LIFE E-VIA

“Electric Vehicle noIse control by Assessment and optimisation of tyre/road interaction”

LIFE18 ENV/IT/000201

Deliverable	Technical Report Actions A1, A2, A3
Content	Review on electric vehicles and their noise emission
Action/Sub-action	A2: Quiet pavement technologies and their performance over time
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Author	Filippo G. Praticò (UNIRC)
Beneficiary	University Mediterranea of Reggio Calabria (UNIRC)
Contact person	Filippo G. Praticò
E-mail	filippo.pratico@unirc.it
Project Website	https://life-evia.eu/

List of keywords and abbreviations

AR	Asphalt Rubber DPAC Double-layer Porous Asphalt Concrete
CPX	Close Proximity Index
DGAC	Dense Graded Asphalt Concrete
HRA	Hot Rolled Asphalt
ISO	ISO 10844 reference surface.
PA	Porous Asphalt
PLSD	Paver-Laid Surfacing Dressing
PMB	polymer-modified bitumen
SMA-LA	Split Mastic Asphalt
TAL	Thin Asphalt Layer
TLPA	Twin Layer Porous Asphalt
AC	Asphalt Concrete
ACFC	Asphalt Concrete Friction Course
ARFC	Asphalt Rubber Friction Course
AV	Air-void Content
b	Binder Percentage
BPN	British Pendulum Number
BWC	Bonded Wearing Course
CB	Controlled Pass-By Method
CPX	Close Proximity Method
CRMB	Crumb Rubber Bitumen Modified
DAC	Dense Asphalt Concrete
E	Dynamic Modulus
ELT	End Life Tires
CR	Crumb Rubber
ENDt	Estimated Noise Difference Due to Texture
ERNL	Estimated Road Noise Level
FC	Friction Course (PA)
GAP	Gap Graded
GAR	GAP with crumb rubber
GG	Gap Graded
HMA	Hot Mix Asphalt OGAC Open Graded Asphalt Concrete
HRA	Hot Rolled Asphalt
k	In-lab permeability
LOA 5D	Lärmoptimierter Asphalt (noise reducing asphalt for surface layer)
MPD	Mean Profile Depth
$NMAS_{90}$	Nominal Maximum Aggregate Size
OG	Open Graded
OGAR	Open Graded Asphalt Rubber
OGFC-AR	OGFC+ Asphalt Rubber
OGFC-SBS	OGFC+ Styrene-Butadiene-Styrene
OGR	OG with crumb rubber
PAC	Porous Asphalt Concrete
P-ACFC	Porous- Asphalt Concrete Friction Course
PEM	Porous European Mic
PERS	Poro-elastic Road Surface
PMFC	Polymer Modified Friction Course
RAC	Rubberized Asphalt Concrete
RAC(G)	Rubberized Asphalt Concrete, Gap Graded
RAC(O)	Rubberized Asphalt Concrete, Open
RAC-O	Rubber Asphalt Concrete-Open

Ref.	Reference
SLPA	Single Layer Porous Asphalt
SM	Stone Mastic Asphalt
SMA	Stone Mastic Asphalt
SPB	Statistical Pass-By Method
SUP	Superpave
TL	Thin Layer
TPA	Two-layers Porous Asphalt
UTLAC	Ultra-Thin Layer Asphalt Concrete
VTAC	Very Thin Asphalt Concrete

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Executive Summary

The project LIFE18 ENV/IT/000201-LIFE E-VIA objectives are (hereafter BEV/PHEV cars are generally referred to as electric vehicles, EV):

- To reduce noise for roads inside very populated urban areas through the implementation of a mitigation measure aimed at optimizing road surfaces and tyres of EVs. Two road surfaces, at least 5 different EV types, one reference ICE Vehicle (ICEV) and at least 3 types of tyres per vehicle type (including tyres specifically designed for EVs) will be tested
- To estimate the mitigation efficiency and potential of tyres, pavements and traffic (traffic spectrum, speeds, handling conditions) at a higher and comprehensive level: a Life Cycle Analysis (LCA) and a Life Cycle Cost Analysis (LCCA) will be performed to demonstrate the individual and synergistic efficiency of pavement surfaces, tyres and vehicles (including the comparison between internal combustion vehicles, mixed traffic, and EV traffic)
- To contribute to EU legislation effective implementation (EU Directives 2002/49/EC and 2015/996/EC), providing rolling noise coefficients within the Common Noise Assessment Method (CNOSSOS-EU), specifically tuned for EVs which are actually in need of data for practitioners, agencies, and departments aiming at developing future scenarios
- To contribute to national and Italian regional policies, issuing guidelines about use and application of the methodology output of the project, which will be adopted, through the Regional Env. Agency (ARPAT), supporting the project, by Tuscany Region, strongly interested in noise issues (partner of LIFE NEREIDE and Leopoldo project, and issued a law about control of road pavements with CPX method). Calabria Region and Città of Reggio Calabria also expressed their interest
- To raise people's awareness of noise pollution and health effects explaining the opportunities provided by EVs through specific dissemination and promotional events, also investigating people perception regarding noise in terms of soundscape methodology and involving them in noise data acquisition
- To demonstrate and promote sustainable road transport mobility (electric), reducing noise emission by 5 dB(A) at receiver's roadside and achieving also CO2 emissions reduction (21%), based on the Italian context (LPG, CNG, Hybrid, EV, petrol cars, diesel cars) and the concerned literature
- To encourage low-noise surfaces implementation in further EU and extra-EU scenarios, demonstrating durability and sustainability, through in-depth LCA&LCCA

All the planned activities have been carried out and all the objectives have been achieved. More details are given below.

Compliance of A2 activities with project submission

The table below summarises the compliance of this report with project assumptions.

Project description	***Answer***
Action A2 Quiet pavement technologies and their performance over time, for urban areas and EV [UNIRC] ***Description and methods employed (what, how, where, when and why):*** A2 focuses on Quiet pavement technologies and their performance over time. This action aims at providing the best scientific and practical bases to design the tracks. Importantly, it includes in-lab tests (**preliminary tests**).	Preliminary tests are discussed in section “Preliminary tests”.
Emphasis is going to be given to Crumb Rubber-added solutions because of their perspectives as per the current literature and because of the compliance with project objectives. To this aim, for each solution, this action focuses on: 1. **Acoustic performance and durability**. Outstanding initial noise performance (for example in terms of close proximity index or coast by method) is not sufficient to effectively target the objectives of the project, because the decay of quietness over time must comply with the decay of the remaining properties and a reasonable “quietness life” must be achieved. Based on the literature, the acoustic durability of several types of bituminous mixtures (e.g., obtained by adding crumb rubber) can be enhanced and can positively fit urban areas requirements. This is crucial for this project because it implies that the objectives stated are realistic and can be achieved through a careful understanding of the literature and through the subsequent actions planned.	For Acoustic performance and durability (including crumb-rubber solutions) see section “Pavement solutions in the literature (including CR-based ones)”.
2. **Non-acoustic performance and durability**. As is well known, the durability of acoustic characteristics interacts with the durability of the remaining characteristics. Therefore, the expected life of the friction course derives from comparing several classes of performance (e.g., mechanistic, volumetric, surface, and noise, cf. Praticò, 2017).	Non-acoustic performance and durability are discussed in section “Non-acoustic performance”
3. Corresponding **mixture composition** (quantities, typology), volumetric characteristics, and their evolution over time. Aggregate mixture and grading, crumb rubber type, size and quantity must fit the requirements in order to target volumetric and mechanical characteristics. This affects acceptance procedures (at the beginning of road life, “cradle”), durability, and end-of-life processes (“grave”).	Mixture composition is given in section “Composition”.
4. Corresponding **agency and user costs**. To effectively encourage low-noise surface implementation (objective 7), agency costs (materials, construction, maintenance, and rehabilitation) must be competitive. This means that raw and processed materials must comply with economic and environmental requirements. Particularly, this applies to crumb rubber content, where higher percentages correspond to a lower depletion of natural resources but, under unwanted circumstances, can bring to unsatisfactory rheological (Li et al, 2018) and volumetric characteristics and therefore to lower durability.	Agency and user costs are discussed in section “Agency and user costs”.
5. Pertaining to **raw materials and processes involved and their impact on environmental indicators**. To this end, it is noted that the carbon footprint of asphalt binders is quite high and that each remaining material has its own carbon footprint that must be carefully considered (including crumb rubber, if any). Furthermore, bitumen – crumb rubber interaction may have different effects in	The raw materials (e.g., aggregates, crumb rubber) and their impact are discussed in section

Project description	***Answer***
terms of mechanical impedance, rolling resistance, and rolling noise. In layman's terms, the potential to reduce noise for roads inside very populated urban areas (objective 1) is very high and an attentive study of materials and processes can lead to an overall reduction of environmental impacts (Wang et al, 2018).	“Environmental impact”.
6. Research and industrial areas and elements to enhance the formula/processes in the pursuit of improving their noise-related and overall characteristics. Based on the preliminary analysis of literature there is room for improving the performance of crumb rubber added bituminous mixtures based on crumb rubber treatment, (prior to the mixing stage), crumb rubber percentage/gradation, and crumb rubber function (cf. Shahrzad et al, 2018).	See section “Room for improvements”
7. Their compatibility and perspectives when analysed in terms of 2015/996/EC directive, CNOSSOS-EU mod. The hierarchical structure of noise quantification according to EU 2015/996 builds on having the steady traffic flow noise depending on traffic flow and single vehicle. In turn, this latter depends on rolling noise and propulsion noise. For rolling noise, it depends on speed, temperature, crossing with traffic light or roundabout, studded tyres, and road surface. In summarising, the following primary components are expected to change in this project: propulsion and road surface. Importantly, internal combustion torque delivery and power have their maxima around 3k-6k RPM, while EV torque delivery is quite immediate. This is likely to affect the rolling noise as well as future pavements (see below).	See section “Quiet pavements and EU approach”
8. Their compatibility and perspectives when compared to the transition from the actual spectrum of traffic to a new scenario in which EVs will be an outstanding percentage. To this end, it is noted that out of a total number of more than 50 million vehicles on the road in Italy at the end of 2016, about 6,000 were electric passenger cars (IA-HEV), while at the end of 2017 they were about 14000. Now this is going to have effects on pavement durability because of the higher weight of EVs compared to ICE vehicles. Under the hypothesis of having about 4.8 million of EVs (PHEV+BEV) in 2030 (E-Mobility Report 2018), compared to a total number of 50 million vehicles, this would imply a tangible increase (about +20%) of pavement damages (Generalized Fourth Power Law). The superposition of higher loads and higher immediate torque (and then shear stress) is going to affect pavement durability (cf. action B1). Indeed, the issue is not only to reproduce and apply the right solution to mitigate the noise impact of EV relevant percentages through low-noise surfaces but to find solutions concretely reliable, sustainable, and suitable.	See section “1.1.1” and section “Quiet pavements and EU approach”
So, the strategy is going to populate the A.2 Technical Report as follows in the pursuit of the analysis of best existing solutions. In this section for each of them the following data and analyses will be focused: 1) Acoustic performance and durability (including their compatibility and perspectives when analysed in terms of 2015/996/EC directive, CNOSSOS-EU and for relevant percentages of EVs in urban areas);	See section “Acoustic durability”.
2) Non-acoustic performance and durability (also for and for relevant percentages of EVs in urban areas);	See section “Non-acoustic performance”
3) Corresponding mixture composition (quantities, typology), volumetric characteristics, and their evolution over time (including what would happen for relevant percentages of EVs in urban areas);	Mixture composition is given in section “Composition”.

Project description	***Answer***
4) Expected data to use when predicting the corresponding road owner costs and user costs (this includes the consideration of raw and virgin material environmental and economic impact);	Agency and user costs are discussed in section "Agency and user costs".
5) Opportunities for improving the performance (e.g., for crumb rubber-added bituminous mixtures). Based on a preliminary analysis and on the literature, **at least six classes of solutions** are foreseen, each of them including a number of attempts and variations (e.g., 3), also as a function of the type of process (where wet and dry are the ideal extreme conditions) and percentage.	See section "Room for improvements". See section "Selected Mixes".
Beneficiary responsible for implementation: UNIRC. UNIRC gathers and structures available references in the pursuit of the following actions (mainly B1 and C2). IFSTTAR and IPOOL provide advice, support and references for tyre-pavement interaction (IFSTTAR) and noise-related issues (IPOOL).	

Table 1. Action A2: expected versus actual activities

Note that Figure 1 shows the main tables in which the main objectives are addressed.

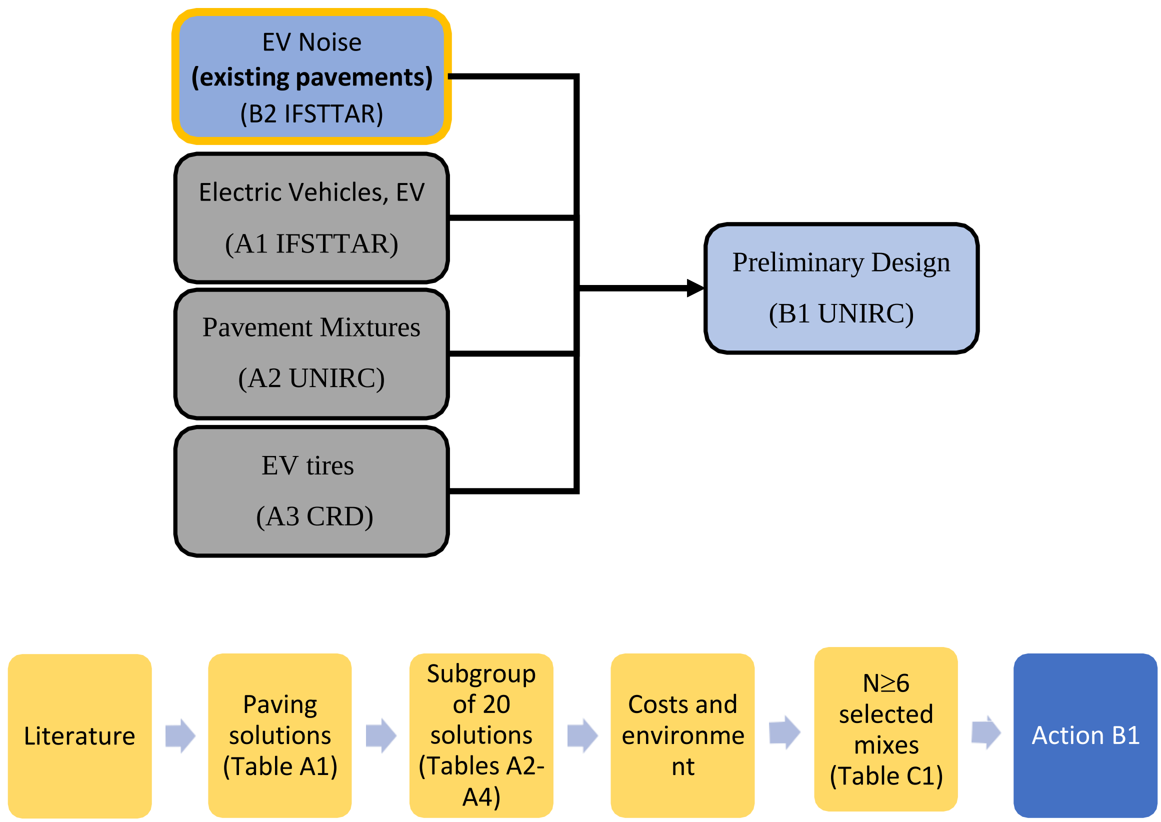


Figure 1. From the literature to more than six solutions

1 Action A2: Quiet pavement technologies and their performance over time

1.1 Main parameters of the project and of A2

Project: E-VIA LIFE18 ENV/IT/000201
Scheduled Duration of the project: 45 months starting from July, 1, 2019
Scheduled Duration of this action (A2): 9 months starting from July, 01, 2019

Deadline: 03/2020

Other actions connected
B1: Tracks design. B1 aims at selecting mixtures (volumetrics, materials, and surface texture), for the tracks to be constructed in France and Italy, in order to minimize noise from EV, taking into account the synergy with actions B2. [UNIRC] B1. Milestone deadline: 31/01/2021. Report deadline: 31/03/2021.

C2: Life cycle analysis (LCA) and life cycle costing (LCC). These analyses will evaluate track efficiency from a comprehensive point of view, including soundscape components (B5), thus achieving obj.6 of demonstrating the durability and effectiveness through LCA/LCC. [UNIRC] C2 Report: deadline: 31/01/2023.

1.1.1 Description of A2 according to the project

A. Preparatory actions (if needed)
ACTION A.2: Quiet pavement technologies and their performance over time
Description and methods employed (what, how, where, when and why): A2 focuses on Quiet pavement technologies and their performance over time. This action aims at providing the best scientific and practical bases to design the tracks. Importantly, it includes in-lab tests (preliminary tests). Emphasis is going to be given to Crumb Rubber-added solutions because of their perspectives as per the current literature and because of the compliance with project objectives.

To this aim, for each solution, this action focuses on:

1. **Acoustic performance and durability.** Outstanding initial noise performance (for example in terms of close proximity index or coast by method) is not sufficient to effectively target the objectives of the project, because the decay of quietness over time must comply with the decay of the remaining properties and a reasonable “quietness life” must be achieved. Based on the literature (Sandberg, 2010 [1]; Krag et al, 2013 [2]; Licitra et al, 2015 [3]; Licitra et al, 2019 [4]), the acoustic durability of several types of bituminous mixtures (e.g., obtained by adding crumb rubber) can be enhanced and can positively fit urban areas requirements. This is crucial for this project because it implies that the objectives stated are realistic and can be achieved through a careful understanding of the literature and through the subsequent actions planned.
2. **Non-acoustic performance and durability.** As is well known, the durability of acoustic characteristics interacts with the durability of the remaining characteristics. Therefore, the expected life of the friction course derives from comparing several classes of performance (e.g., mechanistic, volumetric, surface, and noise, cf. Praticò, 2017 [5]).
3. **Corresponding mixture composition** (quantities, typology), volumetric characteristics, and their evolution over time. Aggregate mixture and grading, crumb rubber type, size and quantity must fit the

requirements in order to target volumetric and mechanical characteristics. This affects acceptance procedures (at the beginning of road life, “cradle”), durability, and end-of-life processes (“grave”).

4. **Corresponding agency and user costs.** To effectively encourage low-noise surface implementation (objective 7), agency costs (materials, construction, maintenance, and rehabilitation) must be competitive. This means that raw and processed materials must comply with economic and environmental requirements. Particularly, this applies to crumb rubber content, where higher percentages correspond to a lower depletion of natural resources but, under unwanted circumstances, can bring to unsatisfactory rheological (Li et al, 2018 [6]) and volumetric characteristics and therefore to lower durability.
5. **Pertaining to raw materials and processes involved and their impact on environmental indicators.** To this end, it is noted that the carbon footprint of asphalt binders is quite high and that each remaining material has its own carbon footprint that must be carefully considered (including crumb rubber, if any). Furthermore, bitumen – crumb rubber interaction may have different effects in terms of mechanical impedance, rolling resistance, and rolling noise. In layman's terms, the potential to reduce noise for roads inside very populated urban areas (objective 1) is very high and an attentive study of materials and processes can lead to an overall reduction of environmental impacts (Wang et al, 2018) [7].
6. **Research and industrial areas and elements to enhance the formula/processes** in the pursuit of improving their noise-related and overall characteristics. Based on the preliminary analysis of literature there is room for improving the performance of crumb rubber added bituminous mixtures based on crumb rubber treatment, (prior to the mixing stage), crumb rubber percentage/gradation, and crumb rubber function (cf. Shahrzad et al, 2018 [8]).
7. **Their compatibility and perspectives when analysed in terms of 2015/996/EC directive, CNOSSOS-EU mod**. The hierarchical structure of noise quantification according to EU 2015/996 builds on having the steady traffic flow noise depending on traffic flow and single vehicle. In turn, this latter depends on rolling noise and propulsion noise. For rolling noise, it depends on speed, temperature, crossing with traffic light or roundabout, studded tyres, and road surface. In summarising, the following primary components are expected to change in this project: propulsion and road surface. Importantly, internal combustion torque delivery and power have their maxima around 3k-6k RPM, while EV torque delivery is quite immediate. This is likely to affect the rolling noise as well as future pavements (see below).
8. **Their compatibility and perspectives when compared to the transition from the actual spectrum of traffic to a new scenario in which EVs will be an outstanding percentage.** To this end, it is noted that out of a total number of more than 50 million vehicles on the road in Italy at the end of 2016, about 6,000 were electric passenger cars (IA-HEV), while at the end of 2017 they were about 14000. Now this is going to have effects on pavement durability because of the higher weight of EVs compared to ICE vehicles. Under the hypothesis of having about 4.8 million of EVs (PHEV+BEV) in 2030 (E-Mobility Report 2018), compared to a total number of 50 million vehicles, this would imply a tangible increase (about +20%) of pavement damages (Generalized Fourth Power Law). The superposition of higher loads and higher immediate torque (and then shear stress) is going to affect pavement durability (cf. action B1).

1.1.2 Beneficiary responsible for implementation

UNIRC (IFSTTAR, IPOOL): UNIRC gathers and structures available references in the pursuit of the following actions (mainly B1 and C2). IFSTTAR and IPOOL provide advice, support and references **for tyre-pavement interaction (IFSTTAR)** and noise-related issues (IPOOL).

1.1.3 Other actions connected

B1: Tracks design. B1 aims at selecting mixtures (volumetrics, materials, and surface texture), for the tracks to be constructed in France and Italy, in order to minimize noise from EV, taking into account the synergy with actions B2. [UNIRC]. B1. Milestone deadline: 31/01/2021. Report deadline: 31/03/2021.

C2: Life cycle analysis (LCA) and life cycle costing (LCC). These analyses will evaluate track efficiency from a comprehensive point of view, including soundscape components (B5), thus achieving obj.6 of demonstrating the durability and effectiveness through LCA/LCC. [UNIRC]. C2 Report: deadline: 31/01/2023.

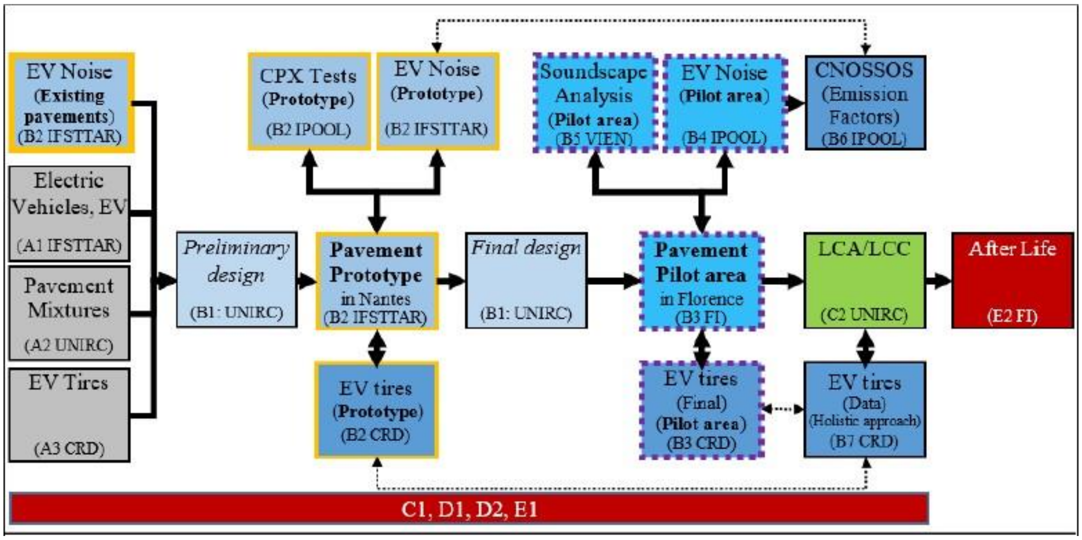


Figure 2. Flow chart of the project

1.1.4 Gaant

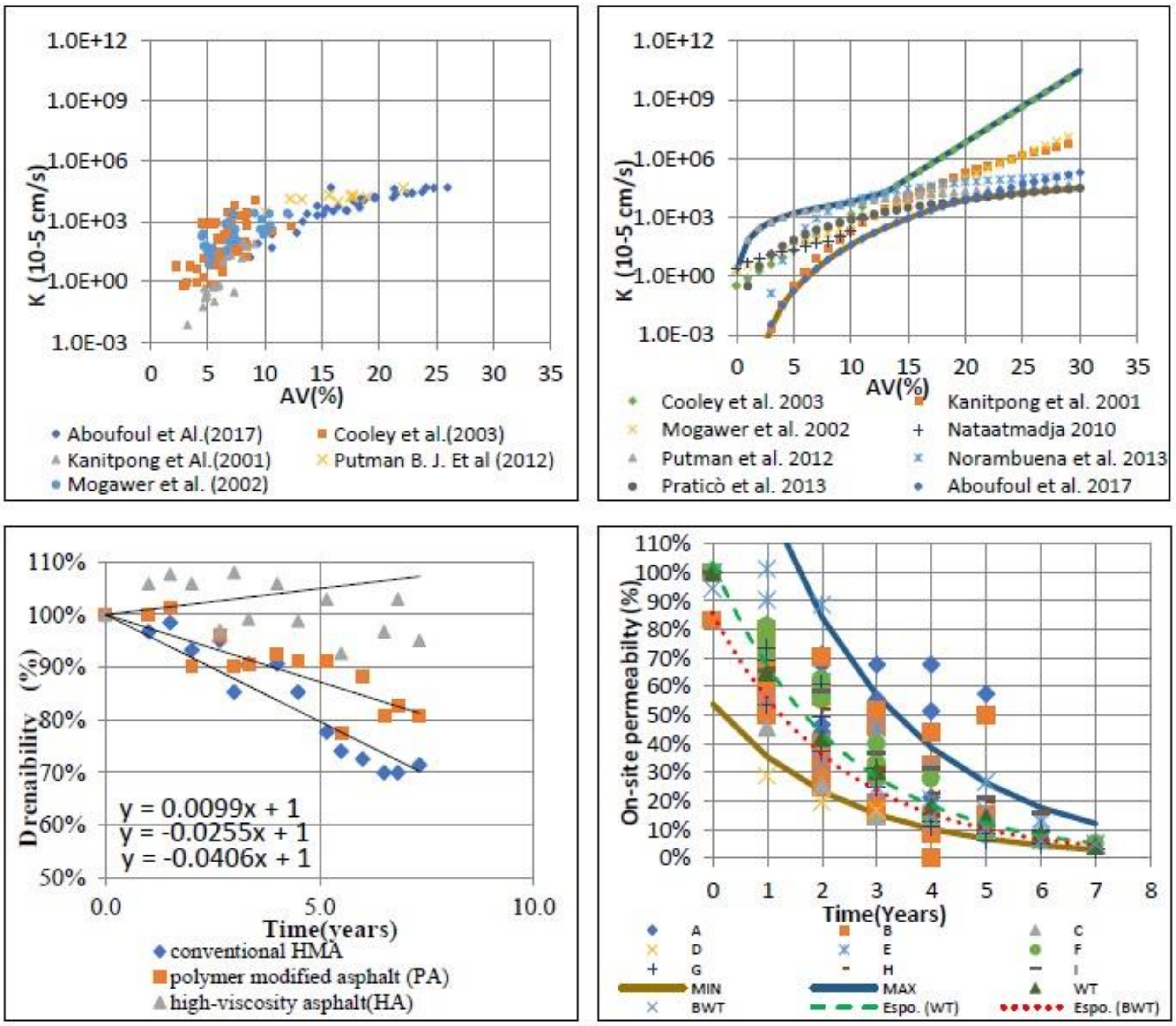
Action		2019				2020				2021				2022				2023				2024			
Action numbe	Name of the action	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
A. Preparatory actions (if needed)																									
A.1	Electric vehicles and their noise emission			■	■	■																			
A.2	Quiet pavement technologies and their performance over time			■	■	■																			
A.3	Tyre role in the new context of EV and ICEV			■	■	■																			
B. Implementation actions (obligatory)																									
B.1	Tracks design				■	■	■	■	■	■															
B.2	Tyre-pavement coupling study and prototype implementation			■	■	■	■	■	■	■	■	■													
B.3	Pilot area: Implementation. Replication and tranferability						■	■	■	■	■	■	■	■	■	■	■	■							
B.4	Track efficiency tests in the pilot area							■	■	■	■	■	■	■	■	■									
B.5	Soundscape analysis			■	■	■	■	■	■	■	■	■	■	■											
B.6	Evaluation of EV noise emissions							■	■	■	■	■	■	■	■	■									
B.7	Holistic performances of tyres			■	■	■	■	■	■	■	■	■	■	■	■	■	■								
C. Monitoring of the impact of the project actions (obligatory)																									
C.1	Monitoring of the impact of the project actions			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
C.2	Life cycle analysis (LCA) and life cycle costing (LCC)			■	■	■	■	■	■	■	■	■	■	■	■	■	■								
D. Public awareness and dissemination of results (obligatory)																									
D.1	Information and awareness raising activities			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
D.2	Technical dissemination activities to stakeholders			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
E. Project management (obligatory)																									
E.1	Coordination, Monitoring and Project management			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■							
E.2	After LIFE Plan																■	■							

Figure 3. Gantt of the project

1.2 Introduction to the problem

This section refers to relationships in the literature to use in order to provide pieces of information that are not explicitly given (for example, permeability).

Based on “Surface properties of porous asphalt concretes: Time, position, and treatment impact” [9] and on and asphalt concrete for electric vehicles [2] the following figures and sections illustrate the main relationships among the different properties of hot mix asphalts. Note that K represent the in-lab permeability while AV stands for Air Void content (on the left: data; on the right: models).



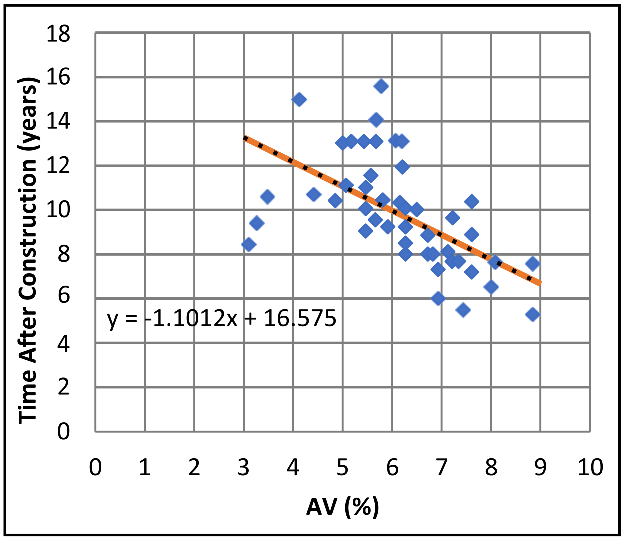


Figure 4. Permeability as a function of time and AV

1.3 Pavement solutions in the literature (including CR-based ones)

A careful study of pavement solutions (including crumb-rubber solutions) in the literature was carried out. The acoustic durability of different types of bituminous mixtures was considered. Clogging phenomena resulted crucial for diminished acoustic performance, especially when dealing with open-graded friction courses.

The following table summarises the pavement solutions considered. When available, the acoustic performance was reported. Note that the following pieces of information are reported: 1) Reference (REF). 2) Solution (type of solution). 3) Thickness (mm). 5) Maximum aggregate size (MAS) or Nominal Maximum aggregate size (NMAS), mm. 6) Macrotexture (MTD, mm) or/and air void content (AV, %). 7) Acoustic indicator used (AC). 8) Noise reduction (RED, dB). 9) Acoustic durability (ACDUR, years). 10) Noise increase NI (dB/year).

Table A1

REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
[10]	PERS	30	2mm (rubber) 8 mm (aggregate)	30-35%		5-15 (vs. DAC)		
	RAC (O)	30	12 (as OGFC)	14-20%		6		
	RAC(G)	30-50	12 (as DGFC)	4%				
	SMA 0/16	30-50	16 mm	4%		-1 ~ -2		
	SMA 0/11	30-50	11	4%		0		
	SMA 0/8	30-50	8	4%		1		
	SMA (general)	30-50	5-16 mm	0.5-1.5 mm 4%		-2 ~ -1		
	DAC 0/11 or DAC 0/8	30	8/11	0.8 mm 4%		0		
	PAC 0/8	45	16	25%		3		
	PAC 0/11	45	11	25%		4		
	PAC 0/8	45	8 mm	25%		5		
	TPA	25 (top)+ 45 (bottom)	8 (top) 16 (bottom)	20% (top) 25% (bottom)		4-6 (vs. DAC)		

Table A1								
REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	Thin layers	5- 8 mm	5 – 8 mm	5 -15%		3-7		
	Bardon	25 – 35 – 50 mm c.a.	14	SH=2mm		3 (vs. HRA)		
	Masterflex (Note: it is not a registered trademark)	(15-50 mm)	6-10-14	2 mm		5-6 (vs. DAC)		
	Novachip	(12 – 25 mm)	6 mm; 9 mm; 12mm; (1/4 – 3/8 – 1/2)	Texture similar to PAC		1 (VS. PCC/DAC)		
	MASTERpave	(20 mm – 50 mm -75 mm)	6 – 14 – 20 mm	1.5-2		4		
	UL-M	20 – 50 mm	6 mm – 10 mm – 14mm	1.5 mm		5-7 (vs. DAC)		
	MicroFlex		6 mm	AV=13%		3.9-4.9 (vs, DAC)		
	Colsoft	20-30 mm	6 mm – 10 mm	2 mm		3~5 (vs. DAC)		
	Rugosoft	20-50 mm	Unknown	Unknown		5~7 (vs. DAC)		
	Nanosoft	25-40 mm	4 mm	Unknown		9		
	MICROVIA	10-30 mm	6 mm	0.8 mm		Unknown		
	Rollpave	30 mm	6 mm	Unknown		4.3		
	Nobelpave	NA						
	Surface dressing	3~20 mm	3~20 mm			+2~-3 dB		
	Porous cement concrete	80	9.5 mm	20-25%		4~8		
	Portland cement concrete - general			4%-25%		-2~8		
[11]	TL	>30 mm	6 – 8 mm (4 mm)	8-12% (18-20%)		1-3 (vs. AC11) 2.5-4.5 (vs. SMA 16)		
	SMA-LA	20-40 mm				2.5 (vs. AC and SMA)		
	PA-1L					2-4 (vs. AC11) 3.5-5.5 (VS. SMA16)		
	PA-2L					1-2 (vs. PA-1L)		
	PERS					8 – 10 dB (vs. AC 11) 10 - 12 dB (vs. SMA 16)		
[12]	PA/SLPA	40 mm	0/11, 0/16 or 0/20 with a gap at 2/7	>20%		5-6	10-15	
	TLPA	35-65 mm (top) 20-30 mm (bottom)	11-20 mm (top) 4-8 mm (bottom)	20-25%		6-7	10-15	
[13]	PA	30-50 mm	6-20 mm	>20%		4		
	PA-2L	45 mm (top) 25 mm (bottom)	11-16 mm (top) 4-8 mm (bottom)		*SPB*	5-6		
	VTAC	20-30 mm	gap graded 20/30 mm + (0/6 or 0/10 and sometimes 0/4).	15-25% HS= 0.7-1.2 mm				

Table A1								
REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	UTLAC	10-20 mm	11 mm			2-3 (vs. AC 0/11)		
	SMA	15-45 mm	11 mm (0/11 -0/6 - 0/16)	3-6%		2-3 (vs. DAC)		
[14]	DAC 11		11	5.4%	SPB/CPX	/		
	OGAC 6		6	/	SPB/CPX	4.3 (vs. DAC 0/11)		
	SMA 6+/5/8		6+5/8	3.4%	SPB/CPX	0.9 (vs. DAC 0/11)		
	SMA 6+/5/8		6+5/8	5.7%	SPB/CPX	1.3 (vs. DAC 0/11)		
	SMA 6		6	15.3%	SPB/CPX	3.2 (vs. DAC 0/11)		
	SMA 0/4		4	8.8%	SPB/CPX	1.6 (vs. DAC 0/11)		
	SMA 4+/5/8		4+5/8	10.2%	SPB/CPX	3.0 (vs. DAC 0/11)		
	SMA 6+/5/8 (opt.)		6+5/8	13.9%	SPB/CPX	3.7 (vs. DAC 0/11)		
[15]	SMA 16		16	/		-1.5 (vs. SMA 11)		
	SMA 11		11	/		1.5 (vs. SMA 16)		
	SMA 8		8	6-8.3%		1.9/3.4 (vs. SMA11/SMA16)		
	SMA 6		6	8-8.9%		2.6/4.2 (vs. SMA11/SMA16)		
	AC 11		11	2.3-2.8%		1.5/3.0 (vs. SMA11/SMA16)		
	AC 8		8	12.2%		1.5/3.1 (vs. SMA11/SMA16)		
	AC 6		6	11.7%		2.7/4.2 (vs. SMA11/SMA16)		
[2]	SMA 16		16	MPD=0.99 mm	CPX	100.5 dB		
	AC 8d		8	MPD=0.7 mm	CPX	97.5 dB		
	AC 6o		6	MPD=0.72 mm	CPX	94.9 dB		
	ISO 10844		8	MPD=0.86 mm	CPX	94.7 dB		
[16]	AC	20-30 mm	5.6	1-2.5%	CPX	-		
	SMA	20-30 mm	5.6	1.5-3%	CPX	-		
	LOA 5 D	20-25 mm	5.6	5-6%	CPX	0.9-2.9 (vs. AC/SMA)		
[17]	LOA 5D	20-25 mm	5.6 mm	6.8%	CPX	/		0.23-2.27
[18]	AR gap-graded (dry)		0/8	7.2	CPX	1.8 (vs. Ref. gap-graded)		
	AR gap-graded (wet)		0/8	6.6	CPX	1.7 (vs. Ref. gap-graded)		
	AR open-graded (dry)		0/8	20.9	CPX	1.1 (vs. Ref. gap-graded)		
	AR open-graded (wet)		0/8	20.7	CPX	1.1 (vs. Ref. gap-graded)		
[19]	ISO-SURFACE (DAC 8)	30	8 mm		CPX	86.9-94.4		
	TL	25	2/4		CPX	84.3-91.7		
	TL	25	2/6		CPX	84.4-91.4		
	TL	25	2/6		CPX	84.6-91.2		
	TL	25	4/8		CPX	86.5-92.9		
	PA	50	0/11		CPX	89.2-94.9		
	PA	50	0/16		CPX	88.2-94.1		
	PA	50	4/8		CPX	85.9-91.3		
	PA	25	4/8		CPX	89.8-95.6		

Table A1

REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	PA	25 (top) +65 (bottom)	4/8 (top) +11/16 (bottom)		CPX	85.2-91.1		
	PA	25(top) +45 (bottom)	4/8 (top) +11/16 (bottom)		CPX	85.2-90.8		
	PERS	32			CPX	79.7-87.1		
	PA	25+25	2/4+8/11		CPX	81.7-87.9		
	PA	25+25	2/6+8/11		CPX	82.4-88.6		
	PA	25	2/6		CPX	84.9-91.4		
	PA	25+45	2/6+11/6		CPX	82.2-88.6		
	PA+EPAC	25+45	2/6+0/16		CPX	82.1-88.4		
	PA+EPAC	25+45	2/6+0/16		CPX	82.0-88.6		
	SMA	20	0/6		CPX	86.6-94.0		
	SMA	25	0/8		CPX	89.3-96.0		
	SMA	30	0/11		CPX	90.7-97.4		
	SMA	40	0/16		CPX	91.6-98.5		
	DAC	40	0/16		CPX	88.4-96.1		
[20]	SMA-10		10	7%	CPX/SPB	/		0.58/0.45
	TAL-Porous type		4	25%	CPX/SPB	3.8/6.3 (vs. SMA-10)		2.39/1.70
	TAL-Porous type		4	25%	CPX/SPB	5.9/5.4 (vs. SMA-10)		1.34/0.43
	TAL-SMA-Like		6.3	11%	CPX/SPB	1.0/5.4 (vs. SMA-10)		1.37/0.96
	DPAC		6.3 (top) + 14 (bottom)	23% (top) + 21% (bottom)	CPX/SPB	5.8/6.1 (vs. SMA-10)		2.45/1.27
	TAL-SMA-Like		6.3	15%	CPX/SPB	3.1/5.1 (vs. SMA-10)		1.46/0.24
	TAL-SMA-Like		6.3	11%	CPX/SPB	2.0/4.3 (vs. SMA-10)		1.31/1.21
	TAL-SMA-Like	25 mm	6.3	11%	CPX/SPB	-0.2/3.6 (vs. SMA-10)		1.13/0.56
	TAL-SMA-Like	30 mm	6.3	11%	CPX/SPB	-1.6/3.2 (vs. SMA-10)		1.00/0.33
	TAL-SMA-Like		8	14%	CPX/SPB	0.1/0.7 (vs. SMA-10)		0.62/0.73
[21]	AC11d	30 mm	11	-	SPB	-		
	AC8d	25 mm	8	-	SPB	1.0 (vs. AC11d)		
	AC6o	20 mm	6	8-14%	SPB	2.3 (vs. AC11d)		
	SMA6+	20 mm	6+5/8	4-8%	SPB	2.0 (vs. AC11d)		
	TP6c	17 mm	6	14%	SPB	3.1 (vs. AC11d)		
[22]	AC11d	33 mm	11	3 %	SPB	-		
	SMA8	29 mm	8	12 %	SPB	0.0- 0.8 (vs. AC11d)		
	AC8o	28 mm	8	15 %	SPB	2.3 - 2.8 (vs. AC11d)		
	TP8c	22 mm	8	14	SPB	1.0-2.2 (vs. AC11d)		
	SMA6+	26 mm	6+5/8	3 %	SPB	1.4-1.5 (vs. AC11d)		
	SMA 8+	23 mm	8+8/11	5.7%	SPB	2.4 (vs. AC11d)		
[23]	ARFC	25 mm	9.5 mm	20-21%	CPX/OBSI	/		0.5 dB/Year
[24,25]	OGFC-AR	19 mm	9.51 mm		OBSI	4.3 (vs. HMA)		2.1
	OGFC-SBS	19 mm	9.51 mm		OBSI	3.4 (vs. HMA)		1.45
	HMA	30 mm	12.5 mm		OBSI	/		1.03
[26–28]	OGAC	25 mm	9.5 mm	/	/	/		0.11-0.19
[27–29]	DGAC	30 mm	12.5 mm	9%	SPB	/		0.24*-0.29**
	OGAC	30 mm	12.5 mm	15%	SPB	1.7 (vs. DGAC)		0.20*-0.12**
	OGAC	75 mm	12.5 mm	12%	SPB	3.3 (vs. DGAC)		0.10*-0.31**

Table A1								
REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	RAC-O	30 mm	12.5 mm	12%	SPB	2.3 (vs. DGAC)		0.40*-0.36**
	BWC	30 mm	12.5 mm	7%	SPB	0.9 (vs. DGAC)		/
[30]	DGAC11	33 mm	11	2.8	SPB/CPX	/		0.72*-0.8**
	UTLAC	22 mm	8	14.4	SPB/CPX	2.2 (vs. DGAC11)		1.06*-0.35**
	OGAC	28 mm	8	15.3	SPB/CPX	2.9 (vs. DGAC11)		0.8*-0.09**
	SMA8	29 mm	8	12.4	SPB/CPX	0.4 (vs. DGAC11)		0.5*-0.21**
	SMA6+	26 mm	6+5/8	3.0	SPB/CPX	1.6 (vs. DGAC11)		0.93*-0.63**
	SMA8+	33 mm	8+8/11	5.7	SPB/CPX	2.5 (vs. DGAC11)		1.32*-0.67**
[31]	Slurry Seal	/	10 mm	0.49-0.60 mm (MPD)	CPX	/		0.09-0.26
	AC	/	22 mm	0.79 mm (MPD)	CPX	/		0.8
	AC	/	22 mm	1.4 mm (MPD)	CPX	/		0.4
[32]	Dense	/	16	/	CPX	/		0.03
		/	11	/	CPX/SPB	/		0.32-.34/0.05-0.48
		/	≤8	/	CPX/SPB	/		0.41-0.48/0.12-0.39
	Thin Layer	/	10	/	SPB	/		0.30
		/	8	/	CPX/SPB	/		0.50/0.30-0.84
		/	≤6	/	CPX/SPB	/		0.43-0.59/0.12-0.76
	Porous	/	16	/	CPX/SPB	/		0.21/0.41-0.43
		/	10	/	SPB	/		0.12-0.21
		/	8	/	CPX	/		0.30
		/	6	/	SPB	/		0.06
	Two Layer-Porous	/	8	/	CPX	/		0.37
[33]	1L-PAC	/	0/16	/	SPB+CPX			0.20-0.62
	1L-PAC	/	0/8-0/11	/	SPB+CPX			0.19-0.65
	1L-PAC	/	0/6	/	SPB+CPX			0.14
	2L-PAC	/	0/8	/	SPB+CPX			0.36-0.52
	TSL semi-open	/	0/6	/	SPB+CPX			0.33/0.67
	SMA	/	0/14	/	SPB+CPX			0.33-0.48
	SMA	/	0/8-0/11	/	SPB+CPX			0.10-0.58
	SMA	/	0/6	/	SPB+CPX			0.18/0.60
	HRA	/	0/20	/	SPB+CPX			0.2/0.25
	2L-PC	/		/	SPB+CPX			0.12-0.16
	DAC	/	0/8-0/11	/	SPB+CPX			0.04-0.53
	DAC	/	0/16	/	SPB+CPX			0.04-0.11
[34]	AC11d	/	11	/	SPB	/		0.27-0.48
	SMA8	/	8	/	SPB	0.2 (vs. AC11d)		0.42

Table A1

REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	SMA6+	/	6	/	SPB	1.7 (vs. AC11d)		0.32-0.65
	AC8o	/	8	/	SPB	2.7 (vs. AC11d)		0.76
	AC6o	/	6	/	SPB	1.9 (vs. AC11d)		0.43
	UTLAC6	/	6	/	SPB	2.5 (vs. AC11d)		0.51
	UTLAC8	/	8	/	SPB	1.6 (vs. AC11d)		0.70
	AC8d	/	8	/	SPB	1.2 (vs. AC11d)		0.30
[23]	PEM	/	19	/	OBSI	/		0.39
	ARFC	/	19	/	OBSI	4.1 (vs. PEM)		0.59
	ACFC	/	19	/	OBSI	1.5 (vs. PEM)		0.65
	SMA	/	19	/	OBSI	0.9 (vs. PEM)		0.48
	P-ACFC	/	19	/	OBSI	0.8 (vs. PEM)		0.71
[35]	AC6	/	0/6	/	CPX	2.25-3.75 (vs. SMA11)		0.4-2.1
	SMA6	/	0/6	/	CPX	1.90-3.2 (vs. SMA11)		1.47-1.53
	AC8	/	0/6	/	CPX	2.43-.2.67 (vs. SMA11)		1.10-1.57
	SMA8	/	0/8	/	CPX	0.45-2.85 (vs. SMA11)		1.27-5.50
	SMA11	/	0/11	/	CPX	/		0.10-2.50
	AC11	/	0/11	/	CPX	0.95-2.03 (vs. SMA11)		0.45-1.67
	SMA16	/	0/16	/	CPX	0.05-0.20 (vs. SMA11)		0.57-0.9
	Thin Layer	/	0/8	/	CPX	1.43-2.40 (vs. SMA11)		1.45-1.80
	1L-PA	/	0/8	/	CPX	2.25-4.33 (vs. SMA11)		1.05-3.0
	1L-PA	/	0/11	/	CPX	2.36-3.11 (vs. SMA11)		1.6-1.85
	2L-PA	/	0/8+0/16	/	CPX	4.1334.55 (vs. SMA11)		1.85-3.95
	2L-PA	/	0/11+0/16	/	CPX	3.47-3.83 (vs. SMA11)		1.20-1.75
[36]	PAC	40	8	18-24%	SPB	6.0 1.6-3.2 (vs. SMA)		2.7
	VTAC	30	8	12-15%	SPB	6.5 1.6-3.2 (vs. SMA)		1.9
	SMA	40	11	3%	SPB	/		0.63
	PA	40	11	18-22%	SPB	1.6-3.2 (vs. SMA)		0.63-0.80
	SMA	40	11	3%	SPB	/		0.20-0.30
[37]	OGAR	/	10	n=14%	CB	0.9-3.9 (vs. GG)		1.1-1.7
	OGAR	/	12	n=13%	CB	0.3-0.8 (vs. GG)		1.1-1.13
	GG	/	12	n=3.6%	CB	/		0.97-1.37
[38]	PAC	50-80 mm	0/10	20-30%	SPB	/		0.55
	VTAC class2	20-30 mm	0/6	18-25%	SPB	/		0.43
[39]	PMFC	30 mm	10	17%	CPX	/		1.44
	Pre-blended PMFC	50 mm	20	20%	CPX	/		1.40
	Pre-Blended PMFC	30 mm	10	17%	CPX	/		1.21
	Pre-blended PMFC	50 mm	10	17%	CPX	/		1.36
	FC	30 mm	10	18-25%	CPX	/		1.50
[40]	SMA with 23 different mixtures: greenhouse plastics (0.5–1%), plastic coming from recycled wires (0.5–1%), nylon from ELT (end life tires) (0.2–0.5%), crumb rubber (CR) from ELT (0.5%–2% of CR with different percentages of bitumen), CR	25 mm			SPB/CPX	6-9 dB	One year later no changes had occurred	

Table A1

REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
	from ELT and plastic cables (0.5% + 0.5%), CR from ELT and greenhouse plastics (0.5% CR + 0.5% plastic and 1% Plastic + 0.5% CR), plastic from masterbatches (0.5–1.0%).							
[41]	polymer-modified bitumen (PMB)	30 mm	10 mm		CPX	1-2 dB		
	crumb rubber bitumen modified by the wet process (CRMB)							
	crumb rubber bitumen modified by the wet process with 2% crumb rubber added by the dry process (CRMB + 2%							
	crumb rubber bitumen modified by the wet process with 1% crumb rubber added by the dry process (CRMB + 1%							
[42]			10 mm		CPX	Between 2008 and 2015 levels increased between 0.7 and 3.0 dB(A), depending on the section studied.		
			22 mm					
[43]	PERS	28/30 mm	4 mm	25/35 %	CPX	8 dB at 50 and 9 dB at 80 km/h	the results of 2004 are almost the same as the results of 2013	

Symbols:
PERS=Poro-elastic Road Surface; **RAC**=Rubberized Asphalt Concrete; **RAC(O)**= Rubberized Asphalt Concrete, Open; **RAC(G**)= Rubberized Asphalt Concrete, Gap Graded; **SMA**=Stone Mastic Asphalt; **DAC**=Dense Asphalt Concrete; **PAC**=Porous Asphalt Concrete; **TPA**=Two-layers Porous Asphalt; **TL**=Thin Layer; **SMA-LA**= Split Mastic Asphalt; **HRA**= Hot Rolled Asphalt; **PA**= Porous Asphalt; **SLPA**= Single Layer Porous Asphalt; **TLPA**= Twin Layer Porous Asphalt; **PLSD**= Paver-Laid Surfacing Dressing; **VTAC**= Very Thin Asphalt Concrete**; LOA 5D**= Lärmoptimierter Asphalt (noise reducing asphalt for surface layer); **AR**= Asphalt Rubber; **DPAC**= Double-layer Porous Asphalt Concrete; **TAL**= Thin Asphalt Layer; **ARFC**= Asphalt Rubber Friction Course; **OGFC-AR**= OGFC+ Asphalt Rubber**; OGFC-SBS**=OGFC+ styrene-butadiene-styrene; **HMA**= Hot Mix Asphalt; **OGAC**= Open Graded Asphalt Concrete; **DGAC**= Dense Graded Asphalt Concrete; **RAC-O**=Rubber Asphalt Concrete-Open; **BWC**= Bonded Wearing Course; **UTLAC**= Ultra-Thin Layer Asphalt Concrete; **ELT**=end life tires; **CR**=crumb rubber; **PMB**=Polymer-Modified Bitumen; **CRMB**= Crumb Rubber Bitumen Modified; **HRA**= Hot Rolled Asphalt; **PEM** =Porous European Mic; **ACFC**= Asphalt Concrete Friction Course; **P-ACFC**= Porous-Asphalt Concrete Friction Course; **OGAR**= Open Graded Asphalt Rubber; **GG**= Gap Graded; **PMFC**= Polymer Modified Friction Course; **FC**= Friction Course (PA)

Table A1								
REF	Solution	Thickness (mm)	MAS/NMAS (mm)	MTD (mm) AV (%)	AC	RED (dB)	ACDUR (years)	NI (dB/year)
*=passenger car; ** multi-axle vehicle **SPB**=Statistical Pass-By Method; **CB**= Controlled Pass-By Method; **CPX**= Close Proximity Method								

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<table>
<tr><th colspan="9">Table A1</th></tr>
<tr><th>REF</th><th>Solution</th><th>Thickness (mm)</th><th>MAS/NMAS (mm)</th><th>MTD (mm) AV (%)</th><th>AC</th><th>RED (dB)</th><th>ACDUR (years)</th><th>NI (dB/year)</th></tr>
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</table>

Table 2. Pavement solutions

The list above includes both quiet and noisy solutions.

1.4 Acoustic durability

1.4.1 Introduction

It is important to underline that the design of a quiet pavement technology should be referred to a precise hypothesis in terms of period of reference. Indeed, the as-built performance and the performance referred to other periods could make the solution chosen not anymore the best one.

Based on preliminary analyses:

The first derivative of OBSI with respect to time may or may not depend significantly on mix type.

For example, values of 0.4-0.7 dBA/year were obtained by Donovan & Jannello [23], while values of about 1.2-2.0 dBA/year were obtained by Anderson et al. [24].

Overall, considering also Rasmussen & Sohaney [44], an average value of 0.4 dBA/year was obtained with minima of -0.4 and maxima around 2. It is important to make it clear that speed may affect these parameters.

1.4.2 CPX

Within the project "Environmentally friendly pavements", a total of 37 test pavements (i.e., dense pavements with maximum chipping size from 6 to 16 mm, thin layers and porous pavements) were tested with CPX (Close Proximity) measurements at both 50 and 80 km/h according the ISO-standard 11819-2 [45].

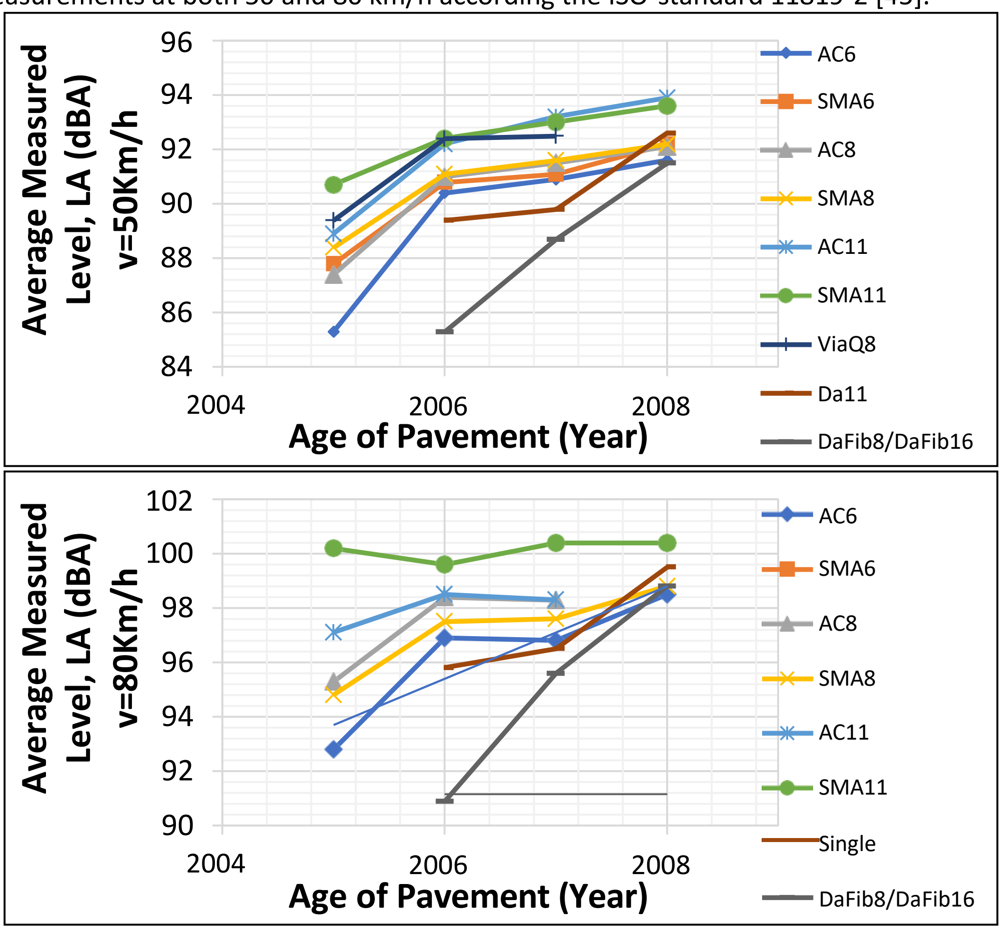


Figure 5. LA versus time [35]

Source: T. Berge, F. Haukland, U. Asbjørn, SINTEF A9721 Report. Environmentally friendly pavements: Results from noise measurements 2005-2008., NO-7465 Trondheim, Norway, 2009 [35].

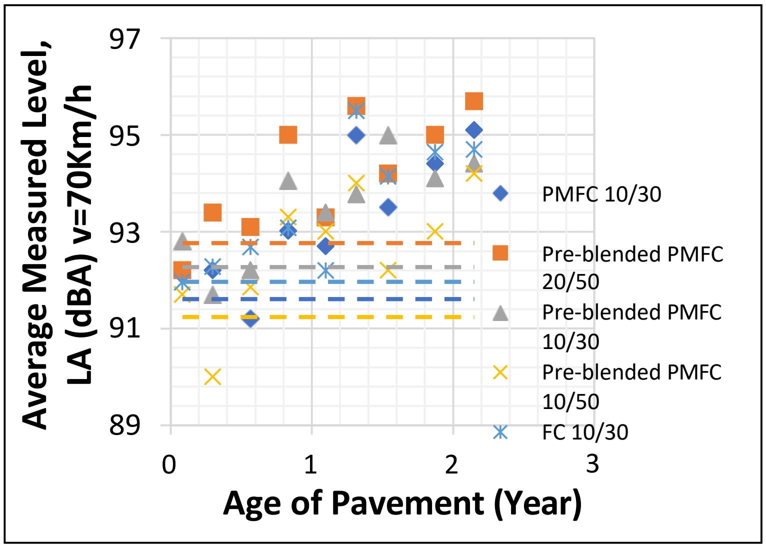
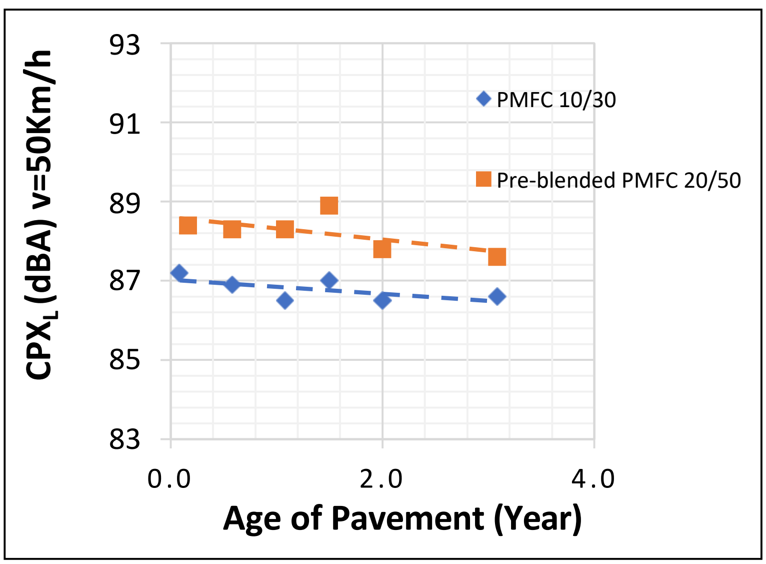
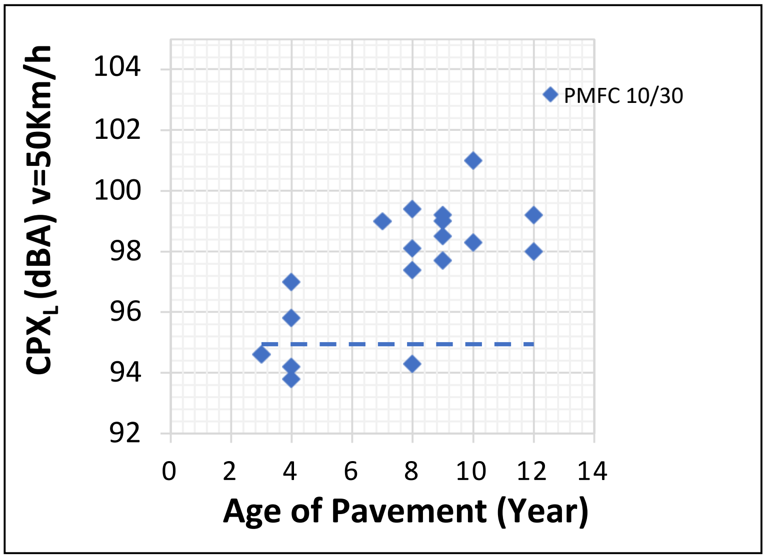


Figure 6. LA over time [39]

Source: K.Y. Ho, W.T. Hung, C.F. Ng, Y.K. Lam, R. Leung, E. Kam, The effects of road surface and tyre deterioration on tyre/road noise emission, Appl. Acoust. 74 (2013) 921–925. doi:10.1016/j.apacoust.2013.01.010 [39].

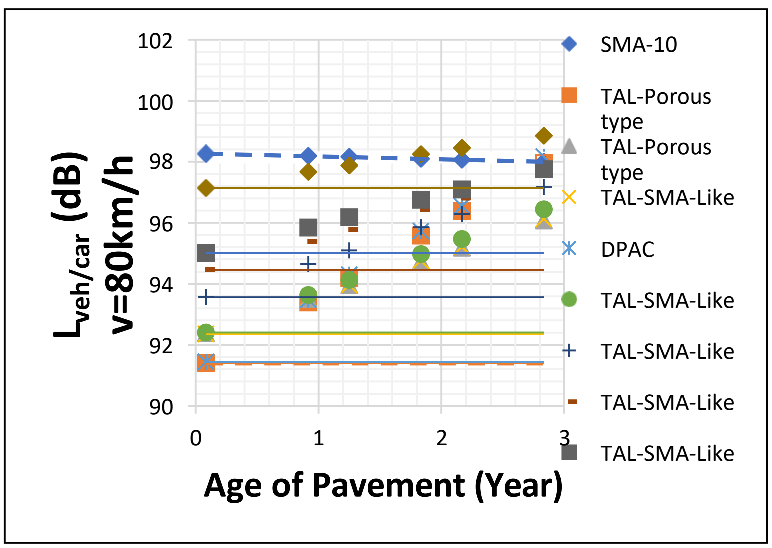


Source: M. Miljković, M. Radenberg, Thin noise-reducing asphalt pavements for urban areas in Germany, Int. J. Pavement Eng. 13 (2012) 569–578. doi:10.1080/10298436.2011.569028 [17].



Source: L.M. Pierce, J.P. Mahoney, S. Muench, H.J. Munden, M. Waters, J. Uhlmeyer, Quieter hot-mix asphalt pavements in Washington state, Transp. Res. Rec. (2009) 84–92. doi:10.3141/2095-09 [25].

Figure 7. CPX versus time



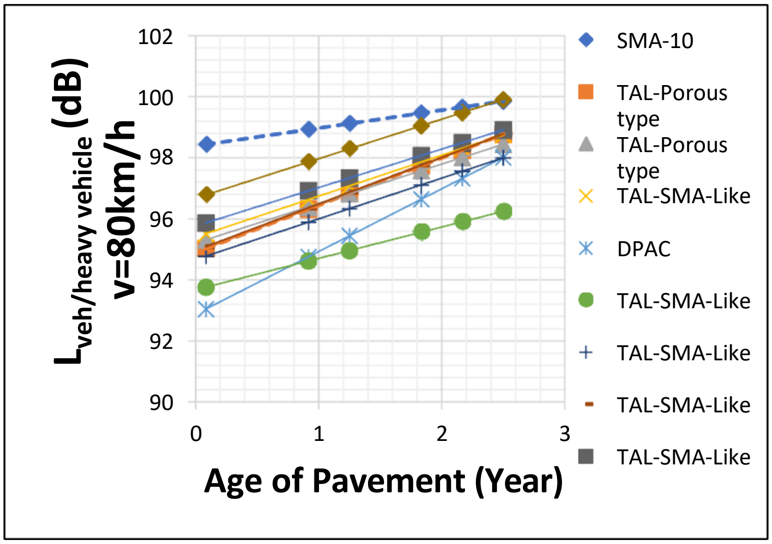


Figure 8. L_{CPX} versus time [20]

Note that L_{veh} is the noise level of the total test section L_{CPX} performed at a reference speed of 80 km/h with two different reference tires. The first is a Standard Reference Test Tire (SRTT, P1) for car while the second is an Avon AV4 (AAV4, H1) representative of truck tires.

Source: C. Vuye, A. Bergiers, B. Vanhooreweder, The Acoustical Durability of Thin Noise Reducing Asphalt Layers, Coatings. 6 (2016) 21. doi:10.3390/coatings6020021 [20].

1.4.3 SPB

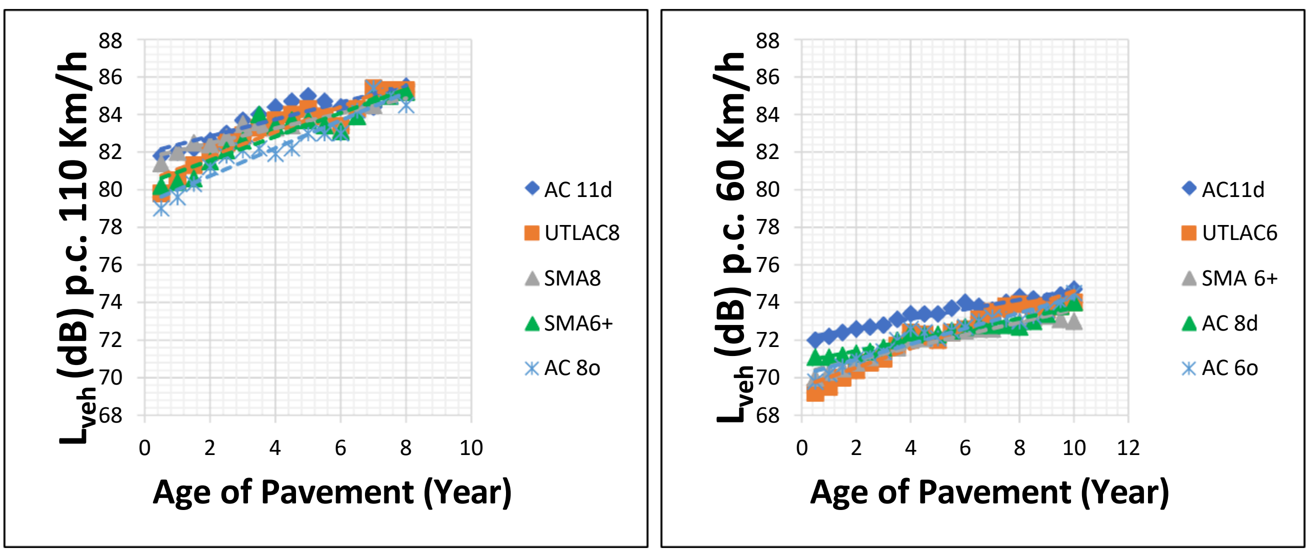


Figure 9. L_{SPB} versus time [34]

Note that L represents the SPB noise level for passenger cars (p.c.) at the reference speed of 110 and 60km/h, respectively.

Source: L.M. Iversen, J. Kragh, Acoustic ageing rates for pavements estimated by means of regression analysis, Proc.. Forum Acust. 2014-Janua (2014) [34].

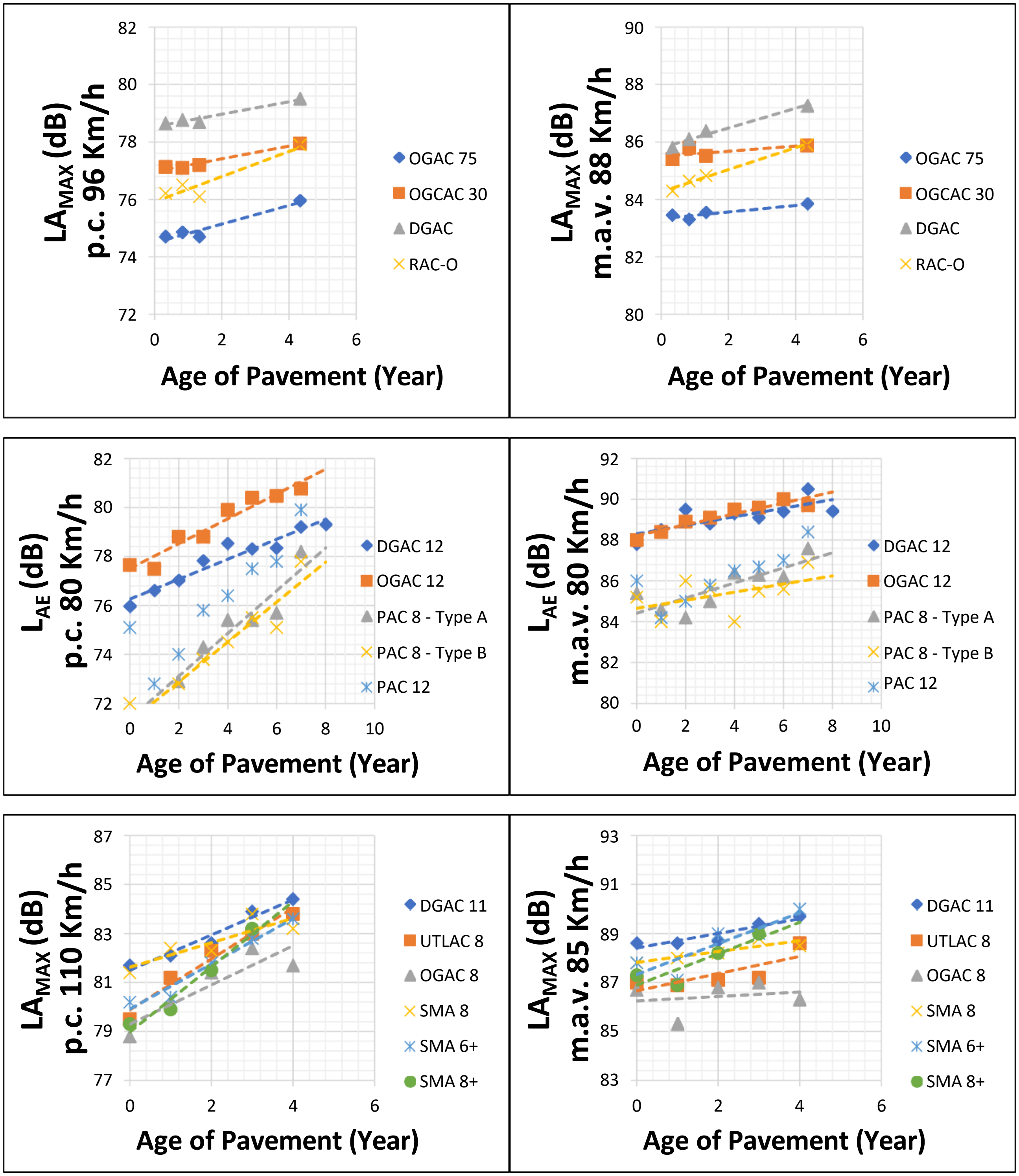


Figure 10. Sound pressure level over time [27]

Note: LA_{max} (LA_{max} : A-weighted, maximum, sound level) is the Maximum SPB noise level for passenger cars (p.c.) and for multi axle vehicles (m.a.v.) at the reference speed. L_{AE} (L_{AE} : A-weighted, sound exposure level) is the SPB noise level from passenger cars (p.c.).

Source: H. Bendtsen, Q. Lu, E. Kohle, Acoustic aging of asphalt pavements A californian/Danish comparison Report 171, Road Directorate, Danish Road Institute, 2009 [27].

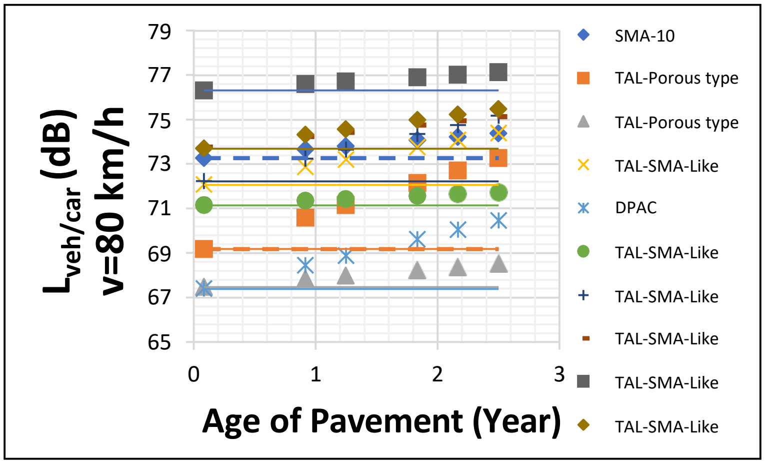
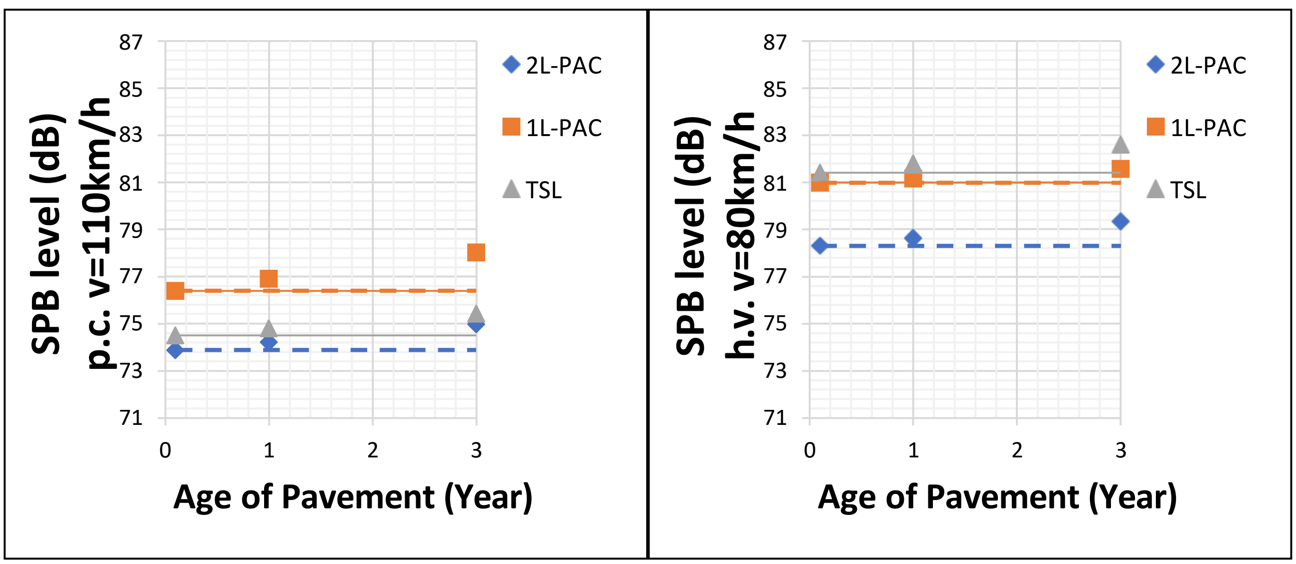


Figure 11. L_{SPB} versus time [20]

Note that Lveh is the average value of the maximum sound pressure level calculated at the reference speed v_0 (80 km/h) for passenger cars.

Source: C. Vuye, A. Bergiers, B. Vanhooreweder, The Acoustical Durability of Thin Noise Reducing Asphalt Layers, Coatings. 6 (2016) 21. doi:10.3390/coatings6020021 [20].



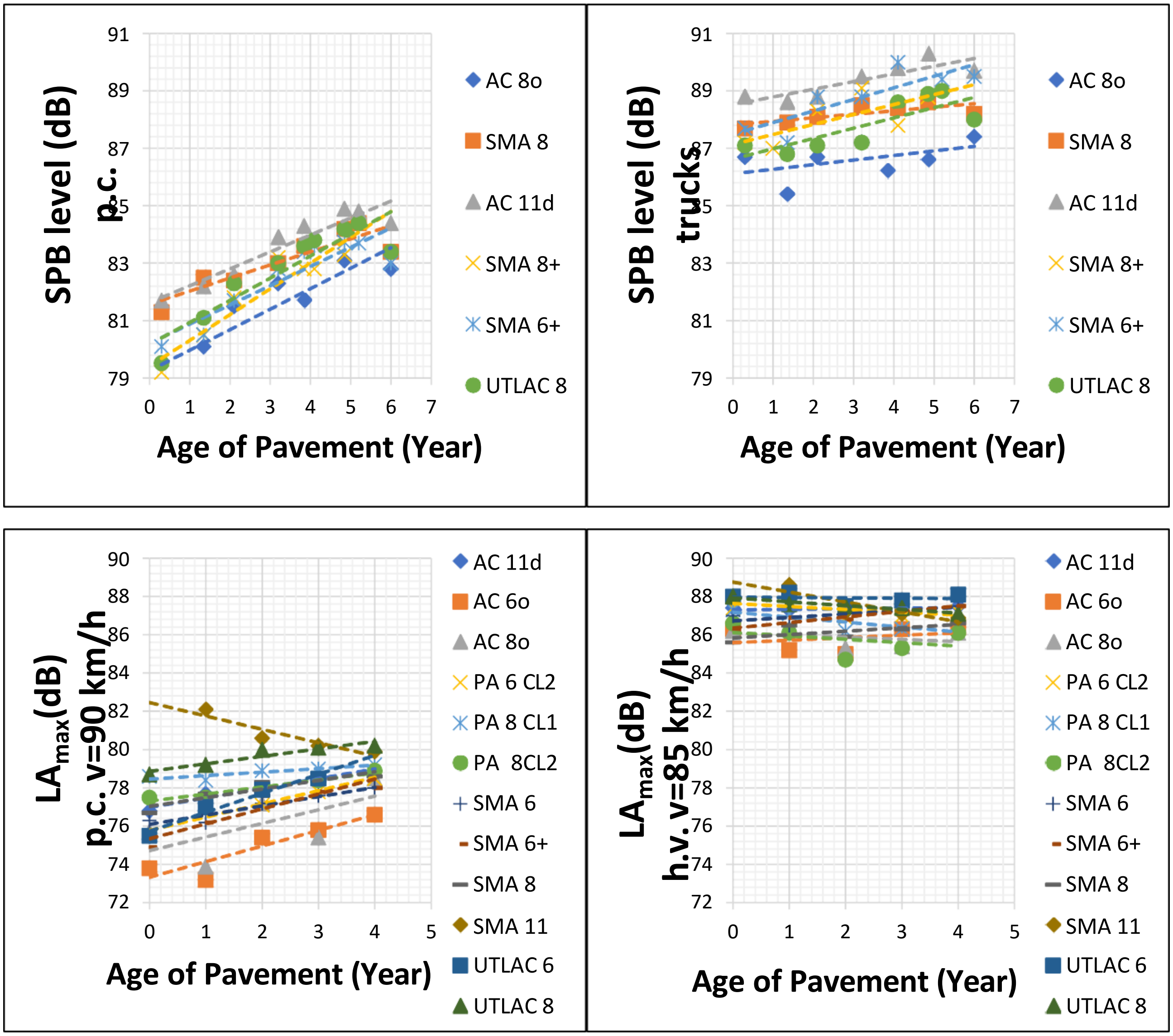
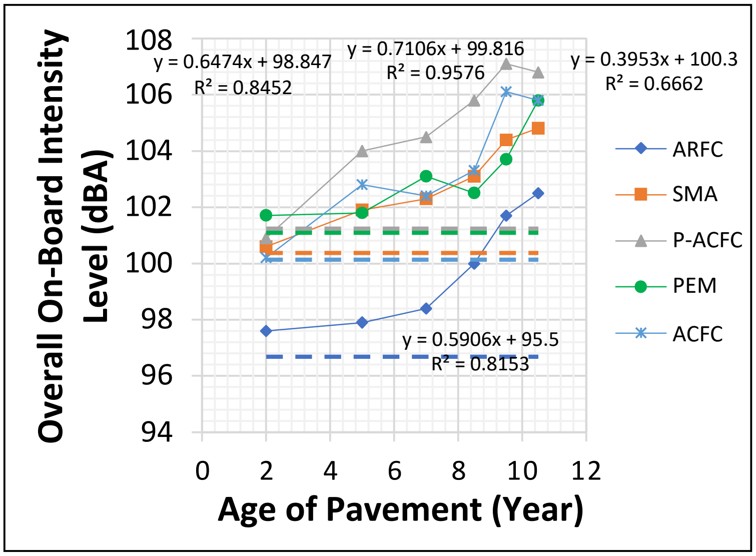


Figure 12. L versus pavement age [33,46]

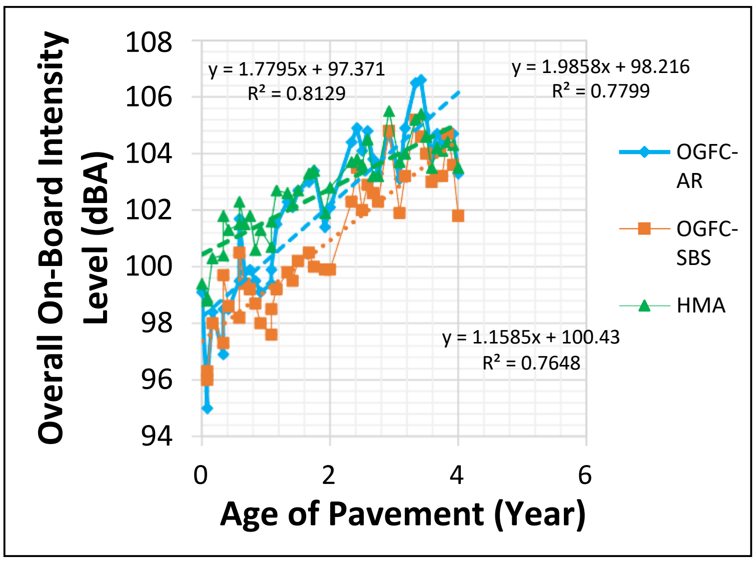
Note: SPB is the total A-weighted value for passenger cars (p.c.) and heavy vehicles (h.v.) at the reference speed. LA_{max} (LAmax : A-weighted, maximum, sound level) is the Maximum SPB noise level for passenger cars (p.c.) and heavy vehicles (h.v.) at reference speed.

Sources: B. Hans, B. Andersen, J. Oddershede, Støjdæmpning over lang tid, 2013 [46]; G. van Blokland, C. Tollenaar, R. van Loon, QUESTIM Modelling of Acoustic Aging of Road Surfaces. Report on Acoustic Aging of Road Surfaces, 2014 [33].

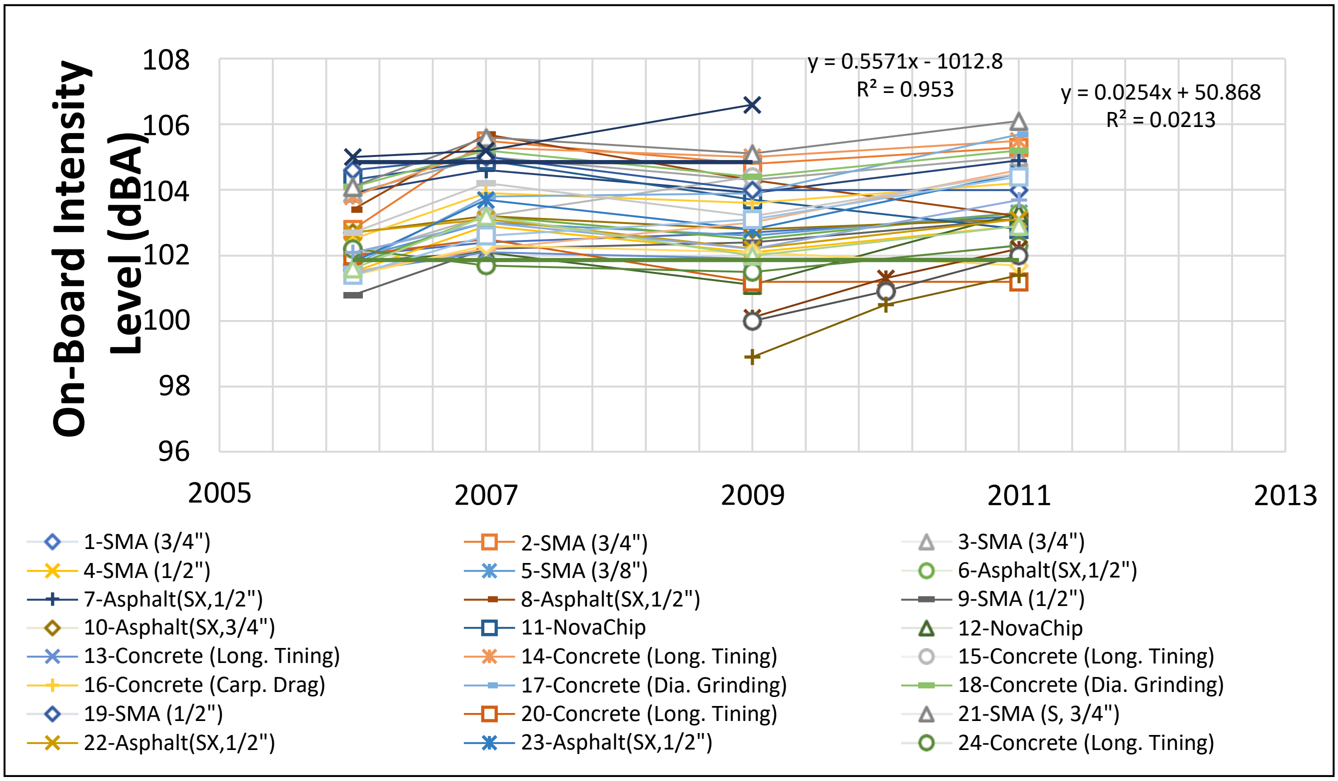
1.4.4 OBSI



Source: P. Donavan, C. Janello, Arizona Quiet Pavement Pilot Program: Comprehensive Report, Phoenix, Arizona, 2018 [23].



Source: K. Anderson, J. Uhlmeyer, T. Sexton, M. Russel, J. Weston, Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses Project 3 – Final Report, Olympia, Washington, 2013 [24].



Source: R.O. Rasmussen, R.C. Sohaney, Tire/Pavement and Environmental Traffic Noise Research Study, (2012) 147p [44].

Figure 13. OBSI over time

1.5 Non-acoustic performance

For non-acoustic performance, the main characteristics related to basic properties (such as air voids, AV) were considered. For each mixture, a tentative array of non-acoustic performance (e.g., in-lab permeability) was derived. Low voids contents resulted associated to better non-acoustic durability, especially in terms of mechanistic properties.

Tables below summarise the main characteristics of considered mixtures.

Furthermore, figures below summarise how important characteristics related to basic properties such as AV. Based on composition and volumetric characteristics, a tentative estimate of the corresponding modulus and expected life was derived.

Table A2

	Acronym	Surface Type	Ref.	ISO GRADED	$NMAS_{90}$ (mm)	λ * (mm)	$L_{tx,max}$ (dB)	END_t (dB)	ERNL (dB)	MPD (mm)	AV (%)	%b	K (10^{-5}cm/s)	CPX (50km/h)	BPN	E (MPa)
1	AC6	AC6	[2,15]	Y	5.2	12.5	43.9	0.7	69	0.72	11.7	5.5	6.1E+03	94.9 [a]	≥60	2906.5
2	AC8	AC8	[2,15]	Y	7.1	12.5	41.2	1.4	69	0.70	12.3	5.5	7.4E+03	97.5 [a]	≥60	2761.3
3	SMA	SMA16	[2,15]	N	15.1	25	45.8	3.3	72	0.99	NA	NA	NA	100.5 [a]	≥60	NA
4	SUP	Superpave	[47,48]	N	5.5	20	39.3	1.2	69	0.92	8.2	4.2	3.8E+05	/	≥60	4135.2
5	OG4	OGFC(w4)	[47,48]	N	11.6	20	46.0	2.9	71	1.79	17.4	6.2	3.8E+05	/	≥55	1137.1
6	OG5	OGFC(w5)	[47,48]	N	12	20	46.0	3.6	71	1.69	17.4	6.1	1.4E+03	/	≥55	1152.2
7	GAP	GAP	[18]	N	7.2	6.3	47.3	0.7	69	0.95	6.9	5.5	1.6E+03	93.8	≥55	3818.5
8	GAR	GAP (CR)	[18]	N	9.7	16	50.8	2.8	71	0.68	7.2	8.0	1.2E+08	92.0	≥55	2995.1
9	OG	OG	[18]	N	10.5	16	54.0	3.9	72	1.66	24.2	4.5	7.2E+06	91.0	≥55	527.1
10	OGR	OG(CR)	[18]	N	7.3	12.5	47.8	1.2	70	0.80	20.9	5.5	1.7E+03	89.8	≥55	875.5
11	SM6	SMA6-1	[49,50]	N	7.7	8	48.2	1.7	70	0.80	7.6	6.6	4.4E+02	90.9	≥60	2478.8
12	SM6*	SMA6-2	[49,50]	Y	4.6	12.5	42.7	2.4	70	1.04	3.7	6.6	1.6E+03	91.5	≥60	4413.8
13	AC6*	AC6	[49,50]	Y	4.2	16	40.5	2.2	70	1.10	7.4	6.1	1.6E+03	90.6	≥60	3935.4
14	SM8	SMA8-1	[49,50]	N	7.5	10	46.6	1.7	70	0.90	7.3	6.4	3.5E+02	91.3	≥60	2621.5
15	SM8*	SMA8-2	[49,50]	Y	7.2	20	44.5	3.2	71	1.11	3.3	6.4	2.4E+03	91.8	≥60	3545.2
16	AC8*	AC8	[49,50]	Y	6.9	20	43.2	2.8	70	1.46	9.0	5.9	1.9E+03	90.9	≥60	3061.7
17	SM11	SMA11-1	[49,50]	N	10.9	12.5	48.2	3.4	71	0.94	7.9	5.8	3.1E+02	92.2	≥60	2797.8
18	SM11*	SMA11-2	[49,50]	N	11.6	25	50.2	6.2	73	0.84	3.1	5.8	9.0E+02	93.3	≥60	3488.1
19	AC11	AC11	[49,50]	Y	10.7	20	46.2	4.3	72	1.05	5.4	5.6	5.1E+02	92.4	≥60	3724.5
20	ISO	ISO 10844	[51]	Y	5.0	5	39.8	0.0	68	0.5	4.0	5.8	8.6E+03	86.9 [19]	≥60	5638.8

Symbols.
Ref.: Reference, **$NMAS_{90}$:** Nominal Maximum Aggregate Size– rule of 90%; **λ *, $L_{tx,max}$:** abscissa and ordinate of texture level maximum, respectively**; ENDt:** Estimated Noise Difference Due to Texture **ERNL:** Estimated Road Noise Level**; MPD:** Mean Profile Depth**; AV:** Air-void content**; %b:** binder percentage**; k:** in-lab permeability**; CPX:** Close Proximity Index**; BPN:** British Pendulum Number**; E:** Dynamic Modulus**; AC:** Asphalt Concrete**; SUP:** Superpave**; OG:** Open Graded**; GAP:** Gap Graded**; GAR:** GAP with crumb rubber**; OGR:** OG with crumb rubber**; SM:** Stone Mastic Asphalt**; ISO:** ISO 10844 reference surface.

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D. Siebert, How wear affects road surface texture and its impact on tire/road noise texture, NTNU Norwegian University of Science and Technology, 2017 [49].
B. O. Lerfald, Miljøvennlige vegdekker. Sluttrapport forsøksstrekninger. SINTEF Rapport SBF INA08012., 2009 [50].
ISO 10844, Acoustics -Specification of test tracks for measuring noise emitted by road vehicles and their tyres, (2014) 45 [51].

Table 3. Acoustic and non-acoustic performance

Main Reference: F.G. Praticò, P.G. Briante, Prediction of surface texture for better performance of friction courses, Constr. Build. Mater. 230 (2020). doi:10.1016/j.conbuildmat.2019.116991 [52].

Notes. MPD =Mean Profile Depth. *K is the average permeability value obtained from the theoretical models in relation to the air void content. [a] CPX at 80 km/h.

Table A3

	Acronym	**AV (%)**	**Aboufoul et al. 2017** [53]	**Cooley et al. 2003** [54]	**Kanitpong et al. 2001** [55]	**Putman et al. 2012** [56]	**Mogawer et al. 2002** [57]	**Norambuena et al. 2013** [58]	**Nataatmadja 2010** [59]	**Praticò et al. 2013** [60]	**Kmin (X10-5 cm/s)**	**Kmax (X10-5 cm/s)**	**Kave (X10-5 cm/s)**
1	AC6	11.7	1.30E+02	6.16E+03	9.77E+02	7.85E+03	1.13E+03	1.21E+04	4.36E+02	1.29E+03	1.3E+02	1.2E+04	6.1E+03
2	AC8	12.3	1.92E+02	1.02E+04	1.58E+03	8.64E+03	1.57E+03	1.47E+04	4.75E+03	1.52E+03	1.9E+02	1.5E+04	7.4E+03
3	SMA16	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	SUP	8.2	8.31E+00	3.22E+02	3.27E+01	4.00E+03	1.70E+02	2.27E+03	4.87E+01	3.84E+02	8.3E+00	4.0E+03	2.0E+03
5	OG4	17.4	2.81E+03	7.51E+05	4.34E+04	1.67E+04	2.48E+04	4.40E+04		4.95E+03	2.8E+03	7.5E+05	3.8E+05
6	OG5	17.4	2.81E+03	7.51E+05	4.34E+04	1.67E+04	2.48E+04	4.40E+04		4.95E+03	2.8E+03	7.5E+05	3.8E+05
7	GAP	6.9	2.18E+00	1.08E+02	6.27E+00	2.88E+03	8.40E+01	7.89E+02	3.12E+01	2.13E+02	2.2E+00	2.9E+03	1.4E+03
8	GAR	7.2	3.03E+00	1.39E+02	9.42E+00	3.12E+03	9.88E+01	1.04E+03	3.45E+01	2.47E+02	3.0E+00	3.1E+03	1.6E+03
9	OG	24.2	3.61E+04	2.31E+08	1.02E+06	3.12E+04	9.87E+05	9.23E+04		1.52E+04	1.5E+04	2.3E+08	1.2E+08
10	OGR	20.9	1.16E+04	1.43E+07	2.50E+05	2.37E+04	1.65E+05	6.84E+04		9.24E+03	9.2E+03	1.4E+07	7.2E+06
11	SM6	7.6	4.61E+00	1.94E+02	1.58E+01	3.46E+03	1.23E+02	1.46E+03	3.94E+01	2.96E+02	4.6E+00	3.5E+03	1.7E+03
12	SM6*	3.7	1.75E-02	7.27E+00	1.62E-02	8.81E+02	1.48E+01	2.48E+00	1.06E+01	2.56E+01	1.6E-02	8.8E+02	4.4E+02
13	AC6*	7.4	3.75E+00	1.64E+02	1.22E+01	3.29E+03	1.10E+02	1.24E+03	3.69E+01	2.71E+02	3.8E+00	3.3E+03	1.6E+03
14	SM8	7.3	3.38E+00	1.51E+02	1.08E+01	3.21E+03	1.04E+02	1.14E+03	3.56E+01	2.58E+02	3.4E+00	3.2E+03	1.6E+03
15	SM8*	3.3	7.23E-03	5.19E+00	5.43E-03	7.09E+02	1.20E+01	5.50E-01	9.00E+00	1.74E+01	5.4E-03	7.1E+02	3.5E+02
16	AC8*	9	1.71E+01	6.33E+02	7.96E+01	4.77E+03	2.62E+02	3.73E+03	6.62E+01	5.27E+02	1.7E+01	4.8E+03	2.4E+03
17	SM11	7.9	6.22E+00	2.50E+02	2.29E+01	3.72E+03	1.44E+02	1.83E+03	4.38E+01	3.38E+02	6.2E+00	3.7E+03	1.9E+03
18	SM11*	3.1	4.46E-03	4.38E+00	2.99E-03	6.30E+02	1.07E+01	2.24E-01	8.27E+00	1.41E+01	3.0E-03	6.3E+02	3.1E+02
19	AC11	5.4	3.27E-01	3.05E+01	6.02E-01	1.81E+03	3.73E+01	1.24E+02	1.92E+01	9.27E+01	3.3E-01	1.8E+03	9.0E+02
20	ISO	4	3.21E-02	9.36E+00	3.42E-02	1.02E+03	1.75E+01	6.30E+00	1.18E+01	3.34E+01	3.2E-02	1.0E+03	5.1E+02

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Table A3

	Acronym	AV (%)	Aboufoul et al. 2017 [53]	Cooley et al. 2003 [54]	Kanitpong et al. 2001 [55]	Putman et al. 2012 [56]	Mogawer et al. 2002 [57]	Norambuena et al. 2013 [58]	Nataatmadja 2010 [59]	Praticò et al. 2013 [60]	Kmin (X10-5 cm/s)	Kmax (X10-5 cm/s)	Kave (X10-5 cm/s)

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A. Nataatmadja, The use of the hyperbolic function for predicting critical permeability of asphalt, in: ARRB Conf. 24th, 2010, Melbourne , Australia, 2010: pp. 1–9. http://worldcat.org/isbn/187659263X [59].
F.G. Praticò, R. Vaiana, T. Luele, Permeable wearing courses from recycling reclaimed asphalt pavement for low-volume roads, 2015. doi:10.3141/2474-08 [60]

Table 4. minimum, average, and maximum permeability based on AV

1.6 Composition

For the corresponding mixture composition (quantities, typology), volumetric characteristics, and their evolution over time, mixture compositions were derived. This involved aggregate mixture and grading, crumb rubber type, size, and quantity.

Based on F.G. Praticò, and P.G. Briante, Prediction of surface texture for better performance of friction courses, Constr. Build. Mater. 230 (2020). doi:10.1016/j.conbuildmat.2019.116991 [52] the following pieces of information are summarised below.

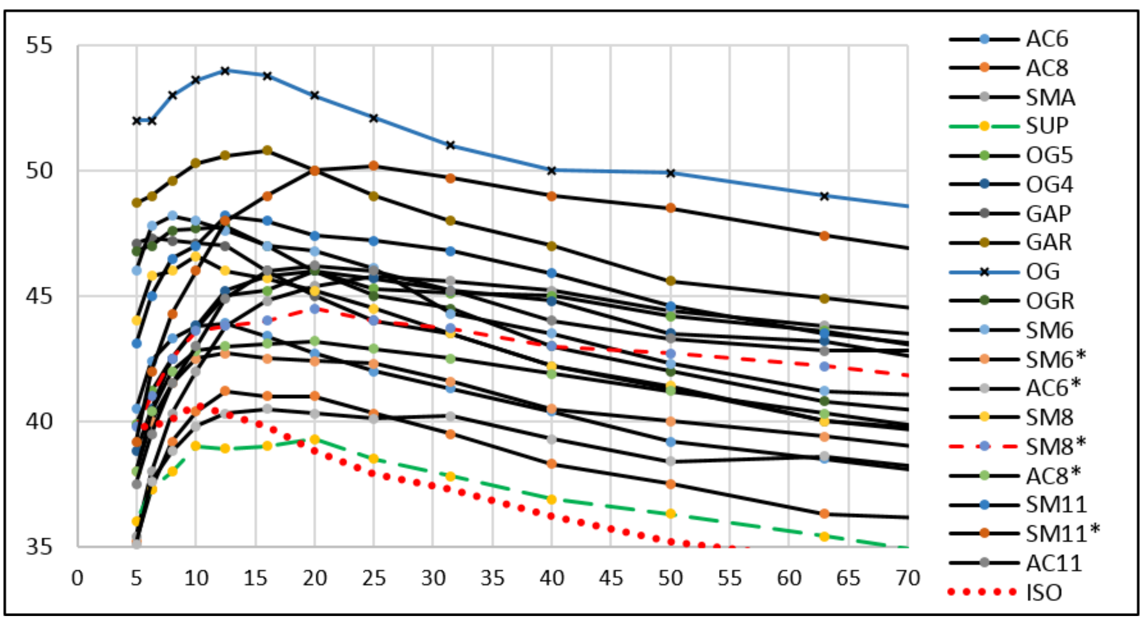


Figure 14. Texture Spectrum [52]

Reference: F.G. Praticò, P.G. Briante, Prediction of surface texture for better performance of friction courses, Constr. Build. Mater. 230 (2020). doi:10.1016/j.conbuildmat.2019.116991 [52].

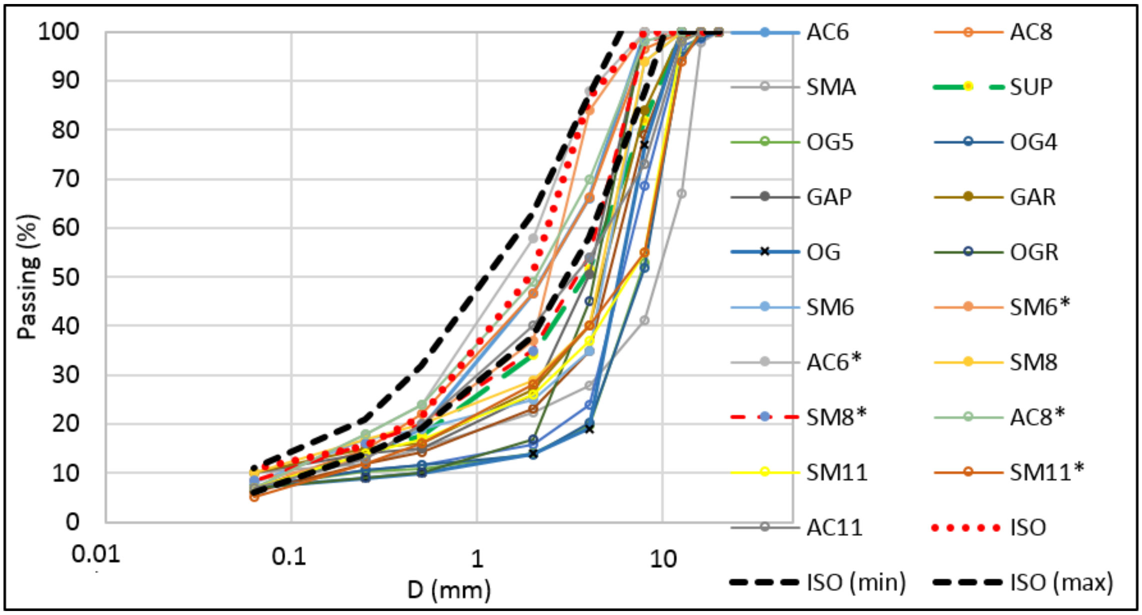


Figure 15. Mixture gradations [52]

Reference: F.G. Praticò, P.G. Briante, Prediction of surface texture for better performance of friction courses, Constr. Build. Mater. 230 (2020). doi:10.1016/j.conbuildmat.2019.116991 [52].

Table A4

	Acronym	Ref	P_{20}	P_{16}	$P_{12.5}$	P_8	P_4	P_2	$P_{0.5}$	$P_{0.25}$	$P_{0.063}$	AV (%)	%b
1	AC6	[2,15]	100.0	100.0	100.0	100.0	66.1	46.6	19.1	13.1	7.2	11.7	5.5
2	AC8	[2,15]	100.0	100.0	100.0	96.4	66.2	46.7	22.1	14.9	7.0	12.3	5.5
3	SMA16	[2,15]	100.0	97.9	67.1	41.2	27.9	22.3	15.0	11.9	10.0	NA	NA
4	SUP	[47,48]	100.0	100.0	100.0	82.0	51.7	34.0	17.8	14.0	6.6	8.2	4.2
5	OG4	[47,48]	100.0	100.0	95.0	52.8	19.8	14.1	11.0	10.2	7.1	17.4	6.2
6	OG5	[47,48]	100.0	99.0	95.0	52.0	20.2	13.7	11.7	10.7	7.2	17.4	6.1
7	GAP	[18]	100.0	100.0	100.0	100.0	50.5	26.0	15.0	14.0	10.0	6.9	5.5
8	GAR	[18]	100.0	100.0	100.0	84.0	40.0	27.0	16.0	15.0	10.0	7.2	8.0
9	OG	[18]	100.0	100.0	100.0	77.0	19.0	14.0	10.0	9.0	7.0	24.2	4.5
10	OGR	[18]	100.0	100.0	100.0	100.0	45.0	17.0	10.0	9.0	7.0	20.9	5.5
11	SM6	[49,50]	100.0	100.0	100.0	94.0	35.0	25.0	19.0	17.0	8.0	7.6	6.6
12	SM6*	[49,50]	100.0	100.0	100.0	100.0	84.0	37.0	20.0	13.0	8.4	3.7	6.6
13	AC6*	[49,50]	100.0	100.0	100.0	100.0	88.0	58.0	24.0	18.0	7.0	7.4	6.1
14	SM8	[49,50]	100.0	100.0	100.0	94.0	40.0	29.0	20.0	17.0	10.1	7.3	6.4
15	SM8*	[49,50]	100.0	100.0	100.0	98.0	54.0	35.0	20.0	16.0	8.4	3.3	6.4
16	AC8	[49,50]	100.0	100.0	100.0	98.0	70.0	49.0	24.0	18.0	7.0	9.0	5.9
17	SM11	[49,50]	100.0	100.0	98.0	55.0	37.0	26.0	17.0	14.0	7.0	7.9	5.8
18	SM11*	[49,50]	100.0	100.0	94.0	55.0	40.0	28.0	16.0	12.0	5.0	3.1	5.8
19	AC11	[49,50]	100.0	100.0	98.0	73.0	54.0	40.0	20.0	13.0	7.0	5.4	5.6
20	ISO	[51]	100.0	100.0	100.0	99.8	86.6	51.2	21.5	15.6	10.9	4.0	5.8

References.

J. Kragh, J. Oddershede, R. Skov, H. Bendtsen, NordTyre, NordTyre - Tyre labelling and Nordic road surfaces – Analysis of data on passenger car tyres, 2018 [15].
J. Kragh, L.M. Iversen, U. Sandberg, Nordtex Final Report Road Surface Texture for Low Noise and Low Rolling Resistance, 2013 [2].
A. de F. Smit, B. Waller, Evaluation of the Ultra-Light Inertial Profiler (Ulip) for Measuring Surface Texture of the Pavements, 277 Technology Parkway Auburn, AL 36830, 2007 [47].

Table A4													
	Acronym	**Ref**	**P_{20}**	**P_{16}**	**$P_{12.5}$**	**P_8**	**P_4**	**P_2**	**$P_{0.5}$**	**$P_{0.25}$**	**$P_{0.063}$**	**AV (%)**	**%b**
E.R. Brown, L.A. Cooley, D.I. Hanson, C. Lynn, B. Powell, B. Prowell, D. Watson, NCAT Test Track Design, Construction, and Performance, Auburn, AL, 2002 [48]. P. Leandri, M. Losa, P. Rocchio, New Low Noise Pavement Surfaces by the use of Crumb Rubber, in: Euronise 2018, Crete, 2018: pp. 2679–2686 [18]. D. Siebert, How wear affects road surface texture and its impact on tire/road noise texture, NTNU Norwegian University of Science and Technology, 2017 [49]. B. O. Lerfald, Miljøvennlige vegdekker. Sluttrapport forsøksstrekninger. SINTEF Rapport SBF INA08012., 2009 [50]. ISO 10844, Acoustics -Specification of test tracks for measuring noise emitted by road vehicles and their tyres, (2014) 45 [51].													

Table 5. Mixture gradations

By referring to mechanistic properties, note that the prediction of the durability has been carried out through the Guide for Mechanistic-Empirical Design OF NEW AND REHABILITATED PAVEMENT STRUCTURES- FINAL DOCUMENT- APPENDIX II-1: CALIBRATION OF FATIGUE CRACKING MODELS FOR FLEXIBLE PAVEMENS- NCHRP - Prepared for National Cooperative Highway Research Program Transportation Research Board National Research Council - Submitted by ARA, Inc., ERES Division 505 West University Avenue Champaign, Illinois 61820 February 2004). Analytical predictions partly comply with Air Voids in Asphalt- pavement work tips no. 17- June 1999- AUSTROADS [61].

1.7 Agency and user costs

For the derivation of the corresponding agency and user costs, a study of the literature was carried out to evaluate the agency and user costs. In particular, for user cost, it was noted that they include three main types of cost: Value of Time (VOT), Vehicle Operating Costs (VOC), and Accident Costs (AC). Higher AV yielded usually higher LCC.

Table B1						
Year	AC		ARAC		Difference	
	MC ($)	UC ($1000)	MC ($)	UC ($1000)	MC ($)	UC ($1000)
0	1515008	0	875776	0	639232	0
5	1844	12296	1317	12325	527	-29
10	7477	12705	4295	12288	3182	417
15	10471	13288	5853	12890	4618	398
20	11998	13981	6471	13172	5527	809
25	12649	14800	6683	13565	5966	1235

Table 6. Maintenance and user costs trends for the conventional bituminous pavements and asphalt-rubber pavements [62]

Note: 0=Initial Cost; MC=Maintenance Cost; UC=User Cost; AC=conventional asphalt concrete; ARAC= asphalt-rubber gap graded mixture.

Reference: Jong-Suk Jung, Kamil E. Kaloush, George B. Way, Life Cycle Cost Analysis: Conventional Versus Asphalt-Rubber Pavements, 2002 [62].

Table B2				
Size of project	Conventional HMA		RUBBERIZED HMA	
	Average ($/ton)	Standard deviation ($/ton)	Average ($/ton)	Standard deviation ($/ton)
Large	80	13.95	91.7	12.8
Medium	83.86	16.66	91.47	15.01

Table 7. Summarized cost information of rubberized and conventional HMA mixtures based on the size of projects [63,64]

References. D. Cheng, R.G. Hicks, M. Rodriguez, Life Cycle Cost Comparison of Rubberized and Conventional HMA in California, 2012 [63]; M.R. Pouranian, M. Shishehbor, Sustainability assessment of green asphalt mixtures: A review, Environ. - MDPI. 6 (2019). doi:10.3390/environments6060073 [64].

Table B3						
Functional classes	Size of project	Conventional HMA		RUBBERIZAED HMA		Percent savings (%)
		Agency Cost/In Mile ($1000)	User Cost/In Mile ($1000)	Agency Cost/In Mile ($1000)	User Cost/In Mile ($1000)	
Interstate highways	Large	365.61	2.24	306.70	0.92	17.29
	Medium	391.71	23.26	330.07	14.24	17.38
State Routes	Large	361.26	1.37	285.10	1.83	21.00
	Medium	389.84	1.19	307.44	0.47	22.00
US highways	Large	370.38	0.33	230.61	0.11	37.50

Table 8. LCCA Results of rubberized vs. conventional HMA for different project sizes and types [63,64]

Note: The sizes of the projects are large (more than 10 lane miles) and medium (4 to 10 lane miles).

References. D. Cheng, R.G. Hicks, M. Rodriguez, Life Cycle Cost Comparison of Rubberized and Conventional HMA in California, 2012 [63]; M.R. Pouranian, M. Shishehbor, Sustainability assessment of green asphalt mixtures: A review, Environ. - MDPI. 6 (2019). doi:10.3390/environments6060073 [64].

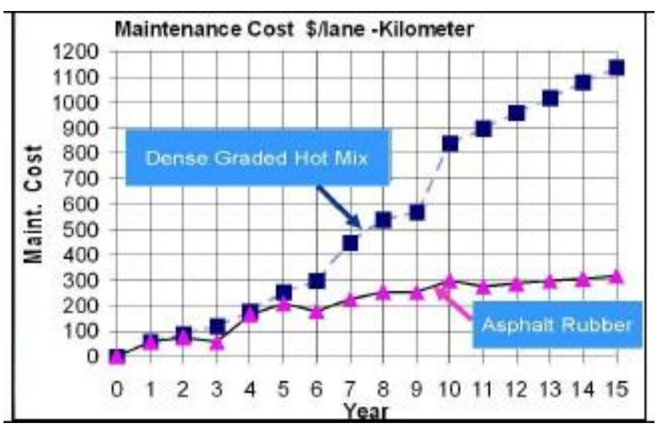


Figure 16. Maintenance cost with and without asphalt rubber [65]

Reference: I. Antunes, G.B. Way, J. Sousa, K. Kaloush, The Successful Rubber World Wide Use of Asphalt Rubber, in: XVI Convegno Naz. S.I.I.V., Campus di Arcavacata di Rende (CS), 2006 [65]

Table B4							
Materials/others	Aver. unitary costs euros/ton	Quantity/ton %	ARwet euros/ton	ARdry euros/ton	ARtb euros/ton	Quantity /ton %	AC Euro/ton
Conventional bitumen 35/50	350	-	-	-	-	5.5	19.3
Bitumen 35/50 modified by wet process	480	6.00	28.8	-	-	-	-
Bitumen 35/50 modified by dry process	460		-	27.6	-		-
Bitumen 35/50 modified by tb process	550		-	-	33.00		-
Aggregates	18	93.4	16.8	16.8	16.8	94.5	17.0
Operation (including energy)	Variable	100.0	8.0	6.8	6.48	100.00	6.4
Total manufacturing costs	-	-	53.6	51.2	56.2	-	42.7
Administrative costs and profit (20%)			10.7	10.2	11.3		8.5
Total			64.3	61.5	67.6		51.2
Difference for AC (%)	-		26%	20%	32%	-	0%

Table 9. Table manufacturing costs for ARwet, ARdry, ARtb, and AC [66]

Symbols: ARwet, ARdry, ARtb: Crumb asphalt rubber mixtures produced by the wet, by the dry, and by the terminal blend process, respectively; AC: hot dense-grade asphalt concrete.

References: L.G. Picado-Santos, S.D. Capitão, J.M.C. Neves, Crumb rubber asphalt mixtures: A literature review, Constr. Build. Mater. 247 (2020) 118577. doi:10.1016/j.conbuildmat.2020.118577 [66]

Table B5 (prices)				
Item	UM	Price	% manpower	Manpower cost
Delivering and construction of wearing course HMA, with a specific gravity of 1.7 t/m3, including lay down, compaction, tack coat (Kg/m2 0.60), final thickness of m 0.03	m^2	€ 5,20	20,00%	€ 1,04
Delivering and construction of HMA wearing courses type Asphalt Rubber, with Open-Graded aggregate gradation, modified bitumen, crumb rubber from exhaust tyres, percentages between 8,5% and 9,5% (by the weight of the mix), laydown, compaction, and tack coat included	m^2*0.01m	€ 3,31	10,00%	€ 0,33
Delivering and construction of HMA binder courses, with a specific gravity of 1.75 t/m3, laydown, compaction (also by hand), and tack coat included. Cleaning of surfaces and workzone management in terms of traffic are included (Kg/m2 0.60). The mixture will be weighted on trucks, at their arrival.	t	€ 70,70	20,00%	€ 14,14
Delivering and construction of HMA binder courses, type asphalt rubber, gap-graded gradation (in between dense and open graded), with calcareous aggregates.	t	€ 130,85	10,00%	€ 13,09

Table 10. Examples of unit costs

Reference: Elenco prezzi unitari - Provincia di Piacenza “S.P. n. 654r Val Nure. Messa in sicurezza del tracciato con adeguamento della sezione esistente e variante su nuova sede 1° stralcio” [67].

Finally, for user cost, it is noted that they include three main cost components (see X. Qin, C.E. Cutler, Review of Road User Costs and Methods, 2013 [68]):

Value of Time (VOT), Vehicle Operating Costs (VOC), and Accident Costs (AC).

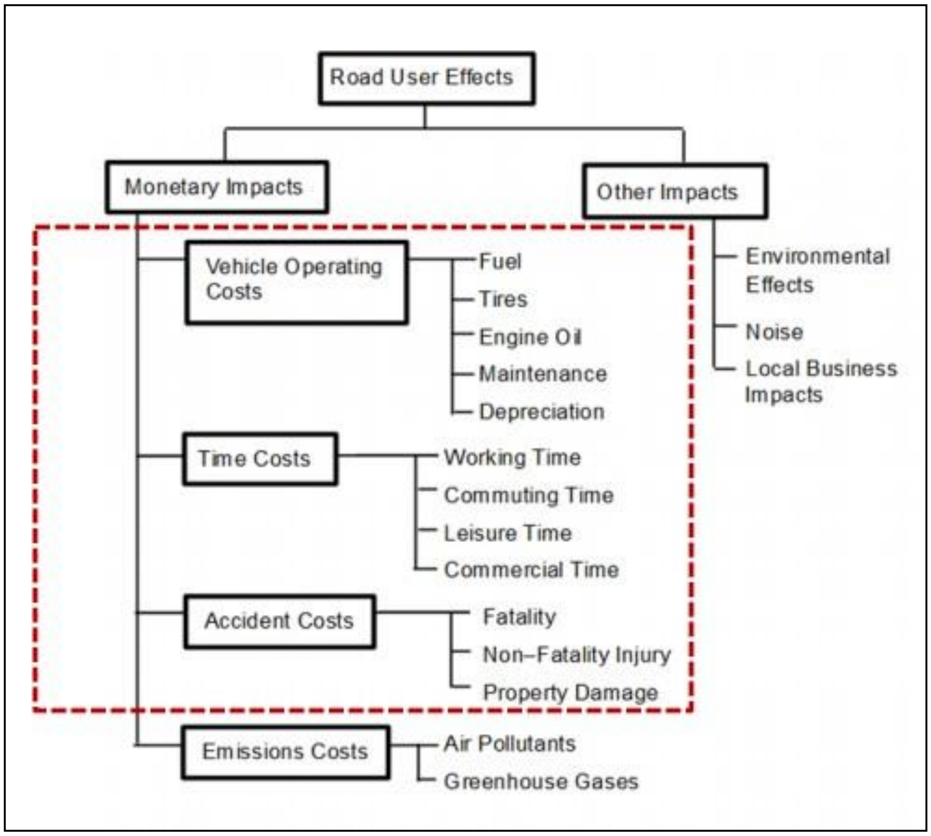


Figure 17. Road user costs.

(see X. Qin, C.E. Cutler, Review of Road User Costs and Methods, 2013 [68])

Note that pavement condition and pavement type impact vehicle operating costs (see Qin and Cutler, 2013 [68]). In more detail (see Estimating Vehicle Operating Costs Caused by Pavement Surface Conditions, December 2014 Transportation Research Record Journal of the Transportation Research Board 2455(-1):63-76, DOI: 10.3141/2455-08 [69]), IRI and MPD affect fuel consumption, repair and maintenance, and tire wear. In more detail:

- Fuel consumption (as well as repair and maintenance, and tire wear) is affected by roughness.
- An increase in IRI of 1 m/km (63.4 in./mi) increases fuel consumption of passenger cars by 2% to 3%, regardless of speed. For heavy trucks, this increase is 1% to 2% at 70 mph and 2% to 3% at 35 mph.
- Surface texture and pavement type have no effect on fuel consumption for vehicle classes except heavy trucks (based on pavements under investigation in this case).
- An increase in MPD of 1 mm (0.039 in.) increases fuel consumption by 1.5% at 55 mph and 2% at 35 mph (heavy trucks).
- The effect of pavement type on fuel consumption is statistically not significant for all light vehicles and statistically significant for heavy trucks only at 35 mph in summer conditions (30 degrees C).
- For repair and maintenance, there is no effect of roughness up to an IRI of 3 m/km (190 in./mi). Beyond this range, an increase in IRI up to 4 m/km (254 in./mi) increases repair and maintenance costs by 10% for passenger cars and heavy trucks. At an IRI of 5 m/km (317 in./mi), the increase is up to 40% for passenger cars and 50% for heavy trucks.

- An increase in IRI of 1 m/km (63.4 in./mi) increases tire wear of passenger cars and heavy trucks by 1% at 55 mph.

Another important issue refers to the effect of work zones on traffic delays and then on user costs. To this end, insights and procedures are given in: State of New Jersey Department of Transportation, Road User Cost Manual, Prepared by the Road User Solutions Unit 2015 [70]. For the solutions considered in this project 1) the time delays due to construction itself are not considered crucial. 2) The durability is supposed to be crucial. This latter, indeed, is going to affect the frequency of maintenance and rehabilitation operations over time, which affect the life-cycle cost and user costs.

1.8 Environmental impact

Pertaining to raw materials and processes involved and their impact on environmental indicators, based on the literature, the following points have been analysed in term of environmental impact: raw material intrinsic carbon footprint and impacts, emissions measured during mixture production, and Kg CO2 equivalent values for mixtures production. Finally, using the data collected, results for a friction course were obtained.

Carbon emissions from pavements constructions derive from many different steps:

- Component production and transport
- Asphalt mixture production (including aggregate stacking, aggregate supply, asphalt and aggregate heating)
- Remaining phases (i.e., transportation, paving and compaction of asphalt mixture).

  Further information about the environmental impact is given by Peng et al. 2015 [71]

Source: Peng, C. Cai, G. Yin, W. Li, Y. Zhan, Evaluation system for CO2 emission of hot asphalt mixture, J. Traffic Transp. Eng. (English Ed. 2 (2015) 116–124. doi:10.1016/j.jtte.2015.02.005 [71].

Emission measured during mixture production [72]

Emissions	Hot mix asphalt	Asphalt rubber mixture - wet process
O2 (%)	12.75	12.10
N2 (%)	81.46	81.88
CO2 (%)	6	6.48
CO (ppm)	430.5	259.5
NOX (ppm)	139.3	124.4
SO2 (ppm)	74.4	76.7
CH4 (ppm)	27.7	10.60

Table 11. Emissions and CR [72]

Reference: L.P. Thives, E. Ghisi, Asphalt mixtures emission and energy consumption: A review, Renew. Sustain. Energy Rev. 72 (2017) 473–484. doi:10.1016/j.rser.2017.01.087 [72].

Component emissions in pavement mixtures [72].

Components	EMISSIONS (Kg CO_2 equivalent/Kg component)				
	Carbon Dioxide CO_2	Methane CH_4	Carbon Monoxide CO	Dinitrogen Monoxide N_2O	Total
Portland Cement	0.8048	0.0151	0.0008	0	0.8207
Gravel	0.0027	0.0001	0	0	0.0028
Sand	0.0023	0.0001	0	0	0.0025
Fly Ash	0	0	0	0	0.
Asphalt Cement	0.3817	0.0041	0.0010	0.0023	0.4260

Table 12. CO2 equivalent of different components [72]

Reference: L.P. Thives, E. Ghisi, Asphalt mixtures emission and energy consumption: A review, Renew. Sustain. Energy Rev. 72 (2017) 473–484. doi:10.1016/j.rser.2017.01.087 [72].

Kg CO_2 equivalent values for mixtures production [72].

Mixtures production	Materials	% Weight	Kg CO_2 equiv./kg	Kg CO_2 equiv. % weight	Total Kg CO_2 equiv./kg	Reduction of CO_2 emission (%)
Portland Cement Concrete	Gravel	0.4	0.0028	0.0022	0.1055	/
	Sand	0.394	0.0025	0.0010		
	Portland Cement	0.126	0.8207	0.1034		
Fly Ash And PCC	Gravel	0.4	0.0028	0.0011	0.0743	29.6
	Sand	0.394	0.0025	0.0010		
	Portland Cement	0.088	0.8207	0.0722		
	Fly Ash	0.38	0	0		
Hot Mix Asphalt	Aggregate	0.95	0.0026	0.0025	0.0238	77.4
	Asphalt Cement	0.05	0.426	0.0213		
Asphalt Rubber	Aggregate	0.92	0.0026	0.0024	0.0299	71.7
	Crumb Rubber	0.016	0.0126	0.0002		
	Asphalt Cement	0.064	0.426	0.00273		

Table 13. Kg CO_2 equivalent values for mixture production [72]

Energy consumed and greenhouse gases emitted during the manufacture of one ton of finished product from extraction until the sale at the production unit [73].

Product	Energy (MJ/t)	CO_2 (Kg/t)
Bitumen	**4900**	**285**
Emulsion 60%	3490	221
Cement	4976	980
Hydraulic road binder	1244	245
Crushed aggregates	**40**	**10**
Pit-run aggregates	30	2.5
Steel	25100	3540
Quicklime	9240	2500
Water	10	0.3
Plastic	7890	1100
Fuel	35	4
Production of HMA	**275**	**22**
Production of WMA	234	20
Production of high modulus asphalt	289	23
Production of cold mix plant	14	1
Surface milling of asphalt for rap	12	0.8
In-situ thermo-recycling	456	34
In situ cold recycling stabilization	15	1.13

In situ soil cement stabilization	12	0.8
Laying of hot mix asphalts	9	0.6
Laying of cold mix materials	6	0.4
Cement concrete road paving	2.2	0.2
Lorry transport (km/t)	0.9	0.06

Table 14. Energy and emissions related to HMA [73]

Reference: J. Chehovits, L. Galehouse, Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements, in: First Int. Conf. Pavement Preserv., 2010: pp. 27–42. doi:http://www.techtransfer.berkeley.edu/icpp/papers/65_2010.pdf [73].

Using the data above, the following results are obtained for a friction course.

Product	**CO_2 (Kg/t)**	**t/m2**	**CO2 kg/m2**	**C02 %**	**CO2 Kg/t**
Bitumen	**285**	0.003	0.98	26%	14.3
Emulsion 60%	221	0.001	0.22	6%	3.2
Crushed aggregates	**10**	0.066	0.66	17%	9.5
Production of HMA	**22**	0.069	1.52	40%	22.0
Laying of hot mix asphalts	0.6	0.069	0.04	1%	0.6
Lorry transport (km/t)	0.06	6.210	0.37	10%	5.4
Sum			3.79	100%	55.0

Table 15. Approximate estimate of emissions (0.03m-thick HMA friction course)

Product	**Energy Consumption (MJ/t)**						**Greenhouse Gas Emissions (kg/t)**					
	B	A	M	T	L	**Total**	B	A	M	T	L	**Total**
Bituminous Concrete	279	38	275	79	9	**680**	16	9.4	22.0	5.3	0.6	**54**
Road Base Asphalt Concrete	196	36	275	75	9	**591**	11	7.6	22.0	5.3	0.6	**47**
High Modulus Asphalt Concrete	284	38	289	79	9	**699**	17	9.4	23.1	5.0	0.6	**55**
Warm Mix Asphalt Concrete	294	38	234	80	9	**654**	17	9.4	20.5	5.3	0.6	**53**
Emulsion Bound Aggregate	227	37	14	81	6	**365**	14	9.4	1.0	5.4	0.4	**30**
Cold Mix Asphalt	314	36	14	86	6	**457**	20	9.1	1.0	5.7	0.4	**36**
Cement-Bound Materials	200	32	14	67	6	**319**	39	5.7	1.0	4.5	0.4	**51**
Cement-Bound Materials & AJ	203	32	14	67	6	**323**	40	5.7	1.0	4.5	0.4	**51**
Aggregate w/Hydraulic Road Binder	50	29	14	61	6	**160**	10	5.1	1.0	4.1	0.4	**20**
Aggregate w/Hydraulic Road Binder & AJ	54	29	14	61	6	**164**	10	5.7	1.0	4.5	0.4	**22**
Cement Concrete Slabs without Dowels	598	40	14	84	2.2	**738**	118	9.6	1.0	5.6	0.2	**134**
Continuous Reinforced Concrete	1,100	29	14	81	2.2	**1,226**	188	5.1	1.0	5.4	0.2	**200**
Untreated Granular Material	0	40	-	68	6	**113**	0	9.6	-	4.5	0.4	**15**
Soil Treated In-situ w/Lime + Cement	63	0	-	7	12	**81**	12	-	-	0.5	1.1	**14**
Thermo-Recycling	98	4	-	12	456	**570**	6	1.0	-	0.8	34.2	**42**
Concrete Bituminous w/10% RAP	250	35	275	73	9	**642**	15	8.6	22.0	4.9	0.6	**51**
Road Base Asphalt Concrete w/20% RAP	157	33	275	64	9	**538**	9	7.8	22.0	4.3	0.6	**44**
Road Base Asphalt Concrete w/30% RAP	137	39	275	58	9	**510**	8	7.0	22.0	3.9	0.6	**41**
Road Base Asphalt Concrete w/50% RAP	98	25	275	47	9	**454**	6	5.2	22.0	3.1	0.6	**37**
Emulsion In-situ Recycling	105	4	-	15	15	**139**	7	1.0	1.1	1.0	0.4	**10**

Note: B=Binder; A=Aggregates; M=manufacture; T=transport; L=Laying

Table 16. Total Energy Use and greenhouse emission for Pavement Construction Materials [73]

Reference: J. Chehovits, L. Galehouse, Energy usage and greenhouse gas emissions of pavement preservation processes for asphalt concrete pavements, in: First Int. Conf. Pavement Preserv., 2010: pp. 27–42. doi:http://www.techtransfer.berkeley.edu/icpp/papers/65_2010.pdf [73].

1.9 Room for improvements

This section discusses research and industrial areas and elements to enhance the formula/processes in the pursuit of improving their noise-related and overall characteristics.

For research and industrial areas and elements to enhance the formula/processes in the pursuit of improving their noise-related and overall characteristics, note that the following aspects emerged:

a. It is noted that when dealing with dry process rubber swelling is a tangible issue (see Hassan et al. 2014 [74]) N.A. Hassan, G.D. Airey, R.P. Jaya, N. Mashros, M.A. Aziz, A review of crumb rubber modification in dry mixed rubberised asphalt mixtures, J. Teknol. 70 (2014) 127–134. doi:10.11113/jt.v70.3501.). This issue can be limited through the pre-treatment of rubber.

b. Overall, there is room for improving the performance of crumb rubber added bituminous mixtures based on crumb rubber treatment (prior to the mixing stage), crumb rubber percentage/gradation, and crumb rubber function (cf. Shahrzad et al, 2018 [8] (S. Hosseinnezhad, S.F. Kabir, D. Oldham, M. Mousavi, E.H. Fini, Surface functionalization of rubber particles to reduce phase separation in rubberized asphalt for sustainable construction, J. Clean. Prod. 225 (2019) 82–89. doi:10.1016/j.jclepro.2019.03.219).

c. CR pre-treatment. There is room for improving the performance of crumb rubber added bituminous mixtures based on crumb rubber treatment (prior to the mixing stage), crumb rubber percentage/gradation, and crumb rubber function (cf. Shahrzad et al, 2018). Indeed, crumb rubber treatment (prior to the mixing stage), crumb rubber percentage/gradation, and crumb rubber function could be optimised. In more detail, it is noted that when dealing with dry processes, rubber swelling represents a tangible issue. This can be limited through the pre-treatment of rubber. Solutions include the pre-treatment of CR through sand-based and asphalt binder-based components.

d. CR percentage. For higher quantities of CR, bituminous mixtures undergo significant modifications, asphalt binder quantities must be modified, mechanistic properties change (e.g., mechanical impedance and its spectrum), air void-related properties may change, as well as surface-related properties (macrotexture). These concurrent modifications make decisions and trade-off evaluations more difficult. In more detail, while the impact on noise generation could appear improved (less noise), the relationship between causes (increase of CR percentage) and effects (e.g., mechanistic impedance, air voids, and impact noise) is complex and still calls for further research.

e. CR effects. Another point that calls for further research and for careful consideration for the next phases of this project refers to the synergetic impact of texture and volumetrics, namely air voids (when affected by CR type, processes, and quantities), on noise, safety, environment, which in turn bring to different agency, user and externality costs. For example, higher CR percentages could improve the noise performance but worsen rolling resistance and emissions during production.

f. Old tyre components. Additionally, old tyres contain an array of components that could and should be considered as a part of the same problem and opportunity (to reduce noise and LCC). For example, other components included in old tyres (e.g., steel) could play a significant role if mixed with CR in the pursuit of optimising noise and at the same time the corresponding LCC, which has a crucial role in terms of overall balance for the given solution.

g. Finally it is here reaffirmed that the elements above are crucial to further encourage low-noise surfaces implementation in EU and extra-EU scenarios, demonstrating their durability and the sustainability, through in-depth LCA&LCCA based on precise and effective technologies and solutions.

1.10 Quiet pavements and EU approach

By referring to quiet pavement technologies, this section discusses their compatibility and perspectives when analysed in terms of 2015/996/EC directive, CNOSSOS-EU mod (Stylianos Kephalopoulos, Marco Paviotti, Fabienne Anfosso-Lédée 2012 [75]) Common Noise Assessment Methods in Europe (CNOSSOS-EU) to be used by the EU Member States for strategic noise mapping following adoption as specified in the Environmental Noise Directive 2002/49/EC).

The hierarchical structure of noise quantification according to EU 2015/996 builds on having the steady traffic flow noise depending on traffic flow and single vehicle.

In turn, this latter depends on rolling noise and propulsion noise.

For rolling noise, it depends on speed, temperature, crossing with traffic light or roundabout, studded tyres, and road surface.

In summarising, the following primary components are expected to change in this project: propulsion and road surface. Importantly, internal combustion torque delivery and power have their maxima around 3k-6k RPM, while EV torque delivery is quite immediate. This is likely to affect the rolling noise as well as future pavements (see below).

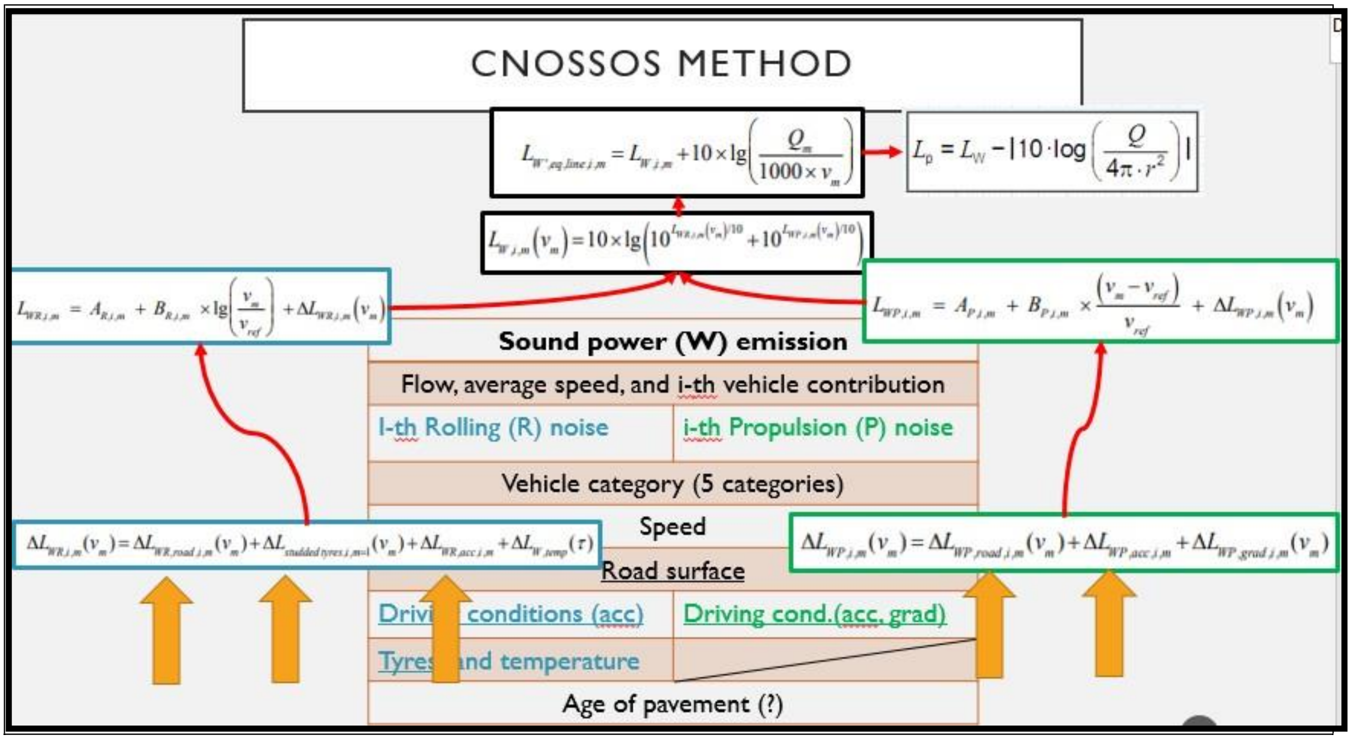


Figure 18. Rolling and propulsion noise (CNOSSOS method)

Source: Praticò, F.G., presentation of Life project given at the SC4 conference in Braga, Portugal, 2019.

Figure above illustrates how road surface impacts sound power emission for both rolling (left) and propulsion (right) component.

For road impact and EV impact, note that

- in the model above the following is considered:
  - a "flat" road
  - a virtual reference road surface, consisting of an average of dense asphalt concrete 0/11 and stone mastic asphalt 0/11, between 2 and 7 years old and in a representative maintenance condition
  - a dry road surface
  - ΔLWR,road,i,m accounts for the effect on rolling noise of a road surface with different acoustic properties from the virtual reference surface as defined in Section III.2.2. It includes both the effect on propagation and on generation. The calculation is detailed in Section III.2.6.
  - ΔLWP,road,i,m accounts for the effect of the type of road surface on propulsion noise. It includes the effect of a porous surface on local propagation of propulsion noise. The calculation is detailed in Section III.2.6.
- ΔLWR,acc,i,m accounts for the effect on rolling noise of a crossing with traffic lights or a roundabout. It essentially integrates the effect on noise of the speed variation. This is described in Section III.2.5.
- ΔLWP,acc,i,m and ΔLWP,grad,i,m account for deviations related to the driving conditions. They are detailed in Sections III.2.5 and III.2.4.b respectively (CNOSSOS REPORT).
- The coefficients CR,m,k (that refers to ΔLWR,acc,i,m) and CP,m,k (that refers to ΔLWP,acc,i,m) depend on the kind of junction k (k = 1 for a crossing with traffic lights ; k = 2 for a roundabout) and are given in

Appendix III-A for each vehicle category. The coefficients are equal for categories 2 and 3. The correction includes the effect of change in speed when approaching or moving away from a crossing or a roundabout.

- **The road surface correction factor on rolling noise emission** is given by: $\Delta L_{WR,road,i,m} = \alpha_{i,m} + \beta_m \times lg(v_m/v_{ref})$, where $\alpha_{i,m}$ is the spectral correction in dB at reference speed v_{ref} for category m (1, 2 or 3) and spectral band i (octave band from 125 to 4000 Hz). β_m is the speed effect on rolling noise reduction. Although this coefficient is in principle frequency- dependent, no spectral data are available in the literature and a constant value is assumed in this method.
- In the case of a porous road surface, the road surface correction factor on propulsion noise is given by $\Delta L_{WP,road,i,m} = \min(\alpha_{i,m};0)$. This correction is identical to that for rolling noise at the reference speed, but with a maximum of zero. Thus, porous surfaces will decrease the propulsion noise, but dense surfaces will not increase it.
- For **age effect on road surface noise properties,** noise characteristics of road surfaces vary with age and the level of maintenance, with a tendency to become louder over time. In particular, the acoustic lifetime of a low-noise surface is usually shorter than a dense surface, especially for concrete surfaces. Therefore, the road surface correction should be based on the average effect over the representative lifetime. A procedure on how to take this effect into account in the establishment of road surface coefficients will be described in the "Guidelines for the competent use of CNOSSOS-EU.

Given that, the following conclusions can be drawn:

1) The choice of a **pavement** is going to affect:
   - $\alpha_{i,m}$
   - β_m
2) **EV percentage and type** could affect
   a. Propulsion noise coefficients $A_{P,i,m}$ and $B_{P,i,m}$
   b. To a certain extent, deviations related to the driving conditions ($\Delta L_{WP,acc,i,m}$ and $\Delta L_{WP,grad,i,m}$).

In terms of qualitative assessment of EV influence on tyre-pavement interaction noise, note that:

- according to Sandberg and Ejsmont, 2002 [76] (U. Sandberg, Jerzy A. Ejsmont, Tyre/road noise reference book, INFORMEX, Harg, SE-59040 Kisa, Sweden, 2002)
- and according to Li, 2018 [77] (T. Li, Influencing Parameters on Tire-Pavement Interaction Noise: Review, Experiments and Design Considerations, Designs. 2 (2018). doi:10.1201/9780203741771),

the potential noise variation (in dB) associated to wheel torque is about 3 while the one associated to pavement is about 10, as well as the one associated to tyre. This latter is sometimes supposed to affect tyre-pavement interaction noise less than pavement.

The following conclusions were drawn:

a. The choice of a pavement is going to affect: $\alpha_{i,m}$ (the spectral correction in dB at reference speed v_{ref} for category m (1, 2 or 3) and spectral band i (octave band from 125 to 4000 Hz)) and β_m (the speed effect on rolling noise reduction).

b. EV percentage and type could affect propulsion noise coefficients $A_{P,i,m}$ and $B_{P,i,m}$, and, to a certain extent, deviations related to the driving conditions ($\Delta L_{WP,acc,i,m}$ and $\Delta L_{WP,grad,i,m}$).

c. For age effect on road surface noise properties, noise characteristics of road surfaces vary with age and the level of maintenance, with a tendency to become louder over time. In particular, the acoustic lifetime of a low-noise surface is sometimes shorter than the one of a traditional dense-graded surface. Therefore, the road surface correction should be based on the average effect over the representative lifetime.

1.11 Preliminary tests

This section refers to section "Action A2" of the project. To this end, it is noted that through this project a device was bought to carry out airflow resistance measurements.

1.11.1 Airflow resistance

The airflow resistance is the resistance of an air particle passing through a material, and it can be expressed as the ratio of pressure gradient in a material to airflow linear velocity [78].

The ratio between the increase of the pressure and the flow is the resistance of the airflow.

The airflow resistance is a very important acoustic parameter used to describe the interaction between the materials and the acoustic waves.

The theoretical background can be retrieved at:

https://www.animations.physics.unsw.edu.au/jw/compliance-inertance-impedance.htm

https://apmr.matelys.com/Parameters/StaticAirFlowResistivity.html#MathematicalExpression

https://www.sciencedirect.com/topics/engineering/flow-resistivity

Airflow resistance can be estimated in accordance with the UNI EN ISO 9053 standard, which gives all the instruments useful in relating acoustic properties to structural properties.

The reference standard is the UNI EN ISO 9053-1:2019 Acoustics - Determination of airflow resistance - Part 1: Static airflow method [79].

In accordance with UNI EN ISO 9053-1 standard the following main parameters are introduced:

a) Airflow resistance, R:

$$R = \frac{\Delta p}{q_V} \qquad (\mathrm{Pa \cdot s/m^3}) \qquad (1.1)$$

Where:

- Δp is the air pressure difference, expressed in Pa, across the test specimen with respect to the atmosphere;

- q_v is the volumetric airflow rate, expressed in m^3/s, thorough the test specimen.

R is the non-normalized value of R_s. R can be computed by dividing Rs by the nominal surface area of the specimen with diameter d (mm).

b) Specific airflow resistance, R_s:

$$R_S = R \cdot A \qquad (\mathrm{Pa \cdot s/m}) \qquad (1.2)$$

Where

- R is the airflow resistance (Pa·s/m^3) of the test specimen;

- A is the cross-sectional area (m^2) of the test specimen perpendicular to the direction of flow.

R_s is the observed resistance normalised to an area for the specimen of 1 m^2.

a) **Airflow resistivity, r** (if the material is considered as being homogeneous):

$$r = \frac{R_S}{d} \qquad (\text{Pa·s/m}^2) \tag{1.3}$$

Where

- R_s is the specific airflow resistance (Pa·s/m) of the test specimen

- d is the thickness, in metres, of the test specimen in the direction of flow.

Based on ISO 9053, for method B, the following quantities are relevant to the measure 1) Airflow rate. 2) Airflow speed. 3) Pressure (effective alternating pressure).

Indeed, ISO 9053 states:

"The measuring device can this be calibrated absolutely in pressure units. With unchanged amplitude of the measuring piston, the scale is able to indicate the <u>specific flow resistance</u> directly."

The root mean square of the volumetric airflow rate (m^3/s), where this airflow is generated by a piston moving sinusoidally at 2 Hz=f, is given as follows:

$$q_{V,r.m.s} = \frac{\pi}{\sqrt{2}} f h A_p \tag{1.4}$$

Where

f is the frequency, in hertz, of the piston;

h is the stroke (peak to peak displacement), in metres, of the piston;

A_p is the cross-sectional area, in square metres, of the piston cylinder.

The corresponding root mean square of the airflow velocity expressed in m/s) is:

$$u_{r.m.s} = \frac{q_{V,,r.m.s.}}{A} \tag{1.5}$$

Where

$q_{V,r.m.s.}$ is the r.m.s. value of the alternative volumetric airflow rate, in cubic metres per second;

A is the area, in square metres, of the test specimen.

The corresponding effective alternating pressure, measured by a laterally mounted condenser microphone is as follows:

$$p_{eff} = 1.4\ \frac{p_0}{\sqrt{2}}\frac{V_{pk}}{V} \tag{1.6}$$

Where

p_0 is the atmospheric pressure, in pascals;

V_{pk} is the product of the amplitude and piston cross-sectional area of the calibration pistonphone, in cubic metres;

V is the volume of the test vessel, in cubic metres.

By referring to the relation between dB (output of the phono meter) and EU ("The measuring device can be calibrated absolutely in pressure units") note that the logarithmic dB scale is a scale relative to a common reference value. In the airflow resistance instrument used, the reference value is always $2x10^{-5}$ Pa corresponding to the common reference value for sound pressure levels: 20µPa. A linear quantity X (pressure X) will correspond to a level L_x given by:

$$Lx = 10\ lg\ \left\{\frac{X^2}{{X_0}^2}\right\} \tag{1.7}$$

Where $X_0 = 2 \times 10^{-5}$ Pa, as abovementioned. This implies that 1 EU=X corresponds to LX=94 dB (reference):

$$\mathrm{X} = (\mathrm{X}_0) \times (10^{\wedge L/20}) = 2 \times 10^{-5} \times 10^{(94/20)} = 1 \tag{1.8}$$

It seems noteworthy to mention that Wittstock and Schmelzer, 2018 [80] (V. Wittstock, M. Schmelzer, Measurement of airflow resistance by the alternating flow method, in: Proc. Euronoise 2018, Crete, 2018: pp. 625–630.) explain the possibility to estimate the airflow resistance (Pas/m^3) and not the specific airflow resistance (Pas/m) by considering the following relationships:

$$N = \frac{\mathrm{V}}{\kappa\, p_s} \tag{1.9}$$

$$\frac{p}{q} = \sqrt{\frac{R^2+(\omega M)^2}{(1-\omega^2 NM)^2+(\omega NR)^2}} \tag{1.10}$$

$$\frac{p_{tight}}{q_{tight}} = \frac{1}{\omega_{tight}\, N_{tight}} \tag{1.11}$$

$$q = q_{tight}\, \frac{h}{h_{tight}} \tag{1.12}$$

$$\omega M << R; \frac{1}{\omega N} >> R \tag{1.13}$$

$$R \approx \frac{p}{p_{tight}} \frac{h_{tight}}{h} \frac{\kappa\, p_{s,tight}}{2\pi\, V_{tight}} \tag{1.14}$$

Further details are provided in the mentioned paper, where the lumped parameter model is explained in more detail.

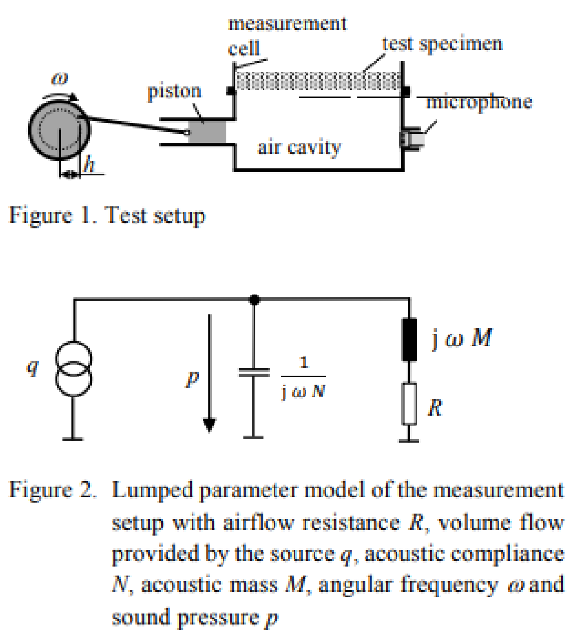


Figure 19. Lumped parameter model and air flow resistance

Source: V. Wittstock, M. Schmelzer, Measurement of airflow resistance by the alternating flow method, in: Proc. Euronoise 2018, Crete, 2018: pp. 625–630 [80]

1.11.1.1 Instruments

The airflow resistance was measured using the apparatus Norsonic Nor1517A, by applying the alternating airflow method (Method B) in accordance with UNI EN ISO 9053-1:2019 [79].

Figure 22. Norsonic Nor1517A Apparatus

For carrying out measurements, a cylindrical specimen is placed into a sample holder (a) which closes the open end of a vessel with known volume and diameter (b). The specimen is locked between two grills or perforated plates (c). A piston (d), moving back and forth in a sinusoidal motion at the frequency of approximately 2 Hz, generates a slowly alternating airflow through the test specimen. The alternating component of the test pressure in the test volume enclosed by the specimen is measured by the microphone (e) and the sound level meter (f). In addition, the holder of the specimen is equipped with an indicator (g) allowing the measurement of the thickness of the specimen.

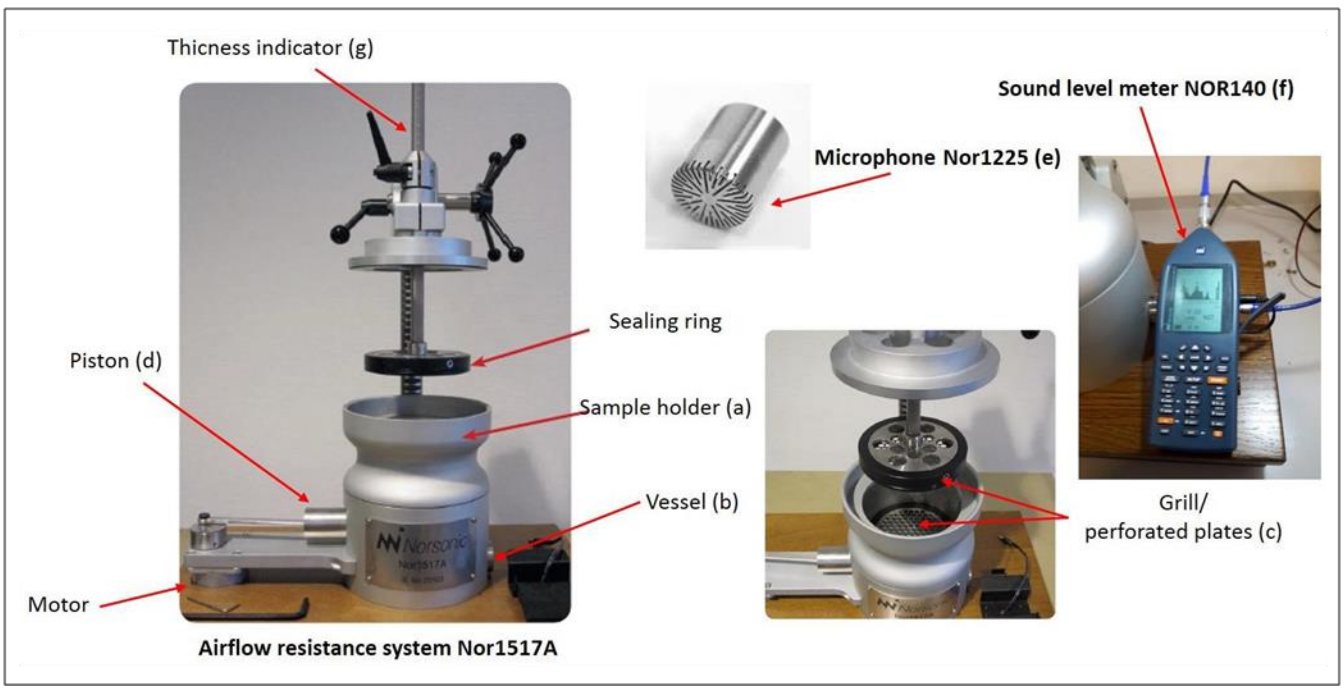


Figure 23. Norsonic Nor1517A Apparatus - Components

The sound level meter "NOR140 Sound Analyzer" equipped with the normal microphone "Nor1225" was used during the preliminary tests. The instrument is set to display results in Engineering Units (EU) where 1 EU corresponds to 1 Pa·s/m [81].

Norsonic, Manual Instrument - Measurement of airflow resistance Norsonic nor1517A, (2012) 20.

1.11.1.2 Test Procedure

The following steps were followed:

1. Calibration
2. Each test specimen was placed into the measurement cell, ensuring that that the edges are properly sealed.
3. The specimen was next locked with the clamped device.
4. The device for measuring the thickness of the test specimens was brought into contact with the upper surface of the test specimen, compressing it lightly where necessary.
5. The engine which operates the piston has been turned on.
6. The Measurement was conducted for 10 s using a sound level meter.
7. The engine has been switched off.
8. The Leq value for the 2 Hz band displayed the specific airflow resistance Rs, expressed in EU.
9. Finally, airflow resistivity r was determined in accordance to the Equation 1.3.
10. Note: Leq is the Integrated Equivalent SPL; SPL is the Instantaneous Sound Pressure Level.

1.11.1.3 Calibration

The measuring instrument was calibrated using an airtight disc (a) 4.7 mm thick with a diameter of 5.66 cm. During this process the sensitivity of the microphone was adjusted to have a value corresponding to that state by Norsonic for the 2 Hz. This value corresponds to 184.3 dB for the device used.

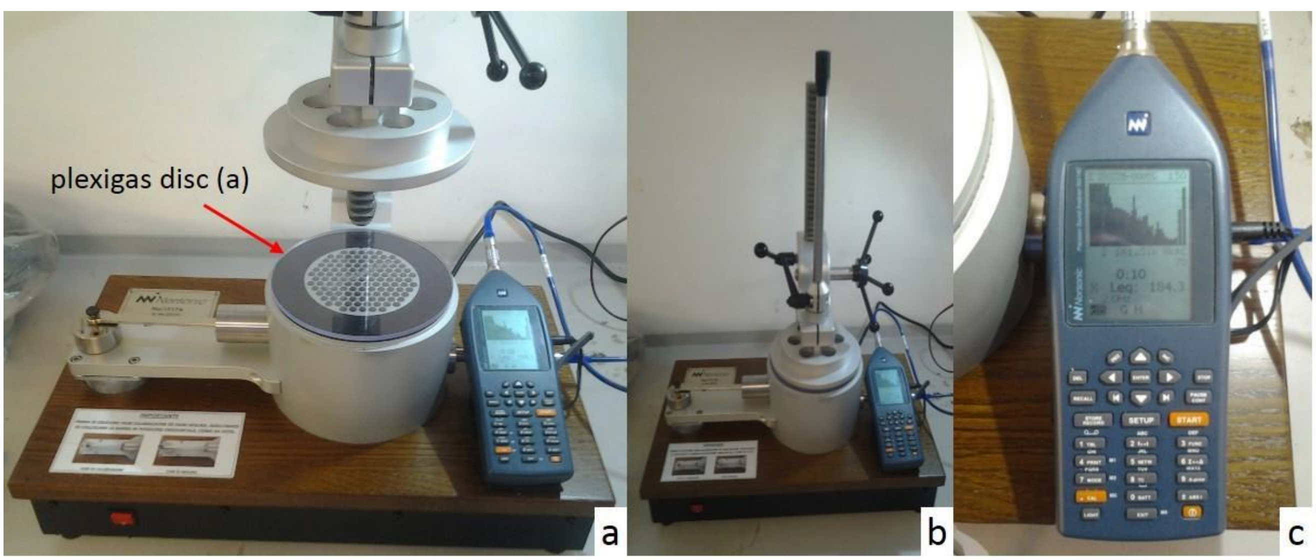


Figure 24. Airtight disk positioning (a), calibration test (b), reading on display (c)

Note. During the calibration process, the microphone sensitivity has to be adjusted to obtain the displayed value of 184.3 dB for the 2 Hz band. This value corresponds to that obtained by Norsonic during instrument calibration.

1.11.1.4 Validation

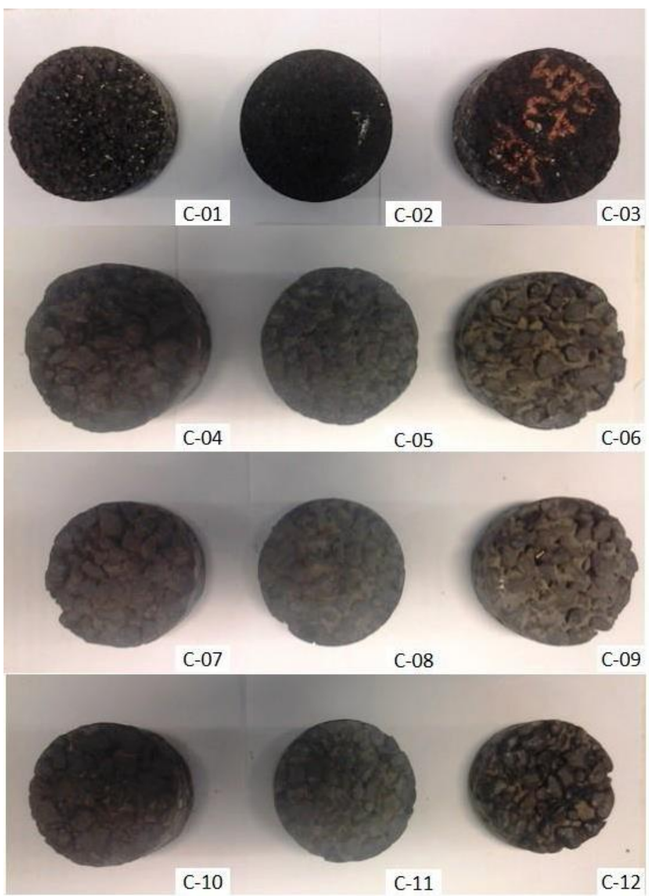
The validation phase involved a series of tests performed on twelve cylindrical cores of two types of bituminous mixtures. Three specimens (C-01, C-02, and C-03) were dense graded (DG), while the others (C-04 to C-12) were open graded (OG). Each specimen was tested five times on both sides (top and bottom). Each measurement lasted 10 seconds.

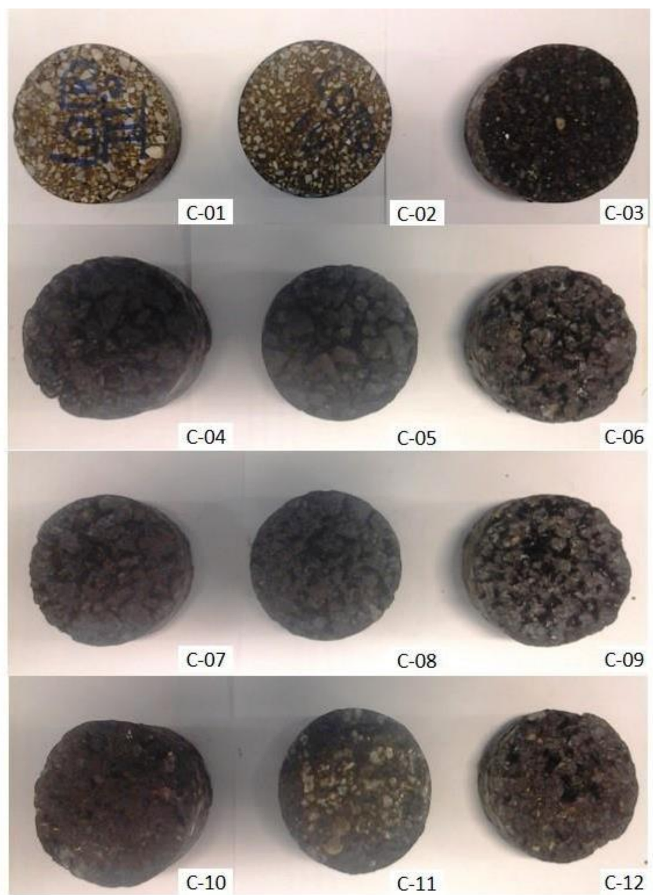
At end the Leq value at 2 Hz was recorded. For this application the level in the 2 Hz band is used

since 2 Hz corresponds to the frequency of the oscillating piston [81].

Reference: Norsonic, Manual Instrument - Measurement of airflow resistance Norsonic nor1517A, (2012) 20.

The airflow resistance was then determined. The average of the five measurements for each specimen is shown in the table below.





Top side Bottom

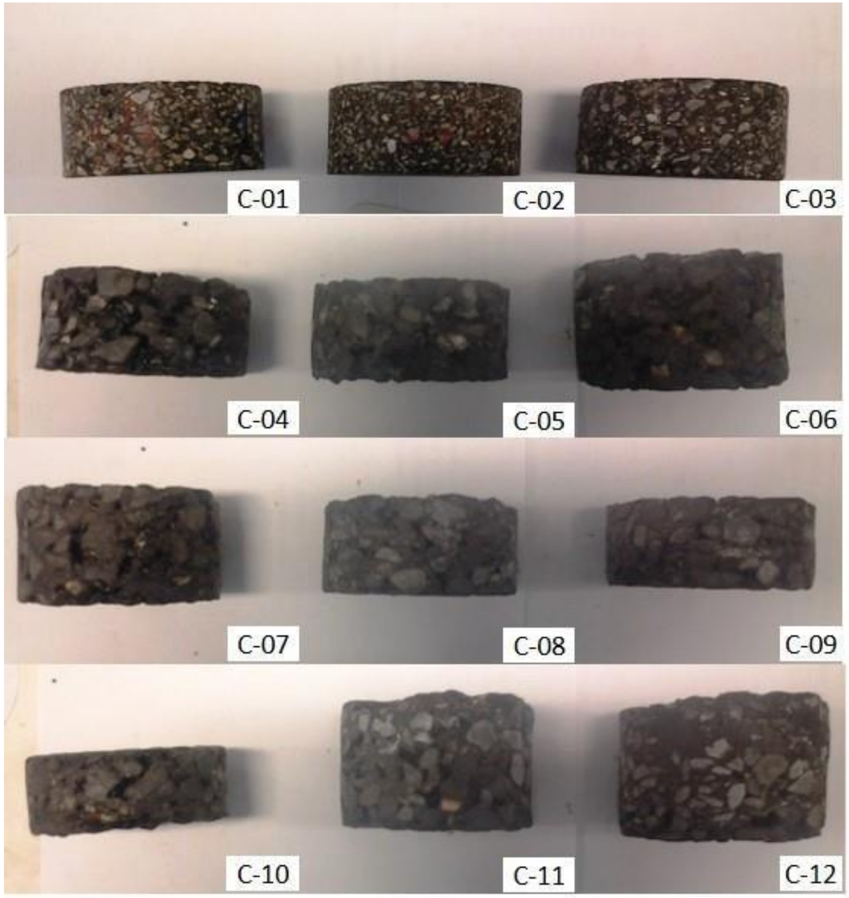


Figure 20. Preliminary experiments

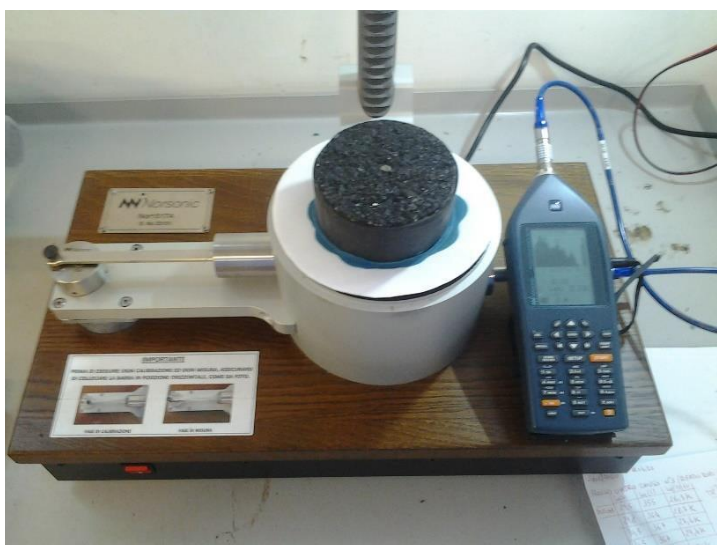


Figure 21. Specimen positioning on test apparatus

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Specimen	Mix	Side	Weight (g)	d (m)	A (m2)	Thickness (m)	Leq (dB)	Leq (EU)	Rs (Pa*s/m)	R (Pa*s/m^3)	Resistivity, r (Pa*s/m^2=Ns/m4)	Gmb Dim. (g/cm^3)
C-01	DG	T	625.02	0.0947	0.0070	0.041	191.9	78710.0	78710.0	11174810.2	1919756.5	2.16
C-01	DG	B	625.02	0.0947	0.0070	0.041	192.86	87908.3	87908.3	12480734.8	2144105.4	2.16
C-02	DG	T	637.86	0.094	0.0069	0.041	196.0	126482.4	126482.4	18225708.0	3084935.9	2.24
C-02	DG	B	637.86	0.094	0.0069	0.041	194.24	103045.7	103045.7	14848562.4	2513310.5	2.24
C-03	DG	T	636.89	0.0947	0.0070	0.043	182.40	26365.1	26365.1	3743175.2	620356.1	2.13
C-03	DG	B	636.89	0.0947	0.0070	0.043	164.44	3334.5	3334.5	473413.0	78458.7	2.13
C-04	OG	T	581.40	0.0944	0.0070	0.044	137.58	151.4	151.4	21627.0	3471.7	1.90
C-04	OG	B	581.40	0.0944	0.0070	0.044	138.36	165.6	165.6	23659.0	3797.9	1.90
C-05	OG	T	577.94	0.0939	0.0069	0.046	132.54	84.7	84.7	12235.1	1858.1	1.83
C-05	OG	B	577.94	0.0939	0.0069	0.046	132.60	85.3	85.3	12319.9	1871.0	1.83
C-06	OG	T	790.43	0.0937	0.0069	0.061	138.46	167.5	167.5	24291.9	2732.6	1.87
C-06	OG	B	790.43	0.0937	0.0069	0.061	136.74	137.4	137.4	19927.9	2241.7	1.87
C-03-bis	DG	T	636.89	0.0947	0.0070	0.043	182.98	28185.8	28185.8	4001659.7	663194.7	2.13
C-03-bis	DG	B	636.89	0.0947	0.0070	0.043	164.4	3326.8	3326.8	472324.2	78278.2	2.13
C-07	OG	T	672.00	0.0938	0.0069	0.052	134.1	101.6	101.6	14707.4	1965.8	1.88
C-07	OG	B	672.00	0.0938	0.0069	0.052	134.56	106.9	106.9	15471.6	2067.9	1.88
C-08	OG	T	560.54	0.095	0.0071	0.041	133.9	99.5	99.5	14044.1	2416.2	1.92
C-08	OG	B	560.54	0.095	0.0071	0.041	134.18	102.3	102.3	14437.5	2483.9	1.92
C-09	OG	T	525.53	0.095	0.0071	0.040	134.72	108.9	108.9	15363.6	2750.0	1.87
C-09	OG	B	525.53	0.095	0.0071	0.040	134.98	112.1	112.1	15821.3	2831.9	1.87
C-10	OG	T	488.14	0.0943	0.0070	0.036	137.00	141.6	141.6	20272.9	3911.3	1.93
C-10	OG	B	488.14	0.0943	0.0070	0.036	136.36	131.5	131.5	18832.9	3633.5	1.93
C-11	OG	T	885.57	0.0938	0.0069	0.063	167.82	4920.7	4920.7	712089.3	77983.1	2.03
C-11	OG	B	885.57	0.0938	0.0069	0.063	144.52	336.5	336.5	48700.6	5333.4	2.03
C-12	OG	T	911.03	0.094	0.0069	0.062	158.10	1607.1	1607.1	231571.1	25836.9	2.11
C-12	OG	B	911.03	0.094	0.0069	0.062	142.06	253.5	253.5	36532.9	4089.2	2.11

Table 17. Resistivity measurements

Note: DG=Dense Graded; OG=Open Graded; B=Bottom side; T=Top side; EU= Engineering Units (1EU= 1Pa· s/m); Rs= Specific airflow resistance; R=Airflow resistance; r= Airflow resistivity.

Based on the literature, table above shows the variation of airflow resistivity [82]. Note that for porous European mixes (PEMs), the resistivity approximately ranges from 1,000 to 60,000 Ns/m^4 (Pa·s/m^2), while for Dense Graded Friction Courses (DGFC) it ranges from 600,000 to 30,000,000 Ns/m^4 (Pa·s/m^2).

Input Parameter	Main effect on the absorption a(f) of a bituminous mixture	Measurability	Reference values based on literature	
			DGFC	PEM
Thickness (t, 0.01m)	The higher the thickness is the lower the frequency of the first maximum is. Absorption tends to be lower and smoothed.	Easy to measure	2 - 4	4 - 6
Porosity (Ω, %)	The higher the porosity is, the higher the absorption coefficient is. Maximum frequency does not depend on porosity.	Quite easy to measure	4 – 8	16 - 30
Resistivity (Rs, Ns/m^4)	The higher the resistivity, the lower the maxima, the smoother the curve.	Quite difficult to measure	600,000 - 30,000,000	1,000 - 60,000
Tortuosity (q^2)	The higher the tortuosity is, the lower the frequency of maximum is. The impact on the maximum value of absorption is usually quite negligible.	Quite difficult to measure	1 – 10 (usually 2.5-4.5 for PEMs)	
Total resistance (RT=Rs×t)	For low values of RT, the higher the total resistance is, the higher the maxima are. For RT higher than about 100 Ns/m^3, the behaviour is opposite. If, Ω, RT, q^2 are constant, the "shape" is constant but the maximum frequency depends on t (the lower, the higher).	See above	See above. Note: DGFC= dense-graded friction course	

Table 18. Reference values [82].

Results show that the values obtained are comparable with those reported in the literature.

1.12 Selected Mixes

To select the mixes, UNIRC analysed many solutions (pavement, bituminous mixtures), based on acoustic and non-acoustic performances. At the beginning, more than 150 mixes were selected spanning from dense-graded to gap-graded ones. Their characteristics and impacts were analysed. Preliminary tests were carried out. In more detail, the following characteristics and parameters have been considered:

- Acoustic response (as-built and over time)
- Expected life by referring to mechanistic properties
- Permeability
- Friction.

The following main criteria were followed to select the mixtures:

- Having a satisfactory expected life.
- Having an ENDt (Estimated Noise Difference Due to Texture) value sufficiently low
- Having satisfactory characteristics for the remaining properties.

Note that the main volumetric and functional parameters were derived. The mixtures AC6, ISO, and GAP resulted in the best noise-related parameters. To this end, the ENDt indicator was used. Based on the above the following mixtures were selected (cf. Table below).

Based on the above the following mixtures were selected.

Table C1

	Acronym	END_t (dB)	MPD (mm)	AV (%)	BPN
1	AC6	0.7	0.72	11.7	≥60
3	SUP	1.2	0.92	8.2	≥60
4	OG4	2.9	1.79	17.4	≥55
6	GAP	0.7	0.95	6.9	≥55
10	SM6	1.7	0.8	7.6	≥60
11	SM6*	2.4	1.04	3.7	≥60
12	AC6*	2.2	1.1	7.4	≥60
13	SM8	1.7	0.9	7.3	≥60
19	ISO	0	0.5	4	≥60

Table 19. List of selected mixes

1.13 A2 References

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