the storage time is exceeded, the bitumen properties improving the mix workability may deteriorate. After this time, it is recommended that the bitumen should be handled in the same manner as conventional paving grade bitumens.
6) The amount of temperature reduction should depend on weather conditions. If the air temperature below is 10°C and/or strong winds occur, the asphalt mix temperature should not be lowered. In such cases, paving grade bitumen WMA should be used in the same temperatures as for the hot-mix technology (to improve mix workability and compactability).

3.5.1.4. Paving grade WMA bitumen test section

An experimental road section with paving grade bitumen 35/50 WMA was constructed in September 2021, in the town of Jastrzębie, in the Kujawsko-Pomorskie Voivodeship, on district road no. 1829.

In this section, a 4 cm binder course (AC 16) with bitumen 35/50 WMA was paved. Section length – 430 metres.

- Weather conditions during construction: air temperature: +18°C, no precipitation, sunny, light wind.
- Asphalt mix temperature in the asphalt mix plant: reduced by 20°C in relation to the standard value (140 – 150°C).
- Asphalt mix temperature during course compaction: measured behind the spreader – 135 -140°C.
- Notes: no problems during paving and compacting processes.

Photos related to this project are shown in Fig. 3.7. – 3.8.

Fig.3.7. *Experimental road section with bitumen 35/50 WMA constructed in 2021; measurement of the binder course temperature behind a spreader [photo K. Niemyjski, ORLEN S.A.]*

Fig.3.8. *Experimental road section with bitumen 35/50 WMA constructed in 2021; measurement of the binder course temperature behind a spreader [photo K. Niemyjski, ORLEN S.A.]*

3.5.2. ORBITON HiMA WMA

Information video – ORBITON HiMA WMA

SCAN ME!

Highly modified bitumen ORBITON HiMA WMA combines the HiMA (*Highly Modified Asphalt*) and WMA (*Warm Mix Asphalt*) technologies initially developed in Poland by the Research, Development and Innovation Department at ORLEN Asfalt.

Highly modified bitumens (HiMA) are the highest class bitumen currently available on the Polish market. These are bitumens containing over 7% m/m of the special SBS polymer. The elastomer content ensures a phase reversal in the bitumen/polymer mix, which results in the fact that the polymer determines the binder properties (Fig. 3.9). In order to understand the highly modified bitumen operation principle, one must be aware of the fact that, in HiMA binder, the polymer (but not the bitumen) is the factor which ensures key bitumen characteristics. Here, a certain type of a synthetic binder is referred to.

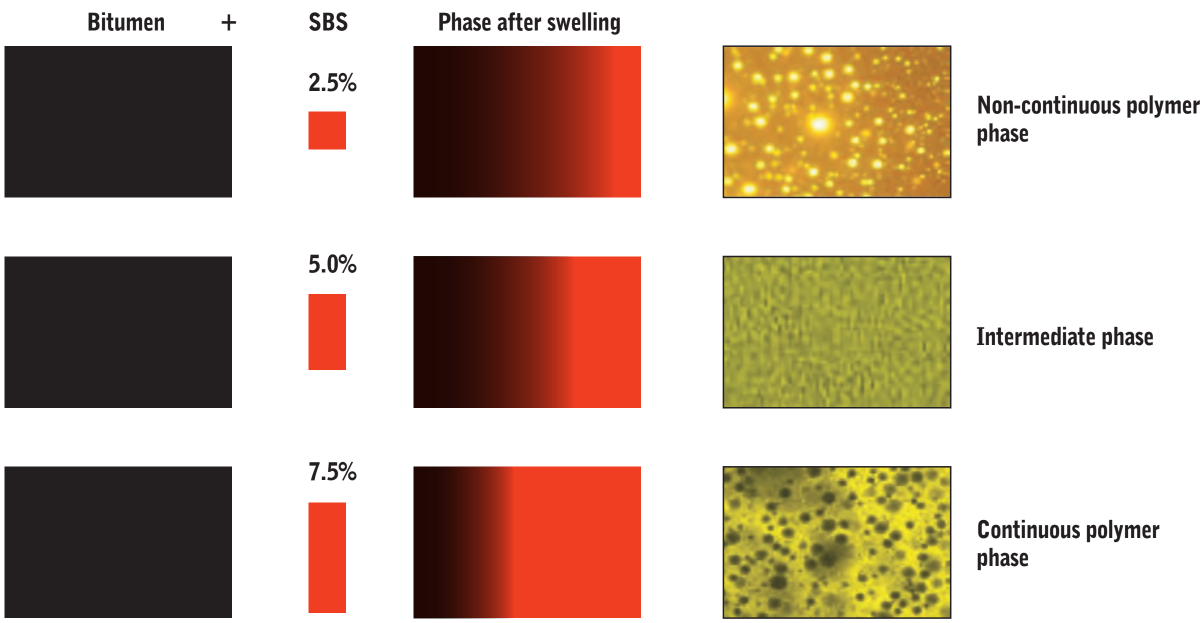

Fig. 3.9. *Volume proportions between bitumen and polymer in a typical polymer modified bitumen – PMB (2.5 – 5.0% m/m) and in highly modified bitumen – HiMA (7.5% m/m) [Kraton Polymers, 2018]*

ORBITON HiMA WMA (similarly to ORBITON HiMA) is a binder with an inverted polymer-bitumen phase, additionally containing special additives to improve workability and compactability of asphalt mixes created with them.

ORLEN Asfalt currently offers two types of the highly modified bitumens ORBITON HiMA WMA:

ORBITON 25/55-80 HiMA WMA
ORBITON 45/80-80 HiMA WMA

3.5.2.1. Bitumen testing

ORBITON HiMA WMA are classified according to EN 14023 and the National Annex to this standard published in Poland in 2020. Their properties are analogous to classic highly modified bitumens of the same consistency (penetration).

Table 3.5. presents a set of standard properties characterising the ORBITON HiMA WMA binders.

Table 3.5.
ORBITON HiMA WMA binder acc. to National Annex (NA), table NA.2, to the PN-EN 14023:2011/Ap2:2020-02 standard

PROPERTY		TEST METHOD	UNIT	ORBITON 25/55-80 HIMA WMA		ORBITON 45/80-80 HIMA WMA	
				REQUIREMENT	CLASS	REQUIREMENT	CLASS
Penetration at 25°C		EN 1426	0.1 mm	25-55	3	45-80	4
Softening point		EN 1427	°C	≥ 80	2	≥ 80	2
Cohesion	Force ductility tested using ductilometer (50 mm/min)	EN 13589 EN 13703	J/cm²	≥ 0.5 at 15°C	8	≥ 2.0 at 10°C	6
Resistance to ageing	Change of mass	EN 12607-1	%	≤ 0.5	3	≤ 0.5	3
	Retained penetration		%	≥ 60	7	≥ 60	7
	Increase in softening point		°C	≤ 8	2	≤ 8	2
Flash point		EN ISO 2592	°C	≥ 235	3	≥ 235	3
Fraass breaking point		EN 12593	°C	≤ -15	7	≤ -18	8
Elastic recovery at 25°C		EN 13398	%	≥ 80	2	≥ 80	2
Drop in softening point after EN 12607-1		EN 1427	°C	TBR	1	TBR	1
Elastic recovery at 25°C after EN 12607-1		EN 13398	%	≥ 50	4	≥ 60	3
Storage stability Difference in softening point		EN 13399 EN 1427	°C	≤ 5	2	≤ 5	2

Table 3.6. presents dynamic viscosity values obtained in the laboratory tests conducted for ORBITON HiMA WMA binders (before and after RTFOT ageing). However, given the unusual characteristics of all HiMA type bitumens resulting from the bitumen-polymer phase reversal, the viscosity-temperature characteristics thus determined should be regarded as approximate.

Table 3.6.
Examples of dynamic viscosity test results for ORBITON HiMA WMA binders

BINDER TYPE	DYNAMIC VISCOSITY ACC. TO EN 13302 [PA·S]							
	BEFORE RTFOT				*AFTER RTFOT*			
	60°C	90°C	135°C	160°C	60°C	90°C	135°C	160°C
ORBITON 25/55-80 HiMA WMA	—	1,285.00	4.260	0.82	—	2,538.00	6.83	1.29
ORBITON 45/80-80 HiMA WMA	31,100.00	290.00	2.50	0.53	69,500.00	990.00	4.36	0.81

See below for the results of the functional property tests for ORBITON HiMA WMA binders obtained according to the AASHTO M320/M332 standard.

Low-temperature property testing

The low-temperature behaviour of the bitumen was tested using a *Bending Beam Rheometer* (BBR) – see Fig. 3.10. The tests were according to EN 14771 and AASHTO PP 42 on samples subjected to ageing with the RTFOT and PAV methods.

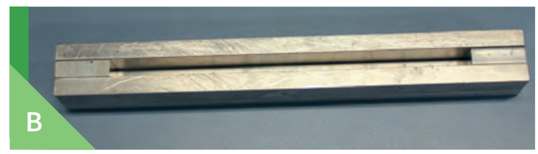

Fig. 3.10. *A) Bending Beam Rheometer, BBR, B) mould for sample preparation (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)*

Table 3.7. shows the results of low-temperature testing of bituminous binders in accordance with AASHTO M320/M332.

The following measurement results were presented:

- lower critical temperature (LCT) at which the creep stiffness is 300 MPa ⟶ $T(S_{(60)}=300\ MPa)$,
- lower critical temperature (LCT) at which the parameter m-value is 0.300 ⟶ $T(m_{(60)}=0.300)$.

Table 3.7.
Low-temperature property test results for ORBITON HiMA WMA [proprietary research, ORLEN Asfalt]

BITUMEN TYPE	LOWER CRITICAL TEMPERATURE LCT [°C]		LCT(S) – LCT(M) DIFFERENCE
	TEMPERATURE T AT WHICH CREEP STIFFNESS IS 300 MPA	TEMPERATURE T AT WHICH PARAMETER M IS 0.300	
	$T (S_{(60)}= 300\ MPA)$, [°C]	$T (M_{(60)} = 0.300)$, [°C]	ΔTc
INTERPRETATION	*less = better*		
ORBITON 25/55-80 HiMA WMA	-12.6	-17.4	4.8
ORBITON 45/80-80 HiMA WMA	-17.5	-21.9	4.5

High-temperature property testing – MSCR test

The high-temperature properties of bituminous binders were tested using the MSCR (*Multiple Stress Creep Recovery*) method. The test is performed in a dynamic shear rheometer (DSR) (Fig. 3.11.) on samples after RTFOT ageing. The test results are used to determine the effect of a given bitumen on the asphalt mix rutting resistance and, in the case of PMB, assess the level of elasticity (modification efficiency) of the material.

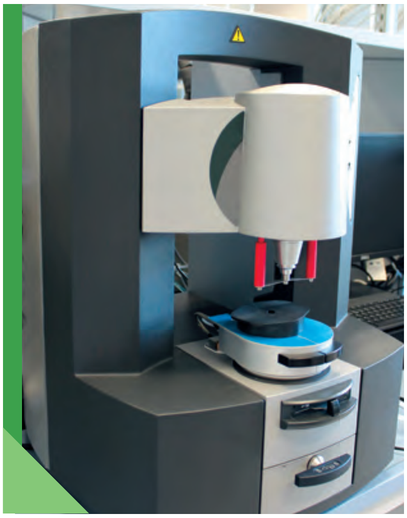

Fig. 3.11. DSR (photo: ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.)

The MSCR test results in the form of two parameters:

- J_{nr} [kPa^{-1}] – non-recoverable creep compliance (under cyclic shear conditions in DSR) – direct indicator of the bituminous binder rutting resistance, determined for two stress levels, i.e. 0.1 kPa and 3.2 kPa;
- percent value of recovery R [%] – an indicator of binder elasticity at a given temperature, determined for two stress levels, i.e. 0.1 kPa and 3.2 kPa.

(Test conducted at **76°C**). See Table 3.8.

The table also presents additional parameters calculated on the basis of the two above-mentioned parameters and R, i.e. $J_{nr,diff}$ and R_{diff}, which are, respectively, indicators of the susceptibility of the bituminous binder to increasing load and the change in elasticity of the binder under increasing load, respectively.

For the ORBITON HiMA WMA binder, the obtained results J_{nr} are so small at the testing temperature (76°C) that they do not fall within the precision range of the MSCR method; therefore, $J_{nr,diff}$ values were not calculated for them.

Table 3.8.
MSCR test results – parameters: J_{nr} [kPa^{-1}] and R [%], obtained at the stress of 0.1 and 3.2 kPa at 76°C, samples after RTFOT. Interpretation: the lower the J_{nr} value, the higher the rutting resistance and the higher the recovery R, the more elastic the binder [proprietary research by ORLEN Asfalt].

PARAMETER		BITUMEN TYPE	
		ORBITON 25/55-80 HIMA WMA	ORBITON 45/80-80 HIMA WMA
Percent value of recovery R, [%]	**R 0.1 kPa**	93.9	95.8
	R 3.2 kPa	93.8	95.4
	R diff	0.2	0.5
Non-recoverable creep compliance, J_{nr} [kPa^{-1}]	**J_{nr} 0.1 kPa**	< 0.1	< 0.1
	J_{nr} 3.2 kPa	< 0.1	< 0.1
	$J_{nr\ diff}$	–	–

Figure 3.12. graphically presents results of MSCR tests, i.e. recovery R in the function J_{nr}, at the stress equal to 3,2 kPa, conducted at 76°C.

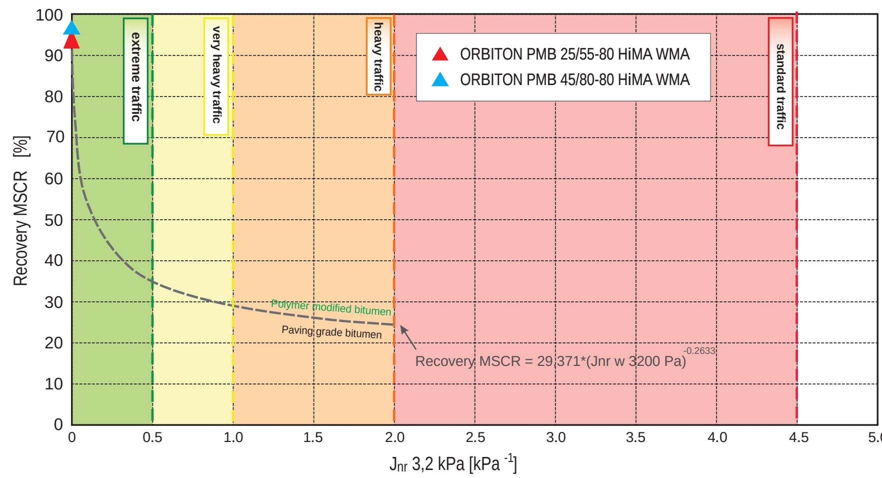

Fig. 3.12. *MSCR test result presentation: recovery R in the function J_{nr}, at the stress equal to 3,2 kPa, conducted at 76°C. Graph interpretation: the higher the J_{nr} value, the better the rutting resistance; the higher the recovery, the more elastic the binder [proprietary tests, ORLEN Asfalt]*

Based on the J_{nr} results, maximum traffic load for a given bitumen can be determined. The suitability of the bitumen for a given traffic load is assessed on the basis of the parameter J_{nr}3.2 [kPa^{-1}] and $J_{nr,diff}$. The classification of requirements is shown in Table 3.9.

Table 3.9.
Classification of bitumen and requirements for traffic load and characteristics acc. to AASHTO M 332 and AASHTO T 350

TRAFFIC LOAD (LETTER CODE)	LOAD (THE NUMBER OF EQUIVALENT, STANDARD AXLES AND TRAFFIC CONDITIONS)	REQUIRED FOR THE BINDER AT THE UPPER PG TEMPERATURE	
		REQUIREMENT FOR J_{nr}3.2	ADDITIONAL REQUIREMENTS FOR J_{nr}diff (*stress sensitivity parameter**)
S – Standard	< 10 million axles (ESAL) and standard traffic (> 70 km/h)	≤ 4.5	≤ 75%
H – Heavy	10 – 30 million axles (ESAL) or slow traffic (20 – 70 km/h)	≤ 2.0	
V – Very heavy	>30 million axles (ESAL) or vehicle parking (< 20 km/h)	≤ 1.0	
E – Extreme	>30 million axles (ESAL and vehicle parking (< 20 km/h)	≤ 0.5	

* binder sensitivity to stress change
ESAL – Equivalent Single Axle Load – US comparison axle with 80 kN (18,000 lbs) load and a twin wheel

Based on the data provided in Table 3.9., – **in relation to the traffic load, ORBITON HiMA WMA binders, at the test temperature equal to 76°C, are classified for EXTREME traffic load**.

3.5.2.2. Asphalt mix tests

Properties of asphalt mixes in which ORBITON HiMA WMA binders are used are analogous to the properties of asphalt mix with classic ORBITON HiMA. This means that mixes containing these bitumens demonstrate very good rutting resistance, excellent fatigue strength and low temperature properties, which was once again confirmed in the tests performed for the purposes of this publication.

The graphs below demonstrate selected test results for asphalt mixes with ORBITON HiMA WMA.

Rutting resistance

The asphalt mix rutting resistance was examined using a small rutting apparatus, according to the standard EN 12697-22, procedure B in the air, i. The tests were performed using the AC 16 mix for the binder course. Fig. 3.13. presents the test results for two basic parameters, i.e. WTS_{AIR} and PRD_{AIR}.

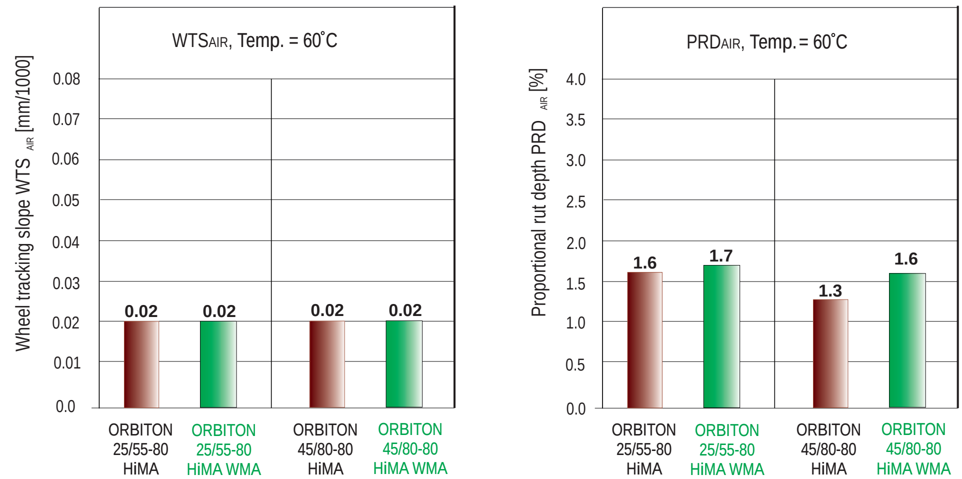

Fig. 3.13. *Results of rutting resistance [proprietary research, ORLEN Asfalt sp. z o.o.].*

Low-temperature failure resistance

Low-temperature failure resistance of asphalt mixes was tested using the TSRST (*Thermal Stress Restrained Specimen Test*) method, in accordance with the standard EN 12697-46. Fig. 3.14. presents the results in the form of the failure temperature ($T_{failure}$,) value.

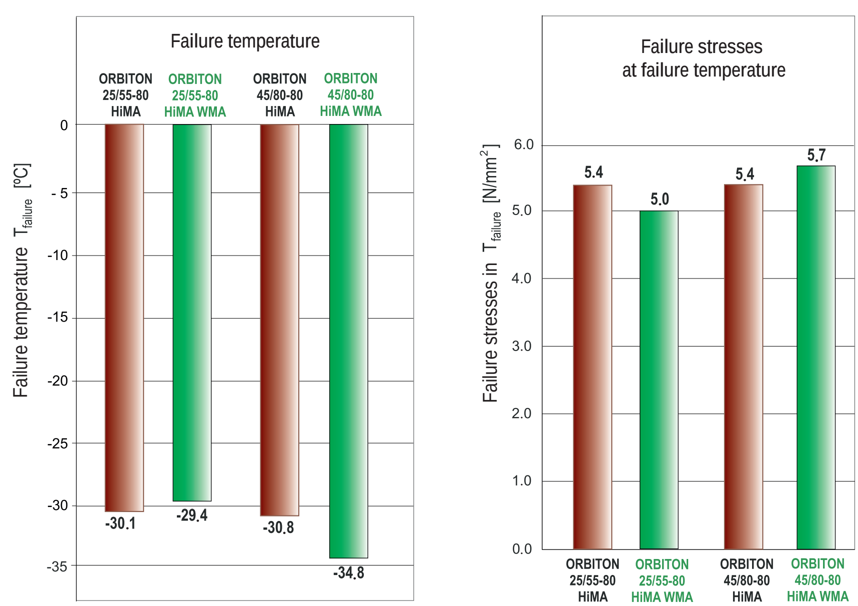

Fig. 3.14. *Results of the resistance against low temperature cracking tests conducted using the TSRST method [source: proprietary research, ORLEN Asfalt]*

Fatigue strength

Asphalt mix fatigue strength tests were conducted according to EN 12697-24, using the 4PB-PR (four-point bending beam test) method. The tests were performed at 10°C, in a controlled strain mode, with a sinusoidal load frequency of 10 Hz. The results obtained in a form of strain ε for fatigue strength for 10^6 cycles are presented in Fig. 3.15.

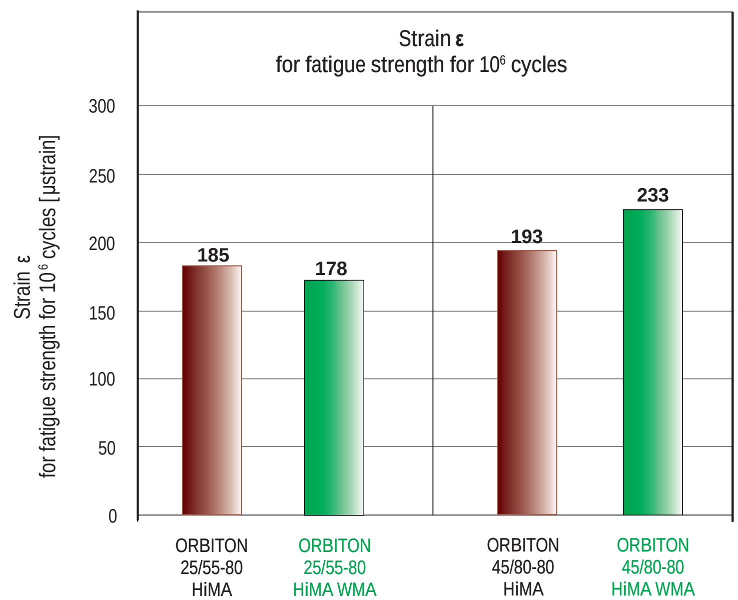

Fig. 3.15. *Fatigue resistance acc. to EN 12697-24 [source: proprietary research ORLEN Asfalt]*

As it can be seen, asphalt mixes with ORBITON HiMA WMA demonstrate properties comparable with asphalt mixes in which classic highly modified bitumens are used.

3.5.2.3. ORBITON HiMA WMA applications

See below for recommended applications of individual types of ORBITON HiMA WMA.

ORBITON 25/55-80 HiMA WMA is designed for special courses requiring exceptional strain resistance (parking lots for heavy vehicles, container terminals, etc.) and where very heavy, slow traffic takes place. Since this binder is very hard, **it should be used only in justified cases** and suitable site conditions need to be ensured. For typical pavement structures, ORBITON 45/80-80 HiMA WMA is recommended instead of ORBITON 25/55-80 HiMA WMA.

ORBITON 45/80-80 HiMA WMA is suitable for all courses of asphalt pavements: base courses, including perpetual pavements, binder courses and wearing courses subject to very high loads. This versatile binder combines elasticity with a very good rutting resistance.

3.5.2.4. Application technology recommendations for ORBITON HIMA WMA binders

• ORBITON HiMA WMA storage

ORBITON HiMA WMA binder should be stored in suitable tanks equipped with a heating system and a mixing system (recommended). The tanks should be equipped with a temperature control units and suitable sampling ports, in accordance to EN 58.

Due to the special properties of the ORBITON HiMA binders, ORLEN Asfalt recommends that the binder should be used immediately upon its delivery to an asphalt mix plant, without any unnecessary storage in the tank.

For ORBITON HiMA WMA, the following temperature ranges in a storage tank in an asphalt mix plant are specified:

- temperature below 160°C – storage period: 3 – 7 days
- temperature 160 ÷ 175°C – working temperature, storage up to 3 days (temperature for asphalt mix production)
- temperature above 175°C – temperature at which there is a risk of product deterioration.

ORBITON HiMA WMA binder can be delivered to asphalt mixplants at temperatures above 175°C, which results from the production process in a refinery. In such a situation, once the bitumen is unloaded into the storage tank, the heating must be deactivated to bring the bitumen temperature brought to the recommended level.

a) Storage up to 3 days

- recommended bitumen storage temperature: 160 ÷ 175°C
- guaranteed period of bitumen service life for asphalt mix production: 3 days*

** It is recommended that the binder is used immediately after delivery, without unnecessary storage in a tank.*

If an asphalt mix plant is equipped with tanks with agitators, bitumen should be periodically mixed in a tank. Circulation can be used for that purpose.

Storing the ORBITON HiMA WMA binder at excessive temperatures (above 175°C) can lead to gradual increase in viscosity, which limits its applicability.

b) Storage for 3 – 7 days

Bitumen can be stored for 3 – 7 days after its temperature is decreased below 160°C, i.e. the recommended storage temperature is 145 ÷ 160°C.

After reheating bitumen to achieve the asphalt mix production temperature, the product should be homogenised by mixing the bitumen in the tank. The tank should be equipped with an agitator. In case a tank with an agitator is unavailable, it is advisable to periodically circulate the product between tanks.

It is not advisable to cool the ORBITON HIMA WMA to the ambient temperature, as it is really difficult to liquefy it on reheating.

Storage of ORBITON HIMA WMA for more than 7 days is not recommended, regardless of the temperature.

• ORBITON HiMA WMA samples in laboratory

a) The handling method for bitumen samples for testing purposes is specified in EN 12594.

b) Heating up samples in a laboratory acc. to the standard-specified method:

- A container must not be tightly sealed.
- Under no circumstances should the samples be heated to the temperature exceeding 175°C.
- Heating-up temperature and time:

SAMPLE SIZE IN A CONTAINER	BITUMEN TYPE	
	ORBITON 25/55-80 HIMA WMA	ORBITON 45/80-80 HIMA WMA
Container capacity up to 1 litre - sample heating time max. 2 hours	max. 175°C	max. 170°C
Container capacity up to 1 ÷ 2 litres - sample heating time max. 3 hours	max. 175°C	max. 170°C
Container capacity up to 2 ÷ 3 litres - sample heating time max. 3.5 hours	max. 175°C	max. 170°C
Container capacity up to 3 ÷ 5 litres - sample heating time max. 4 hours	max. 175°C	max. 170°C
Container capacity up to over 5 litres - sample heating time max. 8 hours	max. 160°C over 6 h, temperature increased to max. 175°C for the last two hours	max. 155°C over 6 h, temperature increased to max. 170°C for the last two hours

c) After heating up the samples in the containers, they should be homogenised by mixing, and care must be taken to avoid the introduction of air bubbles into the sample. The maximum mixing (homogenisation) time is 10 minutes.

d) If the samples are intended to be tested for their properties, is recommended, in accordance with the principles given in the standard EN 12594 p. 7.1, that once the samples are heated up and homogenised, the material should be poured through a heated metal sieve with an 0.5 mm mesh to eliminate any possible impurities affecting the test results.

3.5.2.5. Production temperatures for asphalt mix with ORBITON HiMA WMA

Table 3.10. presents recommended temperatures for production and compaction of asphalt mixes in which the ORBITON HiMA WMA binders are used.

Note that ORBITON HiMA WMA is primarily designed for use as a variant to facilitate the asphalt course, as asphalt mixes with these binders have improved workability and compactability in the typical (not lowered) process temperature range.

Table 3.10.
Production temperatures for asphalt mix with ORBITON HiMA WMA

TYPE OF ORBITON PMB BITUMEN ACC. TO EN 14023	SAMPLE COMPACTION TEMPERATURE FOR TYPE TESTING [1,2,3,4]	BITUMEN TEMPERATURE IN ASPHALT MIX PLANT TANK, FOR ASPHALT MIX PRODUCTION	ASPHALT MIX TEMPERATURE DIRECTLY AFTER UNLOADING FROM MIXER	INITIAL ASPHALT MIX TEMPERATURE DURING COMPACTION
	[°C]	[°C]	[°C]	[°C]
ORBITON 25/55-80 HiMA WMA [5]	145 ÷ 150	165 ÷ 175	165 ÷ 175	> 160
ORBITON 45/80-80 HiMA WMA [5]	140 ÷ 145	160 ÷ 175	165 ÷ 175	> 160

1) Temperatures recommended by the manufacturer can be adjusted according to the contractor's experience.
2) The specified sample compaction temperature ranges in the laboratory should be applied depending on the expected conditions during the asphalt mix paving; lower sample compaction temperatures should be ensured for construction work performed during periods of lower air temperature and for thin pavement layers, and higher sample compaction temperatures should be applied under other conditions.
3) Compaction of samples taken from coarse-grained asphalt mixes and asphalt mixes embedded in thick process courses with high heat capacity requires determination of the individual sample compaction temperature in the laboratory, on the basis of previous experience and anticipated embedding conditions.
4) The specified process temperatures apply to rolled hot-mixes (AC, SMA, BBTM, PA, etc.). For mastic asphalt (MA), the process temperatures should be applied on the basis of the mix workability test conducted in a laboratory.
5) HiMA WMA is primarily designed for use during colder months, and asphalt mixes with these bitumens have improved workability and compactability in the typical process temperature range.

NOTE: Do not mix highly modified bitumens (including modified or paving grade bitumens) supplied by different manufacturers or bitumens of different types from the same manufacturer.

3.5.2.6. ORBITON HiMA WMA test section

Video – ORBITON HiMA WMA paving

SCAN ME!

The first experimental road section with the ORBITON HiMA WMA binder in Poland was paved in December 2021, in the town of Kobiernice located in the Silesia region, within voivodeship road no. DW 948 managed by the Voivodeship Roads Administration in Katowice.

In this experimental section, a 10 cm base course (AC 22) with the **ORBITON 45/80-80 HiMA WMA** was paved. The construction process for the experimental road section provided certain technology-related information – **the characteristics of ORBITON 45/80-80 HiMA in the WMA version included improved workability and compactability in comparison with the classic ORBITON 45/80-80 HiMA**. As a result, despite the unfavourable weather conditions, paving and compaction of the asphalt mix did not cause any problems.

- **Temperature** of the asphalt mix during production in an asphalt mix plant: **170 – 180°C**
- **Weather conditions during construction**: air temperature 0°C, no precipitation, light wind.
- Asphalt mix **temperature during** course compaction, measured behind the spreader: **155 – 157°C**
- No problems during paving and compacting processes. **Compaction indicators > 98.0%**

Photos related to this project are shown in Fig. 3.16. – 3.18

Fig. 3.16. *Construction of an experimental road section using the ORBITON 45/80-80 HiMA WMA bitumen in 2021 – compacted course temperature [photo ORLEN Asfalt sp. z o.o.]*

Fig. 3.17. *Construction of an experimental road section using the ORBITON 45/80-80 HiMA WMA bitumen in 2021 [photo ORLEN Asfalt sp. z o.o.]*

Fig. 3.18. *Construction of an experimental road section using the ORBITON 45/80-80 HiMA WMA bitumen in 2021 [photo ORLEN Asfalt sp. z o.o.]*

IV. NEW ORBITON RC BINDERS FOR ASPHALT MIXES WITH HIGH RECLAIMED ASPHALT CONTENT

#recycling, #RAP, #ecology, #CO_2, # sustainable construction, # natural resources, # transport intensity, #carbon footprint, # sustainable development

4.1. INTRODUCTION

Even the best constructed pavement is subject to wear and tear over time. In the case of asphalt pavements, a wide range of repair measures is available to maintain the required technical condition. One possible solution consists in replacing asphalt courses with new asphalt layers of a better quality. This can involve milling the asphalt surface (Fig. 4.1.) during which the site-won asphalt is generated. It is a valuable raw material that can be reused to manufacture new asphalt mixes.

Do you know what site-won asphalt and reclaimed asphalt is?

Site-won asphalt is a asphalt mix obtained by demolition of old bitumen courses by milling and crushing the slabs cut out of the pavement and lumps obtained from the slabs. The site-won asphalt can also be produced from rejected or surplus asphalt mixes – note the differences in designations, i.e. in English nomenclature it is referred to as site-won asphalt, and in Polish nomenclature (as per WT-2 2014) it is referred to as RA.

Reclaimed asphalt (RA) is the processed site-won asphalt, suitable and ready to be used as constituent material for asphalt mix, after being tested, assessed and classified according to standard EN 13108-8 – note the differences in designations, in Polish nomenclature (as per WT-2 2014) it is referred to as GRA.

Video – ORLEN Asfalt describes
the asphalt pavement recycling process

SCAN ME!

Fig. 4.1. Milling an asphalt pavement – selective milling of individual courses [photo P. Ostrowski, ORLEN Asfalt]

4.2. RECLAIMED ASPHALT

4.2.1. SITE-WON ASPHALT RECOVERY

Before milling the pavement, it is first necessary to assess the thickness and type of individual courses and determine whether the courses selected for milling contain a tar binder. It is necessary to consult the documentation for the road in question, which should contain this information. If such documentation is not available or does not contain the relevant information, it is necessary to drill cores and perform a tar content inspection test. The simplest of such tests is described in [1] and involves using commercially available spray. A test sample should be covered with foam and then exposed to a UV lamp. Tar-containing binders are visible under ultraviolet light, as they glow yellow. The second method consists in extracting a binder from pavement samples and test them for polycyclic aromatic hydrocarbon (PAH) content. Fig. 4.2. presents a drill core in a road pavement in which tar was found in one of the courses using an inspection agent.

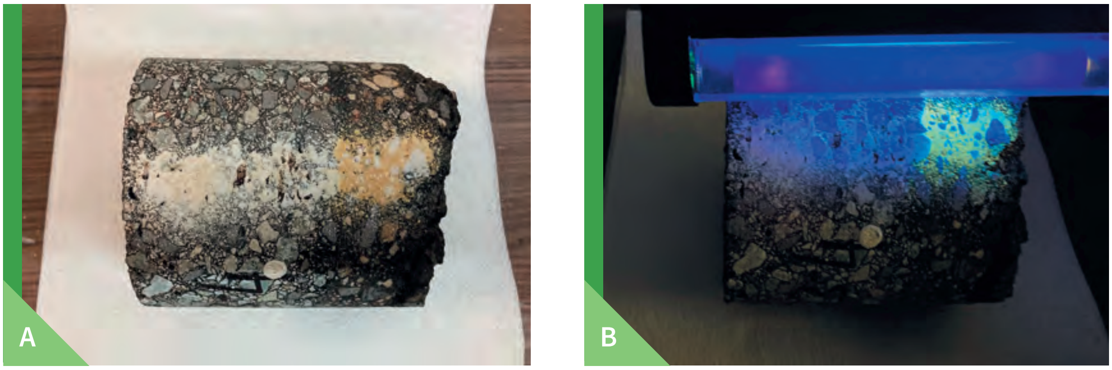

Fig. 4.2. Core drill in which tar was found in the lower pavement course using an inspection agent – (a) in daylight, (b) under a UV lamp – tar layer visible (photo by P. Ostrowski, courtesy of Laboratorium Drogowe Wojciech Bogacki)

If it is found that the milled pavement course contains tar, this material cannot be recycled in any hot technology (due to the confirmed carcinogenic effects of tar), but it can be successfully used to construct a base course using cold recycling technology, e.g. as a mineral-cement-emulsion mix (MCE).

For more information on the MCE technology, scan this QR code

SCAN ME!

Note that, as a general rule, the reclaimed asphalt used in the process of asphalt mix production or a given course should originate exactly from the course in which it was previously placed or, alternatively, from the course above it [2]. Therefore, RA originating from wearing courses can be used for wearing courses, RA from both wearing and binder courses can be used for binder courses and RA from any course can be used for base courses. From the point of view of site-won asphalt reuse, it is therefore most advantageous to mill each course separately. However, it is not always possible, and particularly in the case of obsolete, repeatedly reinforced pavements where the individual courses intermingle, there are numerous patches made of different asphalt mixes.

4.2.2. RECLAIMED ASPHALT PRODUCTION

Depending on the method used to obtain the site-won asphalt, the size of the particles obtained varies. In order to be able to apply it in asphalt pavements, it must first be crushed, then granulated to a suitable grain size and finally homogenised by repeated mixing with a loader (Fig. 4.3.). Then, the generated RA must undergo necessary tests to document its quality (section 4.2.3). A granulator for site-won asphalt is presented in Fig. 4.3.

Fig. 4.3. *Site-won asphalt granulator [photo Rafał Zając, AMMANN]*

4.2.3. RA MATERIAL TESTS

In order to document the quality of the RA obtained, the tests specified in the EN 13108-8 standard must be conducted.

The following must be established during quality control:

- maximum particle size of reclaimed asphalt (U);
- aggregate size (d/D);
- binder content and properties (softening point [R&B]);
- foreign matter (FM).

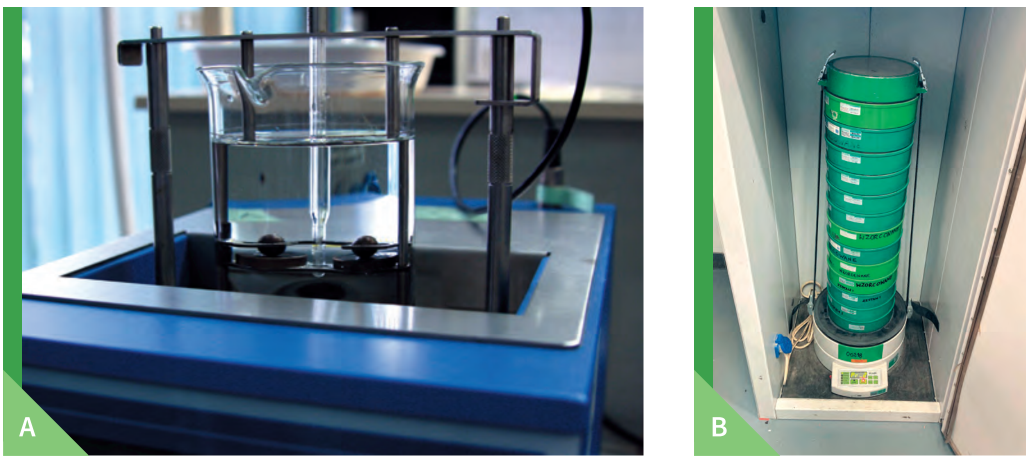

Fig. 4.4. *(a) Softening point testing, R&B method (photo ORLEN Asfalt sp. z o.o., courtesy of ORLEN Laboratorium S.A.); (b) set of sieves used to determine the grain size of a mineral mix obtained from RA (photo P. Ostrowski, courtesy of Laboratorium Drogowe Wojciech Bogacki)*

The homogeneity of the RA material is assessed on the basis of:

- variation in the percentage of coarse aggregate, fine aggregate and dust in the RA;
- binder content in the RA;
- softening point of the binder recovered from the RA.

Classified reclaimed asphalt comes with the following designations:

U RA d/D

where:
U – reclaimed asphalt particle size, in mm (following site-won asphalt break-up);
d/D – aggregate fraction in RA, in mm (grain size).

For example: 32 RA 0/8 – Reclaimed asphalt, of which the aggregate has an upper sieve size of 8 mm and the asphalt mix particles have a maximum size of 32 mm.

4.2.4. RECLAIMED ASPHALT STORAGE

The RA should be separated according to the grain size and type of the course from which is has been obtained, and then stored. RA storage method should prevent mixing different types and fractions. This method should also minimise the moisture in stored material, especially if reuse is planned without heating. It is advisable to store RA under canopies, on a level paved surface with correctly shaped slopes (more information on aggregate storage is provided in chapter 2).

4.2.5. USING RA AND APPLICABLE REGULATIONS

Reclaimed asphalt is an extremely valuable raw material. The recycled material from asphalt pavements built in the last 20 to 30 years contains very good quality aggregates and bitumens, which can easily be reused. Taking into account the technical aspects, there are no grounds for rejecting such material, as it makes it possible to construct new, very good quality asphalt courses if the right technological regime is observed.

Such measures are highly desirable and should be rewarded, if only because of the environmental aspects increasingly taken into account in the road construction industry, i.e. reduction of component transport, rational use of natural resources, and reduction of waste generation.

So far, the environmental legislation in Poland has not allowed using RA in a straightforward manner, due to ambiguities regarding the loss of the waste status for this material.

Following general activities conducted by the Polish road construction industry, the Ministry of Climate and Environment issued the Regulation [4] detailing the conditions in which the site-won asphalt is not treated as waste. The Regulation was implemented in at the beginning of 2022. It attempts to address the issues related to facilitating the RA use from the point of view of environment protection. However, the short-term practice has shown that the detailed provisions of this document still have not removed the legal barriers and the use of RA faces certain formal difficulties. Particular attention should be paid to the additional technical requirements related to the maximum PAH content (16 compounds), i.e. permissible concentrations of substances obtained from the sample eluate. The regulation does not specify any test methods or ways to calculate the PAH content. This can further complicate the process of accepting material for reuse and make it more expensive to implement.

Site-won asphalt, and therefore reclaimed asphalt, is a very valuable material and its use should not be restricted. The Regulation is a step in the right direction, but there is still much to be done to ensure that the legal conditions really support Investors and Contractors in the use of RA.

4.3. METHODS OF ASPHALT MIX PRODUCTION WITH RA

The production process for asphalt mixes using RA varies depending on the way RA is dosed at an asphalt mix plant.

RA can be batched directly into a mixer without being heated, or after being heated in a separate dryer drum (called a parallel drum).

The most common quantities of RA used in Poland are those approved by WT-2, part 1, 2014 edition. For example: 10 − 20% of asphalt mix. Note also that there are different RA types, i.e. they may differ significantly not only in the bitumen type (polymer modified or paving grade bitumen), but also in the degree of ageing or (most often) in the binder content. In such cases, it is quite convenient to use the binder replacement index (BR) which specifies the binder from RA content in the produced asphalt mix RA.

RA content in asphalt mix:

The RA content in asphalt mix is defined by the **binder replacement index (BR)** [3].

BR (*Binder Replacement*) is the ratio of aged bitumen contained in a RA to the total binder content in a new asphalt mix, specified with the following formula:

$$BR = (a \times b)/c$$

where:

- BR – binder replacement index, [%];
- a – content of a soluble binder in RA [% (m/m)];
- b – RA content in a new asphalt mix [% (m/m)];
- c – total content of a soluble binder in a new asphalt mix [% (m/m)].

RA batching without preheating

The RA batching method without preheating is more popular, due to a simpler and cheaper RA batching system, which an asphalt mix plant must be equipped. An example of an asphalt mix plant with a not preheated RA batching system is shown in Fig. 4.5. Fig. 4.6. presents a diagram of an asphalt mix plant with such a batching method.

Fig. 4.5. *Asphalt mix plant with not preheated RA batching system (photo AMMANN)*

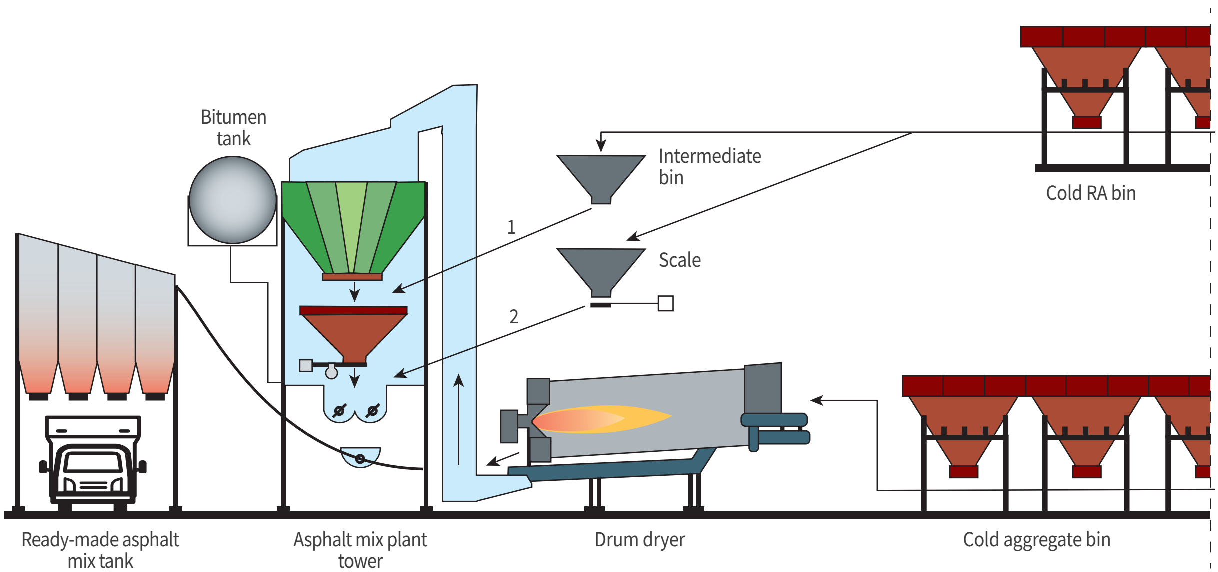

Fig. 4.6. *Asphalt mix plant - heating reclaimed asphalt with hot aggregates [proprietary drawing based on (3)]*

However, this method has some limitations. Because RA material is dispensed at ambient temperatures, in order to heat and dry it, the new aggregate must be heated up to a correspondingly higher temperature.

Recommendations for increasing the aggregate heating temperature depending on the RA amount are shown in Fig. 4.7, while increasing the aggregate temperature depending on the RA moisture content is shown in Table 4.1. (the grey colour indicates values not recommended due to problems in producing asphalt mix with the correct parameters).

The increased aggregate temperature results in the fact that both the binder contained in the RA and freshly added binder are subjected to greater short term ageing. A longer asphalt mix production is also required, which results in increased energy consumption. In addition, the steam released from the RA during mixing operations may cause clogging of the asphalt mix plant filters. Hence, the amount of not preheated RA is limited to a maximum of 20 – 30%[1]. Under certain conditions (low RA moisture, using WMA bitumens), the proportion of RA batched may be higher, which, however, requires checking the production efficiency and confirming the functional properties of the produced asphalt mix.

The current guidelines imposed by the General Directorate for National Roads and Motorways in Poland (Polish abbreviation – GDDKiA) limit the proportion of not preheated RA to 20%, and allow it to be used only in binder and base courses [2]. However, these are not general regulations and each road network manager can individually set a threshold value for RA in new asphalt mix, based on their knowledge and experience.

1 Each time this Handbook refers to the proportion of a RA in new asphalt mixes, it refers to the R (binder replacement) index.

Table 4.1.
Production temperature correction (increase) depending on RA moisture

RA SHARE M [%]	RA MOISTURE [%]					
	1	2	3	4	5	6
	TEMPERATURE CORRECTION °C					
10	4	8	12	16	20	24
15	6	12	18	24	30	36
20	8	16	24	32	40	48
25	10	20	30	40	50	60
30	12	24	–	–	–	–

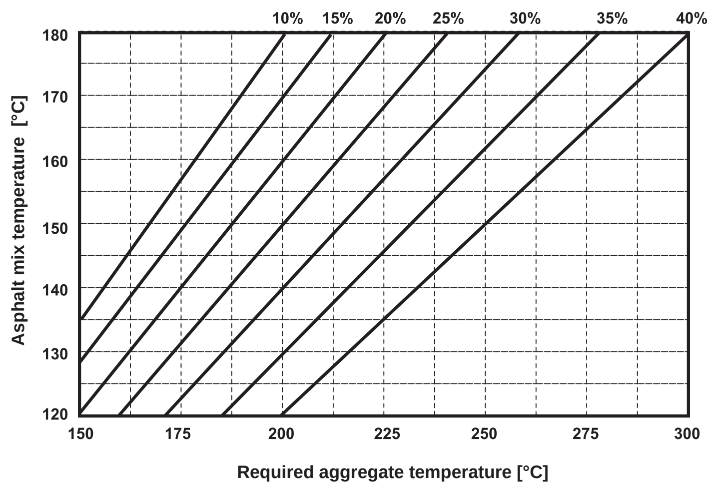

Fig. 4.7. *Required aggregate temperature depending on the percentage of cold and dry RA content in an asphalt mix [proprietary illustration based on (5)]*

Parallel drum – preheated RA batching

Fig. 4.8. presents a diagram of an asphalt mix plant with parallel drum for RA preheating.

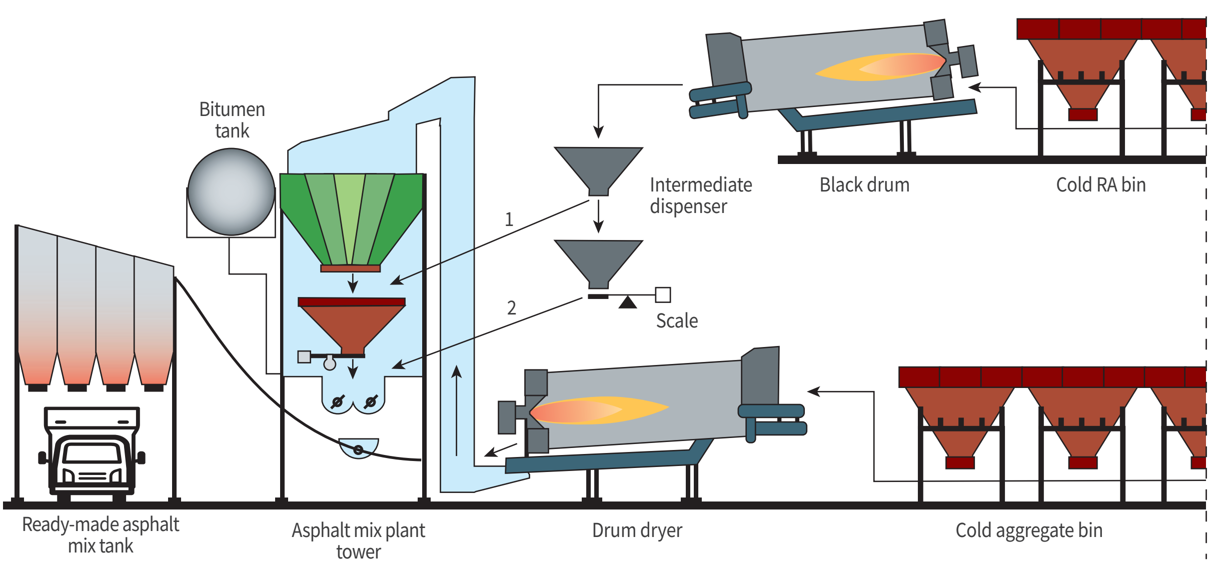

Fig. 4.8. *An asphalt mix plant with parallel drum for RA preheating [proprietary drawing based on (3)]*

In this method, a recycled material is preheated in a parallel dryer drum (technology employed in Poland), or in a drum that allows new aggregate and RA to be heated simultaneously (technology not used in Poland). In our discussion concerning the RA batching technology, we will focus on the methods used in Poland.

The heated RA from the parallel dryer is conveyed to the mixer, where it is mixed together with other asphalt mix components. This method makes it possible to produce asphalt mix even with 100% RA content, which of course requires a material with a suitably composed grain size curve. In practice, a proportion of the recycled material ranges from 40 to 60% is most common, due to the possibility of obtaining a suitable composition of the new asphalt mix.

The parallel drum system is much more favourable due to technological and economic reasons. It allows the RA heating temperature to be set precisely, does not require the aggregate to be heated above this higher temperature, thus limiting technological ageing of the binder. The component mixing time does not have to be significantly extended, so that production efficiency is maintained at a required level. The disadvantage of such a system is the necessity to provide an asphalt mix plant with additional equipment, which results in a significant increase in the capital expenditure incurred. Sticking of hot RA to the parallel drum surface and the need to clean it regularly is another practical problem.

Fig. 4.9. presents an example of an asphalt mix plant with a parallel drum.

Fig. 4.9. *Asphalt mix plantwith a parallel drum [photo AMMANN]*

Applicable technical guidelines [2] specify the RA quantities which can be used, depending on the pavement course, i.e. from 20% in wearing courses to 50% in base courses. In order to make parallel drum devices more popular, it is necessary to allow the highest possible RA content in new asphalt mixes (while maintaining the respective properties of the new asphalt mix). Such an approach makes it possible to offset the high investment costs, as a high RA content in the new asphalt mix results in lower production costs, which ultimately seems to make economic sense for the producers, and allows the government to implement the Circular Economy concept.

4.4. BITUMINOUS BINDER AGEING

Bituminous binder ageing is an extremely complex process. It depends on a great many factors, including the bitumen nature, chemical structure and group composition, and also various external factors. The main bituminous binder ageing mechanism is related to the chemical changes that occur in the bitumen structure, which then affect its rheological properties.

Factors contributing to the ageing process include high temperatures, access to oxygen from the air and UV radiation.

The bitumen ageing process essentially consists of two stages. Beginning with the bituminous binder production and ending with the operation of a pavement containing this binder, a distinction is made between short-term[2] ageing and long-term ageing[3]. The most intensive changes in the bituminous binder properties occur during short-term ageing, when the binder properties are altered by high temperatures.

The degree of bituminous binder ageing determines the period of time during which a pavement will continue to function correctly, regardless of whether conventional paving grade or polymer modified asphalt pavements are used.

The most intensive bitumen ageing occurs when it is mixed with hot aggregate in an asphalt mix plant mixer. At this stage, the temperature is the highest, the access of oxygen from the air is free and the binder film on the aggregate is very thin. When the aggregate is coated by bitumen, evaporation of light fractions and bitumen component oxidation is fastest and most intense. Hence, the limitations associated with the amount of not preheated RA aimed at ensuring that the aggregate temperature is not excessively raised during asphalt mix production. Simply because the extremely hot aggregate will “burn” the new added binder added to the asphalt mix.

After the asphalt mix paving in the pavement, the binder also undergoes an ageing process, i.e. long-term ageing. It takes place at a much slower rate and varies depending on the exposure of the course in question to the weather conditions. Obviously, most intensive ageing processes occur at the wearing course, but they cannot be ignored in the case of other courses located below the wearing course.

2) short-term ageing, concerns the stage during asphalt mix production, storage and paving.

3) long-term ageing, takes place during the service life of asphalt pavement.

As a result of oxidation reactions, changes occur in the bitumen composition and chemical structure, resulting in the following:

- penetration decrease;
- softening point increase;
- increase (deterioration) of Fraass breaking point;
- viscosity increase;
- ductility reduction;
- several other chemical and mechanical changes.

A diagram of the ageing process on the basis of changes in paving grade bitumen 50/70 penetration is presented in Fig. 4.10.

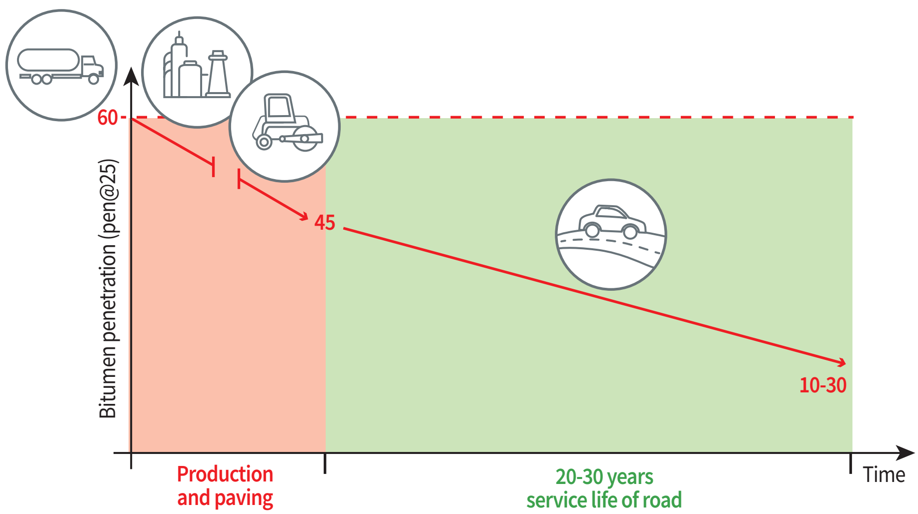

Fig. 4.10. *Diagram showing decrease in paving grade bitumen 50/70 penetration as a result of the ageing process at different operation stages [proprietary drawing]*

4.5. BITUMENS WITH "REJUVENATING" PROPERTIES

4.5.1. REJUVENATORS

During the ageing process, bitumen changes its properties and consequently becomes increasingly harder over time. In order to restore the original properties of an aged bituminous binder, it is necessary to replenish the rheologically relevant bitumen components lost throughout its life cycle.

Products facilitating (at least partial) restoration of the original properties of an aged bituminous binder are called rejuvenators. They usually contain oil and resin fractions rich in aromatic compounds, or are available in the form of dispersing agents (acting as dispersants for asphaltene agglomerates). Regardless of their composition, rejuvenators are designed to restore correct group component proportions in an aged binder. At the molecular level, these products increase the distance between micelles, reverse physical processes (molecule reorientation) and reduce bitumen viscosity. As a result, they make it possible to mitigate (at least to a certain extent) the negative effects of the ageing process [7].

Fig. 4.11. presents the bituminous binder life cycle in a pavement and its required recycling form obtained using a rejuvenator.

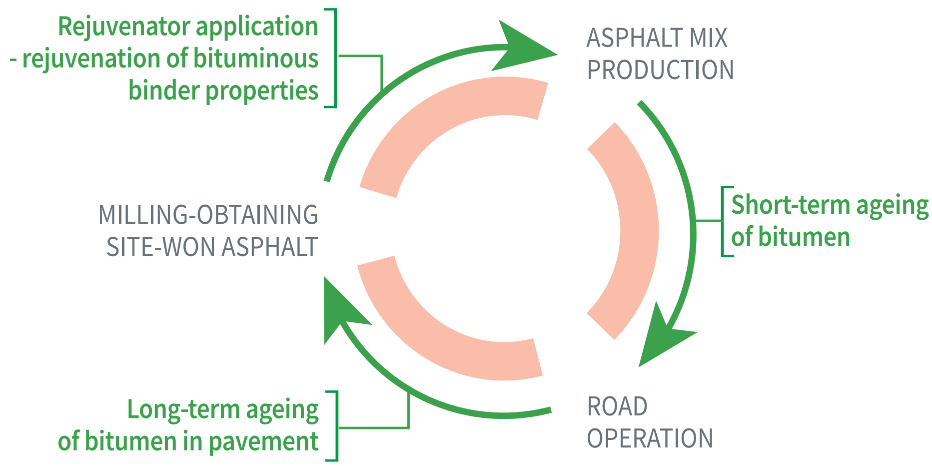

Fig. 4.11. *Life cycle of bituminous binder in pavement including required recycling [proprietary drawing]*

There are several products known as rejuvenators available on the market. Note, however, that effectiveness of such additives should be carefully tested in the laboratory tests. Some of them only affect bitumen viscosity and do not replenish the fractions lost during the bitumen ageing process. In order to assess the effectiveness of a particular rejuvenator, advanced rheological tests are required to determine how a given agent affects a given bituminous binder. While conducting only basic tests, such as penetration or softening point (R&B), we are not able to make a correct assessment.

4.5.2. ORBITON RC BINDERS

ORBITON RC is a specially designed polymer modified bitumen which maintains high quality of asphalt courses with a large amount of RA in the asphalt mix.

orbiton RC30

orbiton RC50

ORBITON RC binders are designed by the Research, Development and Innovation Department at ORLEN Asfalt. The concept employed to design new ORBITON RC binders states that, regardless of the amount of RA used in a asphalt mix, when a given ORBITON RC binder is used, the properties of the binder within a course are the same as those of ORBITON 25/55-60.

What is more, using ORBITON RC binders does not require introducing any modifications in the asphalt mix plant, and asphalt mix production and paving is done in a standard manner.

4.12. presents the diagram of ORBITONRC binder application.

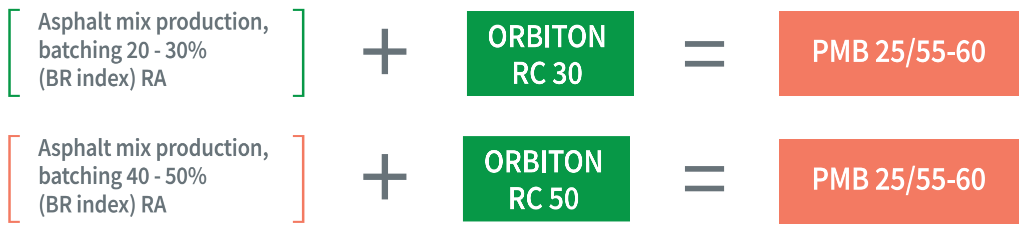

Fig. 4.12. *Approximate ranges of values for a RA to be used with the different types of ORBITON RC binders [proprietary drawing]*

During applying the lower RA (binder replacement index ranging from 20 to 30%), the ORBITON RC30 binder should be selected. During applying larger amounts of RA (binder replacement index ranging from 40 to 50%), the ORBITON RC50 binder should be chosen. It results from the content of polymers and other additives in ORBITON RC30 and ORBITON RC50.

The quantities specified are just indicative values and should be confirmed while designing asphalt mixes and during Type Testing, taking into account the properties of the RA used.

4.5.3 ORBITON RC PROPERTIES

ORBITON RC is a binder manufactured in accordance with National Annex to the PN-EN 14023:2011/Ap2:2020-02 standard. **ORBITON RC30 is classified as PMB 25/55-60, and ORBITON RC50 is classified as PMB 45/80-55**. The required properties of the mentioned binder types are provided in chapter 1, Table 1.7.

See below for selected properties (obtained in the laboratory tests) of ORBITON RC30 and ORBITON RC50 binders.

The following bituminous binder mixes were used in the tests:

- 70% of ORBITON RC30 + 30% of a binder extracted from RA;
- 50% of ORBITON RC50 + 50% of a binder extracted from RA.

> Important note: When performing laboratory tests during which a new binder is mixed with a binder extracted from a RA, note that the asphalt mix produced at an asphalt mix plant does not ensure perfect mixing of the new binder with the binder obtained from a RA.

Fig. 4.13. and 4.14. present the results regarding the softening point (R&B) and penetration for the mixes used. As it can be clearly seen, using the ORBITON RC 30 binder with 30% of RA binder content and ORBITON RC50 binder with 50% of RA binder content resulted in obtaining parameters corresponding to PMB 25/55-60, in both cases.

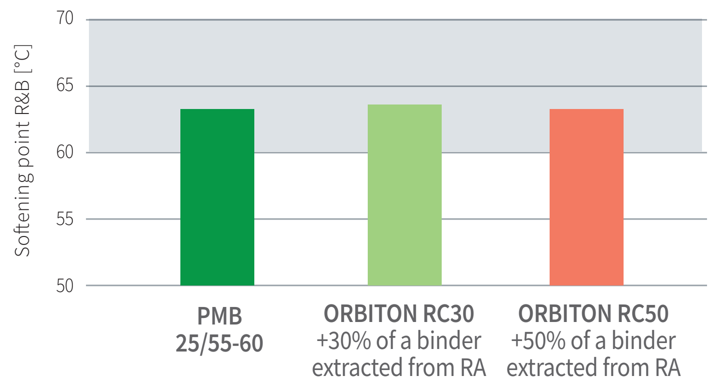

Fig. 4.13. *Softening point (R&B) of original PMB 25/55-60 and the mix of ORBITON RC30 and ORBITON RC50 binders with binders obtained from RA plus the standard range [proprietary research, ORLEN Asfalt sp. z o.o.]*

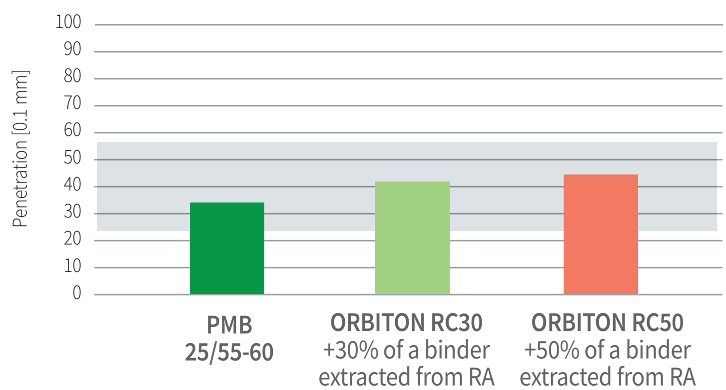

Fig. 4.14. *Penetration of original PMB 25/55-60 and the mix of ORBITON RC30 and ORBITON RC50 binders with binders obtained from RA plus the standard range [proprietary research, ORLEN Asfalt sp. z o.o.]*

Fig. 4.15. presents the elastic recovery values for tested mixes, after short-term ageing acc. to RTFOT.

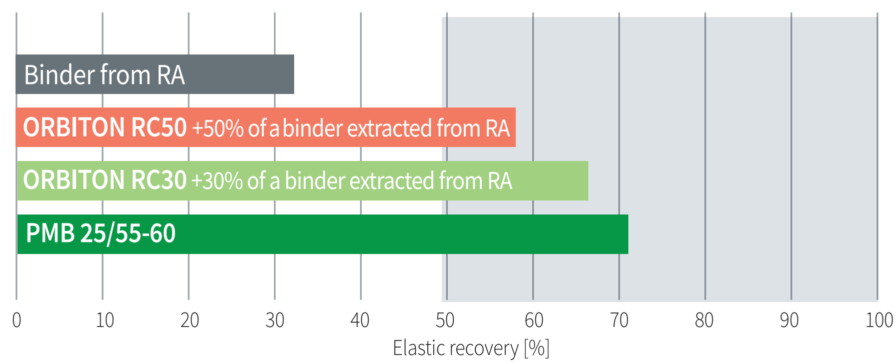

Fig. 4.15. *Elastic recovery after RTFOT of original PMB 25/55-60 bitumen, a binder extracted from a RA and the mix of ORBITON RC30 and ORBITON RC50 binders with binders obtained from RA plus the standard range [proprietary research, ORLEN Asfalt sp. z o.o.]*

The ORBITON RC binders application impact is visible, as a result of which, despite the low elastic recovery value obtained for a binder extracted from a RA, the final results correspond to the PMB 25/55-60 requirements.

Fig. 4.16. and 4.17. present, respectively, the complex stiffness modulus G* obtained for ORBITON RC30 + 30% of a binder extracted from RA and ORBITON RC50 + 50% of a binder extracted from RA. In both cases, the complex stiffness modulus values obtained are comparable to the PMB 25/55-60 stiffness, which is a desirable effect.

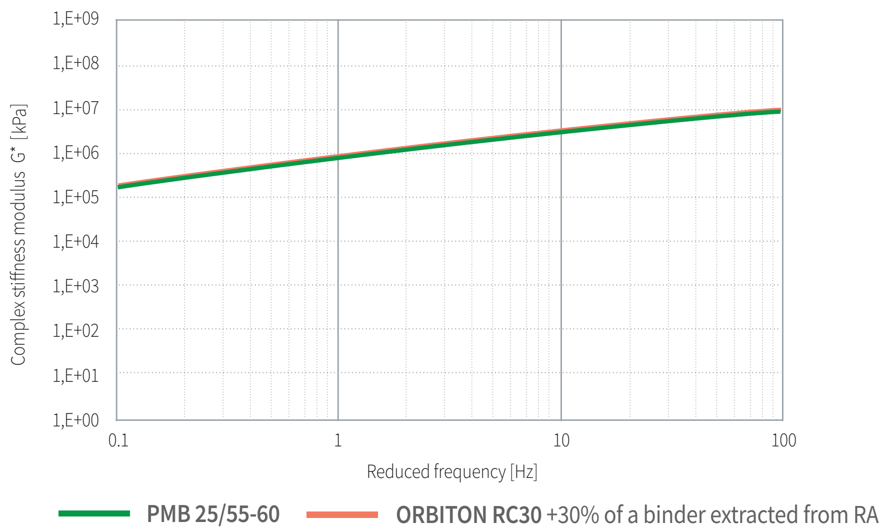

Fig. 4.16. *Complex stiffness modulus G* for the PMB 25/55-60 and ORBITON RC30 + 30% of a binder extracted from RA [proprietary research, ORLEN Asfalt sp. z o.o.]*

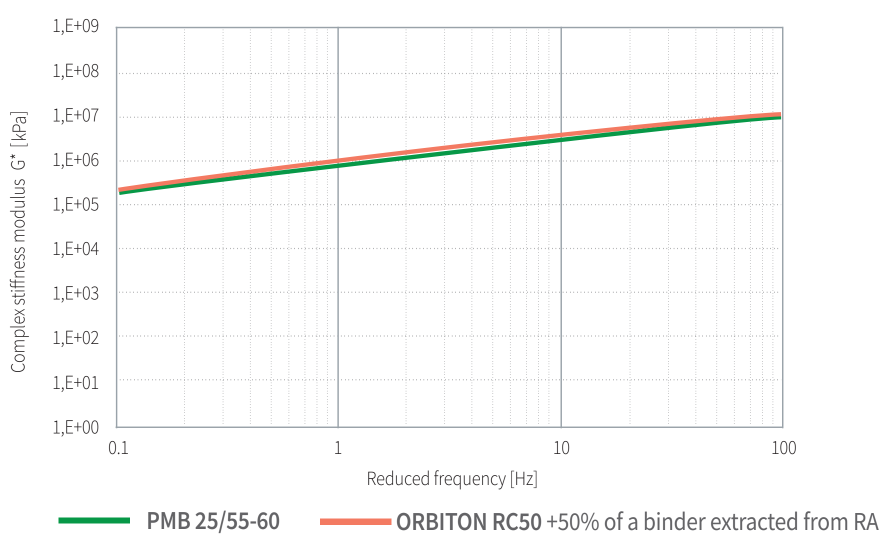

Fig. 4.17. *Complex stiffness modulus G* for the PMB 25/55-60 and ORBITON RC50 + 50% of a binder extracted from RA [proprietary research, ORLEN Asfalt sp. z o.o.]*

The results presented clearly show the beneficial effect of using ORBITON RC binders in combination with a bituminous binder extracted from a RA, both in terms of basic properties (consistency) and predicted stiffness.

4.5.4. PROPERTIES OF ASPHALT MIXES WITH ORBITON RC BINDERS

The functional tests for asphalt mixes with RA conducted with the use of ORBITON RC binders were performed on the AC 16 mix for binder courses (for medium to very heavy traffic load), in accordance with [6]. Within the framework of the tests, five variants of asphalt mixes were created **in laboratory conditions:**

- **AC 16 bin** = AC 16 bin + PMB 25/55-60 + 0% GRA (reference asphalt mix)
- **AC 16 bin GRA 30** = AC 16 bin + PMB 25/55-60 + 30% GRA (BR 30%)
- **AC 16 bin GRA 30 RC30** = AC 16 bin + ORBITON RC30 + 30% GRA (BR 30%)
- **AC 16 bin GRA 50** = AC 16 bin + PMB 45/80-55 + 50% GRA (BR 50%)
- **AC 16 bin GRA 50 RC50** = AC 16 bin + ORBITON RC50 + 50% GRA (BR 50%)

Fig. 4.18 presents the test results for asphalt mix resistance to water and frost (ITSR).

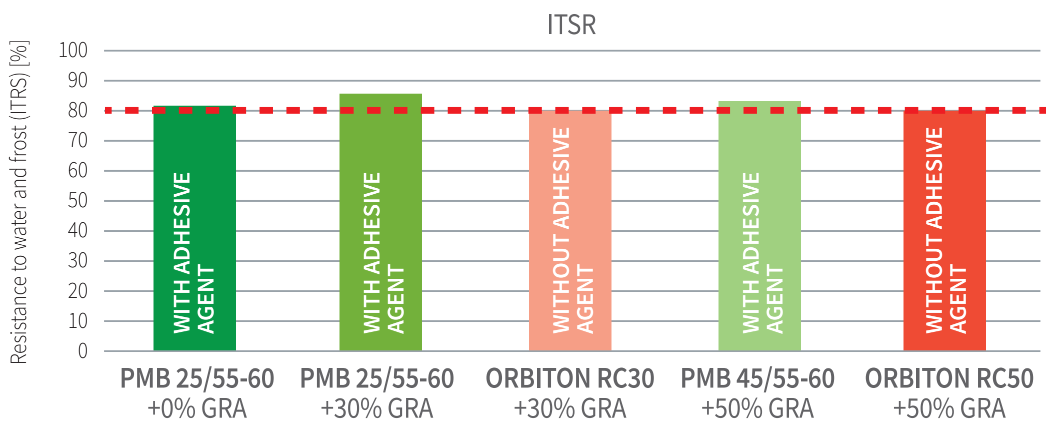

Fig. 4.18. *Resistance to water and frost (ITSR) for AC16 bin with various binders and RA combinations [proprietary research, ORLEN Asfalt sp. z o.o.]*

For all tested mixes, a positive result, i.e. ≥80%, was obtained. Importantly, such a result was achieved for asphalt mixes with ORBITON RC binders despite not using an additional adhesive agent, as in other mixes. However, we do not recommend producing asphalt mixes without an adhesive agent; in our tests, we only tested the RC30 and RC50 binder water and frost resistance potential in the absence of an adhesion agent.

Fig. 4.19. presents the test results for the rutting resistance of asphalt mixes for the WTS_{AIR} parameter. The tests were conducted acc. to EN 12697-22, small apparatus, procedure B in the air, at 60°C.

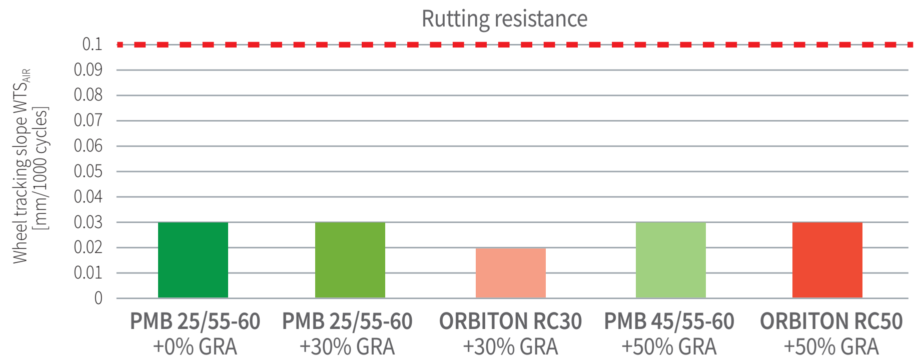

Fig. 4.19. *Rutting resistance test results, WTS_{AIR} parameter, AC 16 bin with various binders and RA combinations [proprietary research, ORLEN Asfalt sp. z o.o.]*

The tests concerning rutting resistance also confirmed excellent properties of asphalt mixes with ORBITON RC binders. Using ORBITON RC binders with rejuvenating properties did not cause any deterioration in performance, as compared to the reference mix without any RA.

Low-temperature cracking resistance was tested using the TSRST method, in accordance with the EN 12697-46 standard. The results are shown in Fig. 4.20.

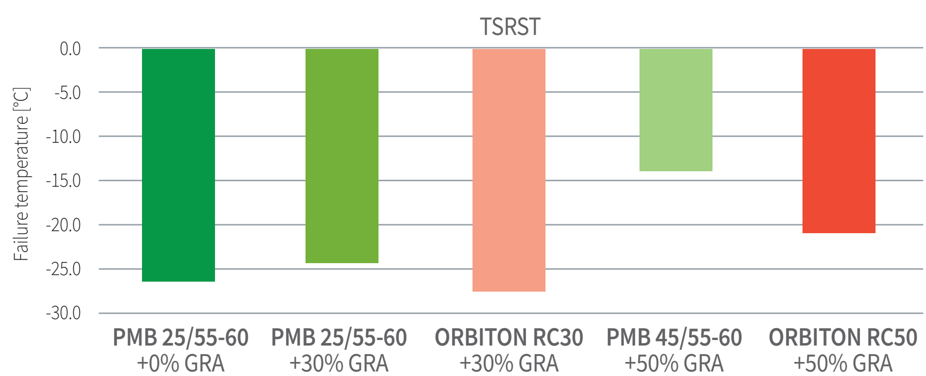

Fig. 4.20. *Results of the resistance of low temperature cracking tests conducted using the TSRST method, AC 16 bin with various binders and RA combinations [proprietary research, ORLEN Asfalt sp. z o.o.]*

Test results for low temperature cracking clearly show the positive impact of ORBITON RC binder application in relation to asphalt mixes containing conventional binders. For asphalt mix containing ORBITON RC30 binder and 30% of RA, the result concerning the low temperature crack similar to that of a reference asphalt mix (without RA) was obtained. As for an asphalt mix with ORBITON RC50 binder and 50% of RA, the TSRST result was slightly lower than for the reference mix, but applying ORBITON RC50 binder ensured a result better than in the case of the asphalt mix containing the RA and PMB 45/80-55. Using the softer PMB 45/80-55 for the mix containing 50% of RA was aimed at obtaining the final PMB 25/55-60 binder.

Fatigue resistance tests were conducted acc. to the standard EN 12697-24 using the 4PB-PR method. The tests were performed at 10°C, in a controlled strain mode, with a sinusoidal load frequency of 10 Hz. The results obtained in a form of strain ε for fatigue strength for 10^6 cycles are presented in Fig. 4.21.

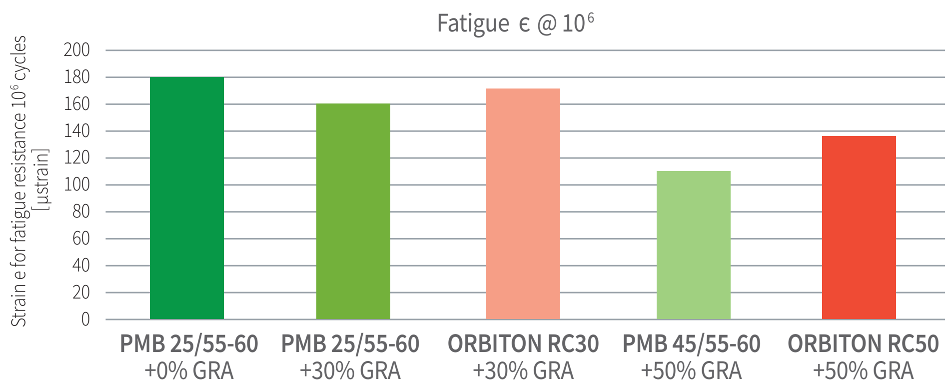

Fig. 4.21. *Resistance to fatigue 4PB-PR test results, AC 16 bin with various binders and RA combinations [proprietary research, ORLEN Asfalt sp. z o.o.]*

The fatigue resistance test also show the beneficial effect of applying binders with special properties, as compared to asphalt mixes with RA and conventional binders. For an asphalt mix containing ORBITON RC30 binder and 30% of RA, the result concerning the critical strain similar as for a reference asphalt mix (without RA) was obtained. As for an asphalt mix with ORBITON RC50 binder and 50% of RA, the critical strain lower than that for the reference asphalt mix was obtained, but applying the RC50 binder ensured a result better than in the case of the asphalt mix containing the RA and conventional binder. Note also that that application of 50% of a RA significantly changes the asphalt mix properties.

The properties of asphalt mixes created with RA clearly show the beneficial effect of using the special ORBITON RC binders dedicated to the asphalt mix with a higher RA content. In the case of a lower RA content (30%), the test results were at least as good as for the reference asphalt mix. However, in the case of a 50% RA content, a noticeable improvement was achieved in relation to the asphalt mix containing a RA and conventional binder. **In addition, note also that the test results presented here concern asphalt mixes made in a laboratory, where the mixing efficiency of individual components is lower than under actual conditions in an asphalt mix plant. It should therefore be expected that asphalt mixes produced on an industrial scale will provide even better tests results when ORBITON RC is used**.

4.6 SUMMARY

New **ORBITON RC30 and ORBITON RC50** polymer modified binders comply with the EN 14023 standard, and can assigned to a given type and class of polymer modified binders. They are designed **for base and binder courses**, where the 35/50 or PMB 25/55-60 binder was to be used.

ORBITON RC30 and ORBITON RC50 facilitate rejuvenating the properties of a binder originating from a RA in an asphalt mix. Additionally, they improve the properties of binders (new RC binder type and binder originating from a RA) in an asphalt mix. Application of ORBITON RC binders does not involve any asphalt mix plant modifications, and the process of asphalt mix production and paving is the same as for the conventional ORBITON products.

ORLEN Asfalt is creating a calculator to enabling users to select a correct RC binder, taking into account the RA content and parameters. See the Company's website for relevant information.

As far as asphalt mix properties are concerned, new ORBITON RC modified binders:

- **ensure the required resistance to rutting, comparable to the values applicable to new asphalt mixes without any RA and containing the 25/55-60 binder**;
- **ensure the required level of** water and frost resistance (**ITSR**), even without any adhesive agent; however, in standard asphalt mix production processes, this additive must still be used;
- using a RA in the amount of **BR 30%** together with ORBITON RC30 ensures retaining a high level of resistance to low-temperature cracking (TSRST test) and fatigue strength;
- using a RA in the amount of **BR 50%** together with ORBITON RC50 showed, at the laboratory test stage, the effectiveness of such an application, but due to the limitations of miscibility under laboratory conditions, the parameters will be finally checked in the asphalt mixes produced under industrial conditions, in an asphalt mix plant.
- the above conclusions are based on results of tests performed under laboratory conditions, and can be updated following industrial-scale tests.

Our current reality necessitates an intensive search for **new technological solutions**. The aim of such changes should be to generate savings in terms of consumption of raw materials, fuels and energy consumption, which are currently extremely cost-intensive.

Current bitumen-related technologies facilitate a number of optimisations, as asphalt pavements can be 100% recycled.

ORBITON RC binders belong to the group of products which support the achieving of the relevant low-carbon economy's objectives.

V. ACBE MIX

#technology, #bitumen emulsion, # GE mix, # ACBE mix

5.1. INTRODUCTION

The previous chapters provided a range of information and arguments concerning the benefits of asphalt mix temperature decrease. Generally, it is clear that the lower the temperature, the greater the economic and environmental benefits. In addition to this, technical benefits such as mitigation of bitumen short-term ageing can also be considered. Lower bituminous binder and aggregate temperatures during the mixing process counteracts the evaporation of bitumen light fractions and group component conversion, which consequently improves the asphalt pavement durability through, for example, lower bitumen stiffness and brittleness, which mostly improves its resistance to water, frost and various other failures.

Apart from the WMA technology gradually becoming a standard in numerous countries, there is also the HWMA (*Half-Warm Mix Asphalt*) technology and "cold-mixes" manufactured using bitumen emulsions. GE (*Grave Emulsion*) mixes are the most popular cold-mixes. The GE mix was designed in France [1] at the turn of the 1950s and 1960s as a material used to construct roads with the lightest traffic load and for road maintenance purposes. The GE mix is usually used to construct levelling courses, base courses and binder courses. Mixing a special cationic bitumen emulsion with a mineral mix at the ambient temperature, usually in a mobile plant, on a construction site, is the essence of GE technology.

This technology is neither known nor popular in Poland. Nevertheless, the trend towards using "cold-mixes" will intensify, just as the trend towards lowering the carbon footprint and ensuring energy efficiency.

In addition to GE, the European Standard for asphalt concrete with a bitumen emulsion (ACBE) was implemented in 2020 in the road construction sector. This chapter presents most important information on the mix for asphalt pavement courses, i.e. ACBE.

5.2. EN 13108-31 STANDARD

In 2019, CEN published the new **EN 13108-31** standard. It belongs to the EN 13108-x (1-9, 20, 21) standard series which also includes the standards related to asphalt concrete, i.e. AC (EN 13108-1), SMA (EN 13108-5) or mastic asphalt (MA) (EN 13108-6). These are, however, "hot-mixes". Additionally, the EN 13108-x standard series contains the standards related to the Type Test (EN 13108-20) and Factory Production Control (EN 13108-21).

Nevertheless, it might seem quite surprising, as EN 13108-31 relates to “cold-mixes”.

5.2.1. DEFINITIONS

The standard defines a mix of asphalt concrete with bitumen emulsion as “*asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure in which all or part of the binder is added in the form of a bitumen emulsion*”.

It is designated as:

ACBE D surf/bin/base BE

where:

- **ACBE** – designation for asphalt concrete with bitumen emulsion;
- **D** – mineral mix size in ACBE (in mm);
- **surf/bin/base** – pavement course code
- **BE** – emulsion code acc. to EN 13808. For example:

ACBE 16 S C 60 B 5

5.2.2. ACBE COMPONENTS

The **cationic bitumen emulsions** compliant with EN 13808 is the most important ACBE mix component. Note, however, that not all bitumen emulsions can be used in ACBE mixes. Moreover, the Polish National Annex to PN-EN 13808 does not mention any emulsion that can be applied in ACBE. Possibly, such bitumen emulsions will be specified in the next edition of this Annex.

An aggregate is another ACBE component, the same as for conventional asphalt mixes, and therefore compliant with EN 13043. Note also that section 4.4 of the standard concerning ACBE includes a provision stating that the properties of the aggregate made of RA or a mix of the aggregate containing RA with a new (added) aggregate should meet the requirements for the aggregate specified in the documents defining the requirements for ACBE mixes. In other words, in Poland the aggregate extracted from a RA should meet the requirements of WT-1[6] as for new aggregates for a given asphalt mix and traffic load (example).

The standard permits using RA for which no upper limit for the content in the mix is specified.

Properties and characteristics of additives should be declared as meeting the requirements of a European Standard, European Technical Assessment, or material specification based on a known history of successful applications.

In the latter case, the evidence should come either from laboratory test results or practical application examples. It is provided for in EN 13108-31; however, this provision contradicts the Regulation of the Minister of Development, Labour and Technology of 4 December 2020 (Journal of Laws 2020, item 2297), which clearly states that all additives to asphalt mixes are treated as construction products and are to be used in accordance with the national system.

The water used must comply with the EN 1008 requirements and should be potable.

5.2.3. REQUIREMENTS RELEVANT FOR THE MIX

Similarly to other EN 13108-x series standards, EN 13108-31 does not provide any specific requirements for ACBE mixes. It only specifies general principles for developing such requirements which must be developed and published in various application-related documents developed by road administrators for their internal use.

The standard states that:

- The Type Test for ACBE must be based on the requirements specified in Annex A to EN 13108-31.
- The Type Test must include the following information:
  - granulary curve for mineral mix;
  - target bitumen emulsion content;
  - additives;
  - water content from the bitumen emulsion, water added separately, water contained in the aggregate;
  - total binder content (from the bitumen emulsion and from RAPs if added) and, in the case of production validation, the soluble binder amount.

With regard to the mineral mix grain size, two tables are provided to specify the limit points for determining the grain size limit curves (in the application-related document). As in the case of other EN 13108-x series standards, we have to take the +1 basic sieve set, and therefore use the information presented in Table 1 of the standard.

The minimum binder content (B_{min}) should be chosen from a range of 3.0% to 8.0% m/m and should be corrected according to the alpha index to the reference density of 2.65 Mg/m^3.

The specification of the final required ACBE mix properties should be obtained from Tables 4 – 9 of the standard in question:

- void content – classes from 6.0% to 26.0% v/v;
- minimum void content after 10 revolutions of a gyratory compactor – classes from 12 to 22% v/v;
- resistance to water – classes from 40% to 90%;
- indirect tensile strength – classes from 100 to 1200 kPa;
- minimum compressive strength – from 1500 to 3500 kPa;
- minimum stiffness (2PB-TR, 4PB-PR, DTC-CY, DT-PR, IT-CY, CIT-CY) – classes from 1000 to 6000 MPa.

If necessary, the maximum and minimum application temperature for an ACBE mix must be specified. Fire resistance and hazardous substance content must also be stated. The standard also indicates what is understood by "conflicting requirements", i.e. the simultaneous specification of minimum stiffness with a minimum binder content exceeding 3.0% or the stiffening properties of the filler or the angularity of the fine aggregate.

5.2.4. ASSESSMENT AND VERIFICATION OF THE CONSTANCY OF PARAMETERS

The standard specifies that the assessment system consists of the Type Test (acc. to normative Annex A) and FPC system (acc. to normative Annex B).

Similarly to EN 13108-20, **Annex B (normative)** (Type Test of the mix) specifies the validity period (5 years), conditions regarding Type Test validity loss, sampling, etc.

A separate **Annex A** section deals with preparation of samples for a Type Test (laboratory validation and production validation). In particular, attention should be paid to the mix curing process in accordance with EN 12697-54, which should be described in a Type Test. It is also interesting to note the requirement stating that, as part of the production validation, not only a mix test must be conducted, but also a test section must be built and, in addition, test samples must be cut out from it. As far as the tolerance range is concerned, the standard refers to EN 13108-21 (values provided in Table A.2.).

Table A.1. specifies the range of tests for each ACBE component. Table A.2. describes various methods of compacting samples for testing purposes. They include: static compaction, gyratory compactor, vibration method, laboratory roller, plate compactor and cores drilled from a test section. However, the methods do not include compaction with an impact compactor (as in the Marshall method).

Similarly to EN 13108-21, **Annex B (normative)** (FPC) specifies the production tolerances for individual samples and an average value out of 4.

Annex C (informative) describes the rules for additional test specification and performance:

- rutting resistance (large apparatus, small apparatus) including classes;
- failure resistance, SCB method, with classes;
- spreading facility as per EN 12697-53;
- coating and homogeneity as per EN 12697-55, method A.

5.3. TECHNOLOGY

In order to get a better idea of the interaction between aggregate grains and bitumen emulsion in a mix, we must realise that an emulsion-based binder is not similar in its characteristics to hot-mix binders.

In a typical binder, there is an easy-to-understand dependence of viscosity on temperature, i.e. as the temperature increases, the viscosity decreases. And vice versa. Therefore, we know that, for example, bitumen must be hot enough to coat the (hot and dried) aggregate, and then the asphalt mix must also be at the right temperature to be compacted on site. In this context, we analyse the time and distance of transport from an asphalt mix plant to a construction site in terms of the temperature drop and bitumen viscosity increase.

Now imagine that we deal with an unusual binder that is insensitive to temperature changes, especially as the mix is not hot at all. Far more important is the fact that bonding of the aggregates by an emulsion-based binder (mix cohesion) only occurs when the emulsion breaks down, i.e. bitumen precipitation out of the water, and this in turn occurs when the water evaporates or the emulsion breaks down over the dust from the mineral mix. So the ACBE workability and is controlled by the emulsion composition and mineral mix composition. Moreover, this material does not have to be placed immediately, but can be stored for some time. As you can see, it is a complex issue which is not typical for the routine developed when handling "hot-mix" technologies. So, obviously, there is quite a lot to learn.

5.4. EXAMPLE OF GRAVEL EMULSION MIX PRODUCTION

Finally, we would like to show several interesting photos, made available by Eurovia Polska, which present the gravel emulsion (GE, Fr. La Grave Emulsion) mix production process, its paving and pavement condition after its paving is completed.

Fig. 5.1. *Mobile GE mixing plant close to a construction site (photo Eurovia Polska S.A.)*

Fig. 5.2. *GE mix in a spreader (photo Eurovia Polska S.A.)*

Fig. 5.3. *GE mix right behind a spreader (photo Eurovia Polska S.A.)*

Fig. 5.4. *GE mix during compacting (photo Eurovia Polska S.A.)*

Fig. 5.5. *Ready-made course made of GE mix (photo Eurovia Polska S.A.)*

VI. MOUNTAIN ROAD PAVEMENTS

#mountain roads, #special pavements, #HiMA

6.1. INTRODUCTION

Paved roads are used in different places and under different loads. Mountain road construction poses a particular challenge because vehicles exert greater impact on the pavements, particularly on ascents (lower speeds) and the climate conditions are more demanding (snowy days with more freeze-thaw cycles) (Fig.6.1.). Mountain pavements on which traditional, horse-drawn vehicle traffic takes place are a certain special case in this context. In order to increase the horse-drawn vehicle traffic safety, it is customary that horseshoes are equipped with horseshoe nails. These elements are made of very hard materials and adversely impact the asphalt mix resistance to crumbling, thus causing surface damage to a wearing course. As a consequence, such a pavement deteriorates faster than usual and necessary repairs are much more frequent.

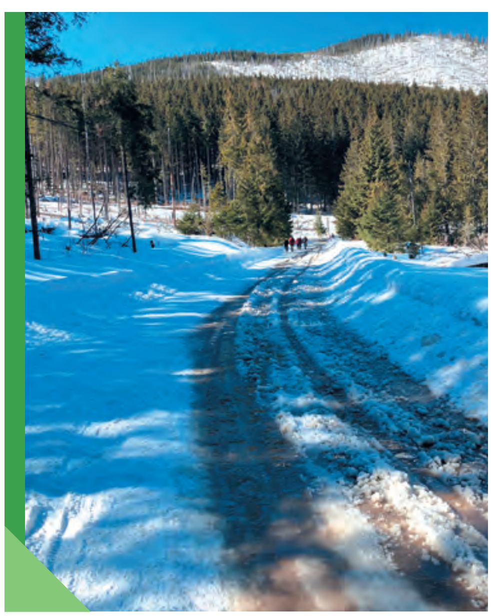

Fig. 6.1. *Mountain roads operate in demanding climate conditions (photo P. Ostrowski, ORLEN Asfalt)*

In 2015, our Research, Development and Innovation Department at ORLEN Asfalt started working with the Tatra National Park and the Tatra District with the view to assessing the condition of the pavement of the road routed from the car park in Palenica Białczańska to the Włosienica Meadow (towards the Morskie Oko shelter). Over a period of several years, a number of laboratory examinations were performed and test road sections were created to test the possibilities of selecting the most resistant asphalt mix for such specific traffic.

This chapter outlines the approach to this technological challenge, and also which tests were conducted and what results were achieved.

6.2. GENERAL ASSUMPTIONS AND PROBLEM IDENTIFICATION

Asphalt pavements operating horse-drawn vehicle traffic are subjected to unusual damage (Fig. 6.2.). This road in the Tatra Mountains is not loaded with conventional vehicular traffic, as cars appear there only sporadically (mostly vans with supplies for catering establishments located on the Włosienica Meadow and for the Morskie Oko shelter). Therefore it is difficult to consider conventional loads in terms of fatigue-related failure. However, considerable loads related to weather conditions are present (long snow and ice coverage periods, many freeze-thaw cycles) and horseshoe nails exerting a mechanical impact on the pavement.

Fig. 6.2. *Atypical wearing course damage (magnification) (photo K. Błażejowski, ORLEN Asfalt)*

When considering the climate-related loads, it must be assumed that a wearing course covered for a large part of the year with snow and ice must come with correspondingly high resistance to water and frost.

On the other hand, the mechanical durability of a course is related to the resistance to damage caused by horseshoe nails. Wearing course surface crumbling is manifested itself by crushed aggregate and mastic fragments, which consequently causes the emergence of 10 – 20 mm deep cavities. In this respect, using materials (aggregates, binders) and mix types that can withstand for a certain period of time this type of load must be considered.

Mountain roads are characterised by significant gradients and are quite winding. Such conditions determine the way horse-drawn vehicles move. Both during the ascent and descent, horses use the horseshoe nails to get a grip on the pavement and stabilise the vehicle movement. The steeper the gradient, the greater the need to dynamically drive the horseshoe nails into the pavement. Therefore, on the one hand, the wearing course must be susceptible to driving the nails to ensure secure grip, and, on the other hand, it must not crumble as a result of this action. These are, in a sense, mutually contradictory requirements, at least in terms of the materials that are currently used in road construction.

During ongoing discussions, several solution options were considered, taking into account durability as well as the safety of humans and (also importantly) horses:

- **Idea I. Hard pavement, resistant to horseshoe nail driving**. We considered constructing a pavement that is extremely hard and resistant to horseshoe nail driving. Here, the course durability is our priority. As a result, horses would not be able to get a good grip and would frequently slip on the road. In turn, this could affect the safety of people, vehicles and also the horses themselves. Therefore, this option does not seem suitable.
- **Idea II. Pavement with a macrotexture and spaces for horseshoe nails**. We considered using one of the well-known asphalt mixes with a considerable macrotexture made of large-sized grains with discrete graining, e.g. SMA 16. The essence of this idea is the fact that very hard grains (e.g. 11/16 mm fraction) will be able to survive the horseshoe nail impact, and the nails will enter the spaces between protruding grains to get a good grip.
- **Idea III. Plastic and flexible pavement**. We considered constructing a flexible course that absorbs the horseshoe nail impact to allow its "plastic" penetration, but that is also resistant to crumbling to a degree preventing the asphalt mix from disintegrating. This option is quite attractive, but it poses significant challenges as to the composition of such an asphalt mix, its cost, material type and, finally, its feasibility.

6.3. ASPHALT MIX CONCEPTS

Taking into account the previous considerations and assessing the wearing course operating conditions, it should be noted that there are contradictory functional expectations regarding the pavement. The pavement must be hard and resistant to horseshoe nail impact, but it should ensure that the horseshoes get a good grip to guarantee the safety of the horses, vehicles and their passengers.

For such a task, the selection of a correct technology is neither easy nor obvious. These conditions characteristic of mountainous regions are quite atypical.

While analysing this problem, the following issues were taken into account:

- asphalt mix type;
- requirements for aggregates;
- bitumen type.

These were considered in relation to their application in the new wearing course for the road in question.

Due to the necessity to enable horses to drive the horseshoe nails into the wearing course surface, possible application of asphalt mixes with a positive macrotexture ("protruding grains"), such as *Hot Rolled Asphalt* (HRA) or mixes with a negative macrotexture (larger pores in the surface between aggregates), such as SMA, were analysed. On the basis of observations regarding the existing pavement in this area, it was assumed that asphalt concrete (AC) would not meet the requirements.

Aggregates used in the new wearing course should be possibly hard and highly resistant to breaking up and impact exerted by studded tyres (simulating the horseshoe nail impact). Obviously, correct aggregate selection can be supported by adhering to the requirements in force in Scandinavian countries where studded tyres are commonly used and an adequate set of requirements based on the following standards has been developed: EN 1097-2 (resistance to fragmentation) and EN 1097-9 (abrasion by studded tyres).

As far as the selection of a correct binder is concerned, highly modified bitumens (HiMA) were considered, as they can be used in a wide spectrum of pavement operating temperatures, i.e. they are resistant to both very low and very high pavement temperatures. Moreover, highly modified bitumens demonstrate very good elasticity, which is consistent with the assumptions of Idea III described in section 6.2.

6.4. ASSUMED TEST METHODS AND NEW TEST METHOD DEVELOPMENT

The task required selecting correct test methods, tailored to the load type and facilitating evaluation of different solutions. A review of laboratory test methods showed that there was no suitable asphalt mix test in the national state of the art to check the materials and develop an optimum asphalt mix formulation, and to verify the resistance of the selected asphalt mix in relation to the specified type of damage.

As a consequence, asphalt mix verification tests were conducted using the method described in EN 12697-16 (abrasion with studded tyres), i.e. the Prall method (Fig. 6.3.), and the tests were performed in the Skanska laboratory, in Sweden.

Fig. 6.3. *Samples tested with the Prall method (photo P. Witkiewicz, SKANSKA AB)*

Fig. 6.4. *Proctor compactor with a horseshoe nail attached (photo P. Ostrowski, ORLEN Asfalt)*

In order to ensure more effective horseshoe nail impact on selected asphalt mixes, a proprietary sample testing method was created. In cooperation with Laboratorium Drogowe W. Bogacki, a device was designed to simulate nail impact onto a pavement. To this end, a manual Proctor compactor with an original horseshoe nail was used (Fig. 6.4.). Mix samples were created as for a rutting test, in a small apparatus. Next, each sample was divided into four sections to be tested with a specified number of hits. The sample weight loss was treated as the test result (Fig. 6.5.).

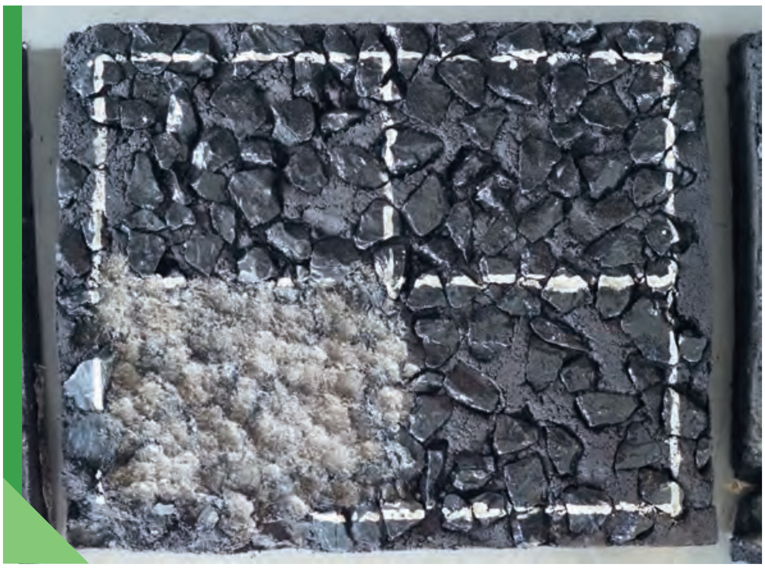

Fig. 6.5. *Sample after an impact test; first part of the test conducted on ¼ of the surface of an HRA sample (photo K. Błażejowski, ORLEN Asfalt)*

One of the more interesting solutions consisted in testing the mastic asphalt MA 5 in the laboratory, i.e. an attempt to specify a correct material in line with Idea III, i.e. a flexible and elastic mix. Additionally, the mix surface was notched to protect horses against slipping. This sample is presented in Fig. 6.6.

Apart from the Prall method and proprietary impact method, mixes were also assessed using the Cantabro method with the Los Angeles drum. Samples of various asphalt mixes tested with the Cantabro method are presented in Fig. 6.7.

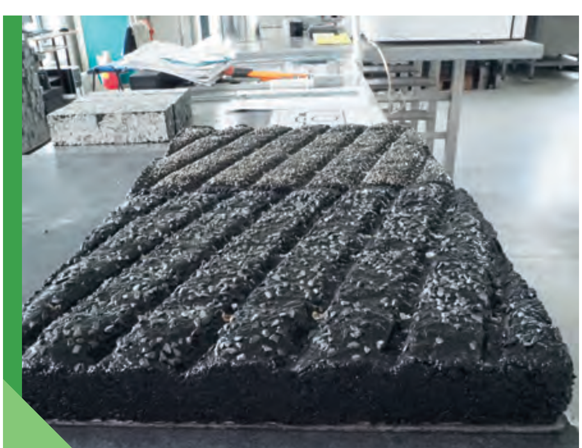

Fig. 6.6. *Mastic asphalt MA 5 as per Idea III (photo K. Błażejowski, ORLEN Asfalt)*

Fig. 6.7. *Samples of various mixes tested with the Cantabro method (photo K. Błażejowski, ORLEN Asfalt)*

6.5. ASPHALT MIX SELECTION FOR FIELD TESTS

On the basis of laboratory test results, four asphalt mixes (SMA16, SMA8, SMA5, MA8) were selected and, consecutively, paved (in autumn 2018) in the form of four slabs lateral to the road axis (Fig. 6.8.-6.9.). The slabs were subjected to normal horse traffic and they were to be used to assess suitability of each asphalt mix. An observation period lasting 2 – 3 years was assumed.

Fig. 6.8. *Placing the slabs in autumn 2018 by OAT sp. z o.o. (photo K. Błażejowski, ORLEN Asfalt)*

Fig. 6.9. *One of the slabs (SMA16 mix) following installation in the pavement, prior to sealing (photo K. Błażejowski, ORLEN Asfalt)*

6.6. TEST SECTION OF SELECTED ASPHALT MIX

In cooperation with the Tarzański District and the Tatra National Park personnel, as a result of observing the damage to pavements made of various types of asphalt mixes, one mix, i.e. SMA 5 PMB 45/80-80 HiMA, was selected to construct a 300 m long test road section in autumn 2021. Photos related to this project are shown in Fig. 6.10. and 6.11. The course was constructed with standard equipment, using a fine grit topping to roughen the surface.

Currently, the section is under observation and preparations for constructing longer sections are under way.

Fig. 6.10. *Compacting pavement section made of the SMA 5 (photo P. Ostrowski, ORLEN Asfalt)*

Fig. 6.11. *General view on site during asphalt works (photo ORLEN Asfalt)*

6.7. SUMMARY

Constructing pavements in mountainous areas presents unusual technological challenges. They result not only from the terrain configuration, i.e. ascents and winding roads, but also from harsher climatic conditions and unusual pavement loads exerted by horse-drawn vehicles. The latter problem is extremely difficult to resolve, as the expected pavement performance characteristics (durability and the need to ensure good grip for horseshoes) are in direct contradiction with the current state of material or implementation capabilities.

The process of selecting correct methods and materials involved an attempt to arrive at an optimal solution, both in terms of the mix type and component characteristics. It was not a trivial process and, although numerous creative ideas were set in motion, there were certainly many challenges to be faces for the process and road construction engineers.

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