

Lecture Notes in Civil Engineering

Christiane Raab *Editor*

Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9



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Christiane Raab
Editor

Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9

Editor

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Preface

The Mairepav Conference series is the famous long-time flagship conference of the International Society of Maintenance and Rehabilitation of Transport Infrastructure (iSMARTi). The inaugural conference was held at Mackenzie Presbyterian University in Sao Paulo, Brazil, in 2000, and the series has steadily grown in number of participants and international visibility over the past 20 years, with installments hosted in various countries all over the world. The Mairepav Conference series is dedicated to the theme of maintenance and rehabilitation of infrastructure of the public and private transport, especially for roads and pavements.

This book gathers the proceedings of the Mairepav 9 Conference held at Empa (Swiss Federal Laboratories for Materials Science and Technology) in Dübendorf, Switzerland, in July 2020.

The contributions share the latest insights from research and practice in the maintenance and rehabilitation of pavements and discuss advanced materials, technologies and solutions for achieving an even more sustainable and environmentally friendly infrastructure. In this sense, it provides a state-of-the-art compendium and valuable source of knowledge for scientists, practitioners and students. The main topics are:

- Advanced Trends in Design, Rehabilitation and Preservation
- Management Systems and Life Cycle Analysis
- Sustainable Pavement Systems
- Recycling and By-products
- Advanced Pavement Materials and Technologies
- Evaluation of Pavement Performance
- Full Scale Studies Accelerated Pavement Testing
- Surface Characteristics and Road Safety

Infrastructure in general and pavements in particular provide a significant value worldwide. Since, the focus in most countries is not on construction of new infrastructure, maintenance and rehabilitation are receiving more and more importance and attention. Moreover, the development in maintenance and

rehabilitation is driven by decreasing public budgets on the one hand and increasing traffic and user demand on the other hand. In addition, demands and requirements regarding digitalization, environmental issues and sustainable development have to be taken into consideration and have led to calls for new solutions. These solutions cover the whole range of sustainable materials, digital and big data technologies as well as life cycle considerations under an economic and environmental point of view. Therefore, it is high time that a new conference is held providing a platform for innovative developments and latest technologies for current and future applications for infrastructure and pavements.

In this sense, the 9th MAIREPAV Conference, July 1–3, 2020, in Switzerland, hosted for the first time by Empa Swiss Federal Laboratories for Materials Science and Technology, is of particular importance. All carefully peer-reviewed contributions present and discuss current knowledge and pioneering developments, clearly demonstrating that research and development in maintenance and rehabilitation of pavements is indispensable for providing durable and environmentally sustainable roads all over the world.

I would like to thank all the authors, peer reviewers, leading iSMARTi and scientific committee members as well as the Springer team who made this book possible and with this showed enormous effort and commitment in favor of the MAIREPAV9 Conference. This is particularly true in view of the extremely difficult situation caused by the COVID-19 pandemic. A situation, which clearly emphasizes that we are living in a global village, depending on each other in order to find effective problem solutions. I am particularly grateful to Manfred N. Partl, the former head of the Laboratory for Road Engineering/Sealing Components at Empa for his constant support. Moreover, I would like to acknowledge my assistant Michèle Köhli for her commitment in all MAIREPAV-related issues.

Dübendorf, Switzerland

Christiane Raab
Chair MAIREPAV9

Contents

Advanced Trends in Design, Rehabilitation and Preservation

Influence of the Aggregate Gradation on the Rutting Resistance of Bituminous Mixtures	3
B. S. Abhijith and J. Murali Krishnan	
Experimental Investigation of Pothole Repair Materials	13
Debaroti Ghosh, Mugur Turos, and Mihai Marasteanu	
A Durable Potholes Repair Method Using Polymer Modified Patching Material in Cold-Wet Weather	23
Sen Han, Jinping Xia, Hui Xu, and Hongwei Zhang	
Maximising Stabilisation and Recycling Benefits for Sustainable Pavement Performance in New Zealand and Australia	35
Allen Browne	
Evaluation of Warm Mix Asphalt Produced from Iraqi Materials	45
Noor J. Mahdi, Duraid M. Abd, and Taher M. Ahmed	
Influence of Curing on the Mechanical Properties of Cement-Bitumen Treated Materials Using Foamed Bitumen:	
An Interlaboratory Test Program	55
Marco Pasetto, Emiliano Pasquini, Andrea Baliello, Simone Raschia, Amir Rahmanbeiki, Alan Carter, Daniel Perraton, Francesco Preti, Beatriz Chagas Silva Gouveia, Gabriele Tebaldi, Andrea Grilli, and Eshan V. Dave	
Laboratory Tests for the Characterization of Cold Asphalt Patching Mixtures	67
Pier Paolo Riviera, Davide Dalmazzo, and Ezio Santagata	

Performance Evaluation of Long-Life Pavements Using the Mechanistic-Empirical Asphalt Pavement Analysis (MEAPA) Web Application	79
M. Ghazavi, A. Seitllari, and M. E. Kutay	
Management Systems and Life Cycle Analysis	
The Challenges of Warm Mix Asphalt as a Mature Technology	93
Ali Jamshidi and Greg White	
A Framework for Network Level Pavement Maintenance Planning for Low Volume Roads	103
H. R. Pasindu, R. M. K. Sandamal, and M. Y. I. Perera	
P-F Curves in Modelling of Pavement Performance	115
Adam Zofka	
Combined Life Cycle Cost Analysis and Life Cycle Assessment of Road Pavements	123
Egemen Okte and Imad L. Al-Qadi	
Decision Support for New Holistic Uri Road Asset Management Process	133
Frank Schiffmann, Rade Hajdin, and Alfredo Seroli	
Life Cycle CO₂ Analysis of Low Rolling Resistance Asphalt Pavements	143
A. Kawakami, M. Yabu, and H. Nitta	
Accuracy Comparisons Between ASTM 1318-09 and COST-323 (European) WIM Standards Using LTPP WIM Data	155
Syed W. Haider and Muhammad Munum Masud	
Detecting Significant Changes in Traffic Patterns for Pavement Design	167
Gopi K. Musunuru, Syed W. Haider, and Neeraj Buch	
Development of Road Maintenance Management System for India's National Highway Network Using HDM-4 and Genetic Programming	177
Abhishek Sharma and Tanuj Chopra	
Sustainable Pavement Systems	
SENSO JOINT—An Innovative Sensor System for a Sustainable Joint Design of Concrete Pavements	191
Ch. Recknagel, S. Spitzer, J. Hoppe, N. Wenzel, and S. Pirskawetz	

Numerical Evaluation of Crushing Resistance of Unbound Road Material	201
Erik Olsson, Denis Jelagin, and Manfred N. Partl	
Developing and Modeling a Piezoelectric Energy Harvester (PEH) for Highway Pavements	211
Mohamadreza Khalili, Sara Ahmed, and A. T. Papagiannakis	
Performance Optimization of Warm Recycled Mixtures	221
F. Cardone, F. Canestrari, X. Jiang, and G. Ferrotti	
Development of Durable Pavement in Japan	231
Shigeki Takahashi, Shouichi Kanno, Yu Shirai, and Tamotsu Yoshinaka	
Laboratory Evaluation of Recycled Asphalt Pavement Material in Warm-Mix Asphalt	243
Haritha Malladi, Abhilash Kusam, and Akhtarhusein A. Tayebali	
Assessing Self-healing Asphalt by the Heating of Asphalt Mixtures	253
Caio Santos, Marina Cabette, Jorge Pais, Vitor Carvalho, and Paulo Pereira	
Ultrasound Monitoring and Microwave Self-healing of Top-Down Cracks in Asphalt Pavements	263
Miguel A. Franesqui, Jorge Yepes, and Juan Gallego	
Effects of Moisture and Aging on Asphalt Binder Adhesion Failure Using Pull-Off Tension Test	275
Muhammad Rafiq Kakar, Meor Othman Hamzah, and Christiane Raab	
Effect of Addition of Plastic Fibres on Strength Characteristics of Subgrade Soil	285
Ashutosh Kaushal, Rajesh Pathak, and Tanuj Chopra	
Modeling Rutting Behavior of Crumb Rubber Modified Binders Using Design of Experiments	295
Reza Azadedel, Nader Solatifar, and Maghsoud Rahbarnia	
Self-healing Asphalt for Road Pavements	307
A. Tabaković and E. Schlangen	
Recycling and By-products	
Experimental Investigation on the Effect of Rejuvenator on the Use of a High Amount of Recycled Asphalt Binder	321
Di Wang, Maximilian Koziel, Augusto Cannone Falchetto, Chiara Riccardi, Martin Hugener, Laurent Porot, Yun Su Kim, Goshtasp Cheraghian, and Michael P. Wistuba	
Rubber-Oil Distillation Bottoms Blends as a New Recycling Solution for Bitumen Extension	331
G. Tarsi, C. Sangiorgi, A. Varveri, and C. Oliviero Rossi	

Improving the Sustainability of Semi-Dense Asphalt Pavements by Replacement of Recycled Concrete Aggregate Fractions	343
Peter Mikhailenko, Muhammad Rafiq Kakar, Zhengyin Piao, Moises Bueno, and Lily Poulikakos	
Combined Effect of Warm Mix Processes and Multi-recycling on the Main Criteria of the French Asphalt Mix Design Method	353
P. Marsac, C. Petiteau, O. Burban, J. P. Terrier, G. Didelet, J. Demoncheaux, T. Lorino, and S. Pouget	
Mechanical Behaviour of Cold Recycled Asphalt Mixtures for Binder Courses Produced with Bitumen Emulsion and High Strength Cement	365
Chiara Mignini, Fabrizio Cardone, and Andrea Graziani	
Performance Evaluation of Hybrid EAF Slag and RAP in Pavement	375
Shih-Huang Chen, Hasnae Amal Smimine, Wei-Lun Tsai, Ching-Tsung Hung, Meng-Hsin Kuo, and Ching-Lien Zen	
Effect of Waste Fillers on the Rutting and Fatigue Behavior of Asphalt Mastic and Mixes	385
Jayvant Choudhary, Brind Kumar, and Ankit Gupta	
Evaluating the Properties of Bioasphalt Produced with Bio-oil Derived from Biodiesel Production	397
Caio Rubens Santos, Jorge C. Pais, Jorge Ribeiro, and Paulo Pereira	
Evaluating the Characteristics of Crumb Rubber Modified Asphalt Binders Produced with Neat Bitumen—Case of Kuwait	409
Taha Ahmed, Dawoud Bahzad, Abdullah Al-Marshed, Zein-Eddine Merouani, and Mohamed Omar	
Properties of Hot Mix Asphalt Containing Treated Recycled Concrete Aggregates Using SCB and ITS Tests	419
A. Kavussi, F. Kazemian, and M. Bayzidi	
Bituminous Mixtures with High Environmental Compatibility: Laboratory Investigation on the Use of Reclaimed Asphalt and Steel Slag Aggregates	433
C. Nodari, M. Crispino, and E. Toraldo	
Investigation of Selected Properties of Crumb Rubber Modified Bitumens with Different Rubber Contents	443
E. Manthos, J. Valentin, L. Benešová, D. Giannaka, P. Gravalas, and Ch. Tsakalidis	

Performance Assessment of Rubberized Mixtures Containing Reclaimed Asphalt and a Viscosity Reduction Additive	457
Leonardo Urbano, Davide Dalmazzo, Pier Paolo Riviera, and Ezio Santagata	
Evaluation of the Properties of Asphalt Concrete Modified with Crumb Rubber Using Marshall Test	469
Olumide M. Ogundipe, Omotola C. Aboloye, and Stephen O. Fatuase	
Advanced Pavement Materials and Technologies	
Influence of Source and Ageing on the Rheological Properties and Fatigue and Rutting Resistance of Bitumen Using a DSR	481
Mrinali Rochlani, Sabine Leischner, Gustavo Canon Falla, Puneet Goudar, and Frohmut Wellner	
Permanent Deformation Characterisation of Gap-Graded and Continuous Graded Aggregate Blends for Bituminous Mixtures	493
V. T. Thushara and J. Murali Krishnan	
Linear Viscoelastic Properties of a Half Warm Asphalt Mixture (HWM) with Bitumen Emulsion	507
Silvia Angelone, Marina C. Casaux, Luis Zorzutti, and Fernando Martinez	
Long Lasting Asphalt Materials with Highly Modified Asphaltic Binder	517
Laurent Porot, Erica Jellema, and David Bell	
Mechanical Properties of Bio-Asphalt on Recycled Asphalt Pavement Binder	529
Atmy Verani Rouly Sihombing, Bambang Sugeng Subagio, Eri Susanto Hariyadi, and Anwar Yamin	
The Effect of Fly Ash Based Geopolymer on the Strength of Problematic Subgrade Soil with High CaO Content	539
Nawfal Farooq Kwad, Ahmed H. Abdulkareem, and Taher M. Ahmed	
Low Temperature Behavior of Asphaltite Modified Binders and Asphalt Concretes	553
Andrea Themeli, Emmanuel Chailleux, Cyrille Chazallon, and Nicolas Bueche	
Repeatability Study on the Laboratory Production Process of Cement Bitumen Treated Materials with Foamed Bitumen	565
Simone Raschia, Amir Rahmanbeiki, Daniel Perraton, Alan Carter, Andrea Graziani, and Andrea Grilli	

Effect of Global Thresholding Algorithms on Pervious Concrete Pore Network Properties Using XRCT-Based Digital Image Processing	575
Ajayshankar Jagadeesh, Ghim Ping Ong, and Yu-Min Su	
Performance Characteristics of Nano-Modified Asphalt Mixtures	587
Lucia Tsantilis, Giuseppe Chiappinelli, Orazio Baglieri, Pier Paolo Riviera, Fabrizio Miglietta, and Ezio Santagata	
Properties of Styrene-Isoprene-Styrene (SIS) Modified Asphalt Binder	597
Mithil Mazumder, Soon-Jae Lee, and Moon-Sup Lee	
Effects of Binder Modification on Rutting Performance of Asphalt Binders	607
A. Seitllari, M. Ghazavi, and M. E. Kutay	
Viscoelastic Response of Bitumen Emulsion Mastic with Various Active Fillers	617
Ahmed Al-Mohammedawi and Konrad Mollenhauer	
Numerical Studies on Coir Geotextile Reinforced Flexible Pavement . . .	627
V. Anusudha, V. Sunitha, Chithu Babu, Chetan R. Bhole, and Samson Mathew	
Evaluation of Pavement Performance	
Relating Asphalt Mixture Performance to Asphalt Mastic Rheology . . .	639
Johannes Büchner and Michael P. Wistuba	
Shear Bonding Performance of Reinforced Asphalt Pavements by Using Polyester Grids	651
Fabiana Leite-Gembus and Andreas Elsing	
Discrete Element Simulations of 4-Point Bending Fatigue Tests of Asphalt Concrete Samples Reinforced by Fiberglass Grids	663
G. Liu, G. Koval, and C. Chazallon	
Non-destructive Pavement Testing for Sustainable Road Management	675
G. Kneib	
Precision Assessment of the Modified Wheel Tracking Device Based on Small-Scale Testing of New Zealand Hot Mix Asphalt	687
Abhirup Basu Roy-Chowdhury, Mofreh Saleh, and Miguel Moyers-Gonzalez	
Simulation of Heavy Weight Deflectometer Test: Spectral Element Method vs Finite Element Method	699
Jean-Marie Roussel, Hervé Di Benedetto, Cédric Sauzéat, and Michaël Broutin	

Three Dimensional Finite Element Model for Active Crack Control in Continuously Reinforced Concrete Pavement	709
Muhammad Kashif, Pieter De Winne, Ahsan Naseem, Nouman Iqbal, and Hans De Backer	
Inference of Pavement Properties with Roadside Accelerometers	719
Julius Nielsen, Eyal Levenberg, and Asmus Skar	
Behaviour of the Interface Bonding Between Asphalt Overlays and Rigid Pavements	729
K. Bayraktarova, M. Dimitrov, B. Hofko, and L. Eberhardsteiner	
Estimation of Resilient Modulus for Fine-Grained Soils Using Ground Penetrating Radar	741
Logan Tihey and S. Sonny Kim	
Impact of Construction Practices on Air Voids and Permeability of Asphalt Mixtures	751
Syed W. Haider, Michele Lanotte, Khurram Malik, and Aftab Quadri	
Application of Dynamic Creep Testing to Investigate Permanent Deformation Characteristics of Asphalt Mixes	761
Amir Kavussi and Seyed Mohsen Motevalizadeh	
A Performance Prediction Model for Continuously Reinforced Concrete Pavement Using Artificial Neural Network	771
Hakan Yasarer, Mohammad Najmush Sakib Oyan, and Yacoub Najjar	
Full Scale Studies Accelerated Pavement Testing	
Parameter Identification of Asphalt Pavements Subjected to Moving Loads	785
Zhaojie Sun, Cor Kasbergen, Karel N. van Dalen, Kumar Anupam, Athanasios Skarpas, and Sandra M. J. G. Erkens	
Effects of Field Compaction Method on Water Permeability and Performance of Asphalt Concrete Pavements	795
Chinecherem Agbo Igboke, Eslam Elsayed, Yasser Hassan, and Abd El Halim Omar Abd El Halim	
Cooling Time Requirements for Asphalt Pavement Repairs	805
L. Chu and T. F. Fwa	
Cold Recycling in Germany—Current Experiences and Future Projects	813
B. Wacker, M. Kalantari, and M. Diekmann	
Distributed Fiber Optic Strain Measurements in an Airfield Pavement	825
D. Hauswirth, F. Fischli, C. Rabaiotti, and A. M. Puzrin	

Pavement Distress from Channelized and Lateral Wandering Loads Using Accelerated Pavement Tests	835
Martin Arraigada and Manfred N. Partl	
Correlating Air Freezing Index and Frost Penetration Depth—A Case Study for Sweden	847
Sigurður Erlingsson and Denis Saliko	
Simulating Deflection of a Jointed Rigid Pavement Under Rolling Wheel Deflectometer (RAPTOR) Loading	859
Pawan Deep, Mathias B. Andersen, Søren Rasmussen, Alessandro Marradi, Nick H. Thom, and Davide L. Presti	
Study on the Asphalt Pavement Response in the Accelerated Pavement Testing Facility	871
Ruxin Jing, Aikaterini Varveri, Xueyan Liu, Athanasios Scarpas, and Sandra Erkens	
In-Situ Measurement of Discontinuity Movements in Concrete Pavement Structures	881
Dongkyu Kim, Hyunsik Hwang, Christopher Jabonero, and Yoon-Ho Cho	
Surface Characteristics and Road Safety	
Pavement Surface Evaluation Interacting Vibration Characteristics of an Electric Mobility Scooter	893
Kazuya Tomiyama and Kazushi Moriishi	
Acoustic Maintenance of Pavements by Large-Scale Grinding	901
Françoise Beltzung and Tobias Balmer	
Framework for Pothole Detection, Quantification, and Maintenance System (PDQMS) for Smart Cities	913
Naga Siva Pavani Peraka, Krishna Prapoorna Biligiri, and Satyanarayana N. Kalidindi	
Stochastic Prediction of Short-Term Friction Loss of Asphalt Pavements: A Traffic Dependent Approach	923
Christina Plati, Maria Pomoni, Andreas Loizos, and George Yannis	
Tire Contact Stress Distribution Considering the Tire Inclination in Bend	933
Y. Oubahdou, E. Manyo, P. Reynaud, B. Picoux, J. Dopeux, and C. Petit	
LCMS-2 Measurements of the Quality of Road Markings	943
Kars Drenth, Jun Yew Tan, Marc Drenth, and Ong Ju Kit	

**A Study on the Effect of Milling on Stress Distributions
in Asphalt Pavements 953**
Kaoutar Diouri, Rajae Bousselham, Anirban De, Adriana Hera,
Tahar El-Korchi, and Rajib B. Mallick

**Assessment of Preformed 3D-Thermoplastic Road Markings
for Long-Term Durability, Skid Resistance
and Texture Functionality 965**
Kalpesh Purohit, Mujib Rahman, Andrew Price, and Alan Woodside

**Multiple Linear Regression Models for Predicting Surface
Damage Due to Repeated Dynamic Loading on Submerged
Asphalt Pavement. 975**
Fauzia Saeed, Mujib Rahman, and Maher Mahmood

Ultrasound Monitoring and Microwave Self-healing of Top-Down Cracks in Asphalt Pavements



Miguel A. Franesqui, Jorge Yepes, and Juan Gallego

Abstract Surface-initiated cracking with top-down propagation (TDC) is one of the most frequent and important failure modes of asphalt pavements. In order to achieve long-lasting pavements, it is necessary to control the evolution of these cracks and so repair them before they become deeper and deteriorate the lower layers. Self-healing of asphalt mixtures is possible if the temperature is raised near the softening point of the binder, thus allowing the fusion of the cracks. For this purpose, conductive additions can be used to promote induction heating when applying electromagnetic fields. This laboratory work shows the self-healing results of TDC on bituminous mixtures after microwaves exposure. Different mixtures (semi-dense asphalt concrete AC-S, gap-graded asphalt concrete for very thin layers AC-VTL and porous asphalt PA) with diverse types, sizes and proportions of metallic additions from industrial waste were tested. Three aspects were studied: (a) analysis of the type, particle size and content of each addition on the heating speed; (b) temperature increase with the specific energy; (c) monitoring of the healing process by using ultrasounds. Microwave exposure allowed the total closure of cracks using an industrial waste, with reduced exposure times and applied energies. The results validate the microwave healing capacity, as well as the use of ultrasounds for tracking the crack depth.

Keywords Self-healing · Microwave · Metallic addition · Industrial waste · Crack depth · Ultrasound

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263

1 Introduction

Adequate monitoring and timely treatment of partial-depth top-down cracks (TDC) are essential to prolonging the life cycle of long-lasting pavement structures. This is one of the most frequent failure modes and cause of deterioration in asphalt pavements. Therefore, in order to achieve perpetual pavements, it is necessary to track the evolution of these cracks and so repair them before they become deeper and deteriorate the lower layers (Fransesqui et al. 2017).

Self-healing of bituminous mixtures is possible if the temperature is raised high enough to reduce the binder viscosity, allowing the fusion of the crack faces. A possible technique is the electromagnetic induction heating of mixtures with inductive additions that raise electric conductivity. Decisive factors to ensure the efficiency of this method are the type, size and proportion of the additions. Studying the electrical conductivity of PA mixtures with steel wool, some researchers concluded that short length fibres provide optimal performance in comparison to longer fibres (Liu et al. 2010, 2011).

Some laboratory studies determined that it is also possible to raise the temperature of AC mixtures with steel wool by using microwaves with brief exposure times (Gallego et al. 2013). Consequently, microwaves seem to be promising for the self-healing of cracks in asphalt pavements (Norambuena-Contreras and García 2016).

However, the main limitations of the previous studies have been:

- (a) Self-healing of dense asphalt concrete (AC) and porous asphalt (PA) have been studied, but up until now other common types such as asphalt concrete for very thin layers (AC-VTL)—also known in European Standards as BBTM “Béton bitumineux très mince”—have not been analysed. This is usually employed in wearing courses of only 2–3 cm thick.
- (b) Due to the formation of clusters during mixing, the steel wool fibres are difficult to homogenize in order to reach a uniform heating (Gallego et al. 2013) and thus, increasing the air void content (Yang et al. 2016).
- (c) The induction devices are difficult to use for field applications and require certain safety measures. Furthermore, the time required in order to heat the asphalt mixes by induction still remains excessive (García et al. 2015). Hence, microwave devices could be more manageable and risk free for this application.
- (d) The evolution of the crack depth after microwave radiation and how the macro-cracks heal has yet to be experimentally examined.

Consequently, this research focused on the evolution of the crack depth with the specific energy applied by microwave equipment. At the same time, this laboratory study sought after an optimal addition in reduced proportions from industrial waste (Norambuena-Contreras et al. 2018) that would allow significant energy saving and achieve a complete self-healing of TDC.

Table 1 Percentages of steel addition (by total weight of mixture)

Type of mixture (HMA)	Type of metallic addition						
	Ref	SW10	SW5	SF1-2	SF0.5-1	SPC0.063-0.5	SPC<0.063
AC 16 surf 50/70 S	0.0	0.6	0.4	1.0	2.0	–	5.37
BBTM 11B PMB 25/55-65	0.0	0.6	0.4	1.0	2.0	15.51	5.5
PA 11 PMB 25/55-65	0.0	0.6	0.4	1.0	2.0	9.63	4.5

(Ref) Reference mixture without additions; (SW10) Steel wool of length 10 mm; (SW5) Steel wool of 5 mm; (SF1-2) Steel filing of size 1–2 mm; (SF0.5-1) Steel filing 0.5–1 mm; (SPC0.063-0.5) Steel filing with corundum powder of size 0.063–0.5 mm; (SPC<0.063) Steel and corundum powder less than 0.063 mm [metallic filler]

2 Materials

Cylindrical and slab specimens of the three different types of hot mix asphalt (HMA) were compacted in the laboratory: AC 16 surf 50/70 S (semi-dense) with 4.5% (by wt. of mixture) of conventional penetration bitumen (50/70 indicates the penetration grade in 10^{-1} mm); BBTM 11B PMB 25/55-65 with a bitumen content of 5%; and PA 11 PMB 25/55-65 with 4.5% of the same type of polymer-modified bitumen (25/55 indicates the penetration grade in 10^{-1} mm, and 65 is the softening point in °C). All the aggregate fractions came from massive phonolite of high density (a type of volcanic rock) with a bulk density of 2.62 g/cm³.

Six types of steel additions were used to speed up the microwave heating. These varied in size, composition and proportion (Table 1). The additions were prepared from low-carbon steel profiles and sheets, all cut manually by the same operator: (a) steel wool fibre (5 and 10 mm long, 0.3–0.4 mm diameter approximately); (b) steel filing (1–2 mm and 0.5–1 mm) obtained from metal profiles cut with a metal lathe machine; (c) steel filing (90%) with corundum powder (10%, approximately) obtained from radial saw grindings (0.063–0.5 mm and #<0.063 mm). The steel filing with corundum powder was used to substitute either the finest aggregate or the mineral filler (#<0.063 mm), in this last case acting as a metallic filler. Thus, the mix design depended on the aggregate gradation of each type of mixture (Fig. 1) and the corresponding fractions. The mixtures were produced following the Spanish road specifications [PG-3] (Spanish Ministry of Infrastructures 2014).

3 Methodology

The cylindrical specimens (D = 101.6 mm; h = 63.5 mm) were compacted using a Marshall hammer according to EN 12697-30 with 50 blows/side. The prismatic specimens were obtained from slab specimens (300 × 300 × 60 mm), compacted by

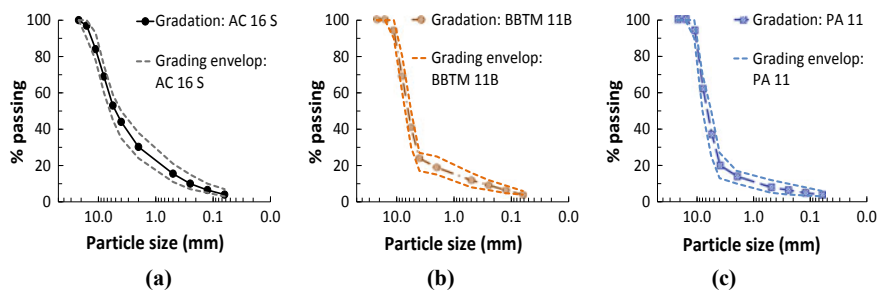


Fig. 1 Aggregate gradation and specified grading envelope for the three types of mixtures: **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

rolling according to EN 12697-33. The cylindrical specimens underwent basic characterization tests: maximum specific gravity (EN 12697-5; volumetric procedure), bulk specific gravity using the hydrostatic method (EN 12697-6; SSD procedure), air voids (EN 12697-8), moisture sensitivity (EN 12697-12) and particle loss (EN 12697-17).

Once characterized, each cylindrical specimen was cut into two halves in order to measure the temperatures inside of each compacted specimen after microwave exposure. The slab specimens were divided into three prismatic samples. A total of 110 test samples were obtained: 92 from cylindrical specimens and 18 from slab specimens.

The different test samples were initially conditioned in a heater-refrigerator at 15 °C (± 0.1 °C) during 4 h, thus making this the starting temperature (T_0) from which the microwave exposure began. Exposure in the microwave oven (at 800 W and 2.45 GHz) lasted long enough to surmount the softening point of each binder (52 °C for 50/70 pen bitumen) and 67 °C for PMB 25/55-65). Using an infrared thermometer (resolution ± 0.1 °C; precision ± 1.5 °C) several measurements were carried out at 10 or 20 s intervals; these measurements were made at three points on the cut surface of each halved cylindrical specimen.

By cutting the slab specimens (300 × 300 × 60 mm), different prismatic beam samples were obtained to measure the evolution of the crack depth after microwave exposure (300 × 110 × 60 mm and 300 × 80 × 60 mm). With this partition of the slab specimens, a height safeguard of 50% at least was achieved for the deeper cracks studied in the laboratory in order to ensure that the notches and cracks will not fracture the samples.

The prismatic beams underwent cracking by means of three-point bending test at a low temperature (−20 °C) and deformation rate (0.5 mm/min). A notch was previously made in the centre of each beam using a radial saw in order to ensure the initiation of cracking at this point. The minimum notch depth was 20 ± 1 mm for the AC-S and 10 ± 1 mm for the BBTM and PA mixtures (according to the maximum size of each aggregate), and with a 4–5 mm slot between notch faces (Fig. 3b). The net initial crack depths (subtracting the notch depth) ranged between 11 ± 1 mm and 40 ± 5 mm.

Measurements of the initial crack depth as well as measurements of the same crack at different intervals of microwave exposure were carried out using the non-destructive method postulated by Franesqui et al. (2017), where the analytical models are founded upon a self-calibration technique based on ultrasound measurements on a single surface. This method allows the immediate determination of the depth of surface-initiated cracks in asphalt mixtures, is economically feasible and provides errors below 13% (at 95% statistical confidence level), even with micro-cracks unobservable to the naked eye. The ultrasound device was utilized with cylindrical CPC (couplant plate contact) piezoelectric transducers (26 mm diameter, 54 kHz).

In order to use the proposed models of this methodology, the mathematical functions should be previously calibrated on each specific material and with the ultrasonic equipment to be employed (see Franesqui et al. 2017). For this calibration, ultrasound propagation time measurements were carried out on the cracked surface of the beam samples at 20 °C. Figure 2 shows the functions of the calibrated models for the three types of HMA, at T = 20 °C with measurement baseline (B = linear distance between transducers) 70, 120 and 150 mm.

Before exposure, all the prismatic samples were placed in an oven for acclimatization (4 h at 20 °C). From this temperature the samples were radiated until the crack healed (total maximum exposure time of 110–210 s). The process was carried out during several cycles of microwave exposure between 20–40 s each. The ultrasound measurement of the crack depth after each gradual microwave exposure interval has allowed the assessment of the depth evolution with the exposure time and therefore, the effectiveness of the self-healing technique (Fig. 3).

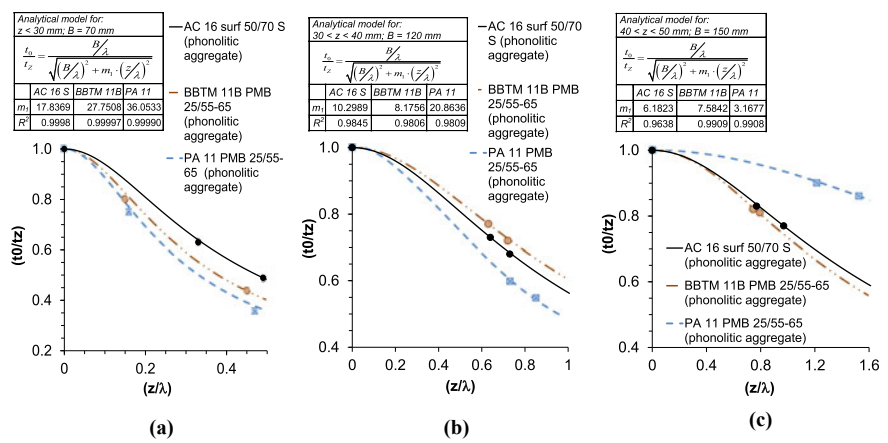


Fig. 2 Calibrated functions used to predict crack depth using ultrasounds at 20 °C: **a** For cracks up to 30 mm depth ($B = 70$ mm); **b** For cracks from 30 to 40 mm ($B = 120$ mm); **c** For cracks from 40 to 50 mm ($B = 150$ mm). $[(t_0/t_z)$ transmission time ratio on the non-cracked HMA surface ($z = 0$) and on the same specimen with crack depth (z); (λ) Ultrasound wavelength; (B) distance between transducers]

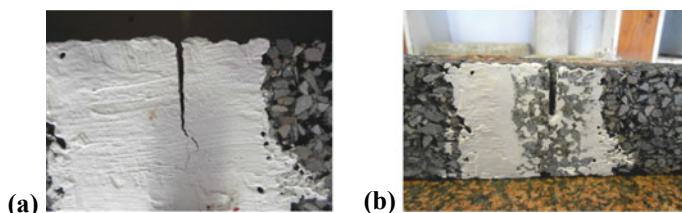


Fig. 3 Prismatic sample of BBTM 11B PMB 25/55-65 with metallic filler (SPC<0.063 mm) and height 80 mm: **a** Net initial crack depth of 19 ± 1 mm, excluding the notch; **b** Detail of the same crack, completely closed in its entire depth, after an exposure time to microwaves of 110 s (starting temperature 20 °C)

4 Results and Discussion

4.1 Engineering Properties of the Mixtures

The mixtures with steel additions complied with the specifications for roads ($4 \leq V_m \leq 6\%$, for AC-S; $V_m \geq 12\%$, for BBTM; $V_m \geq 20\%$, for PA; $ITSR \geq 85\%$, for AC-S; $ITSR \geq 90\%$, for BBTM; $PL \leq 20$ -25%, for PA). However, the AC-S mixtures with steel wool fibres caused some problems during compaction which led to an increase in air voids (see Table 2).

4.2 Effect of Different Steel Additions on the Heating Speed

In order to determine the most efficient addition for each HMA, the average temperatures were calculated for each microwave exposure time. These points were fitted by linear regression functions, which allowed the assessment of the performance differences among the different metallic additions (Fig. 4). The coefficient of determination (R^2) of the fitting varied between 0.953–0.992 for AC-S; 0.958–0.997 for BBTM; and 0.907–0.998 for PA mixtures.

After examining the results, the following observations are presented:

- The filler used to substitute the mineral powder (SPC<0.063 mm) offered good results with AC-S and BBTM mixtures: exposure time reduction by 18.6% in the AC-S (with 5.4% addition) and 7.6% in the BBTM (with 5.5% addition). Nevertheless, the performance was irregular in the case of porous mixtures (PA) [4.5% of addition], being less efficient than the control specimens. On the contrary, the PA mixtures showed a good performance with the short steel wool fibres (5 mm) [0.4% of fibres], which produced a 5.6% of time reduction (González et al. 2019).
- The addition of short steel wool fibres (5 mm) [at 0.4%] proved to be more efficient than the 10 mm fibres [at 0.6%].

Table 2 Characterization properties of the mixtures (EN 12697 Standards)

Type of mixture (HMA)	Property	Type of metallic addition						
		Ref	SW10	SW5	SF1-2	SF0.5-1	SPC 0.063-0.5	SPC<0.063
AC 16 surf 50/70 S	$D_{b,SSD}$ (g/cm ³)	2.39	2.16	2.18	2.28	2.13		2.40
	V_m (%)	4.57	13.05	10.78	5.75	6.46		5.75
	ITSR (%)							85.37
BBTM 11B PMB 25/55-65	$D_{b,SSD}$ (g/cm ³)	2.19	2.14	2.07	2.20	2.13	2.19	2.06
	V_m (%)	11.99	15.58	18.59	13.26	16.36	13.69	18.63
	ITSR (%)							92.36
PA 11 PMB 25/55-65	$D_{b,SSD}$ (g/cm ³)	1.94	1.72	1.99	1.94	1.96	1.90	1.94
	V_m (%)	24.15	32.75	22.20	24.37	23.59	25.63	24.32
	PL (%)							22.0

(Ref) Reference mixture without additions; (SW10) Steel wool of length 10 mm; (SW5) Steel wool of 5 mm; (SF1-2) Steel filing of size 1–2 mm; (SF0.5-1) Steel filing 0.5–1 mm; (SPC0.063-0.5) Steel filing with corundum powder of size 0.063–0.5 mm; (SPC<0.063) Steel and corundum powder less than 0.063 mm (metallic filler); ($D_{b,SSD}$) Bulk density [saturated surface dry]; (V_m) Air void content in the mixture; (ITSR) Indirect tensile strength ratio; (PL) Particle loss

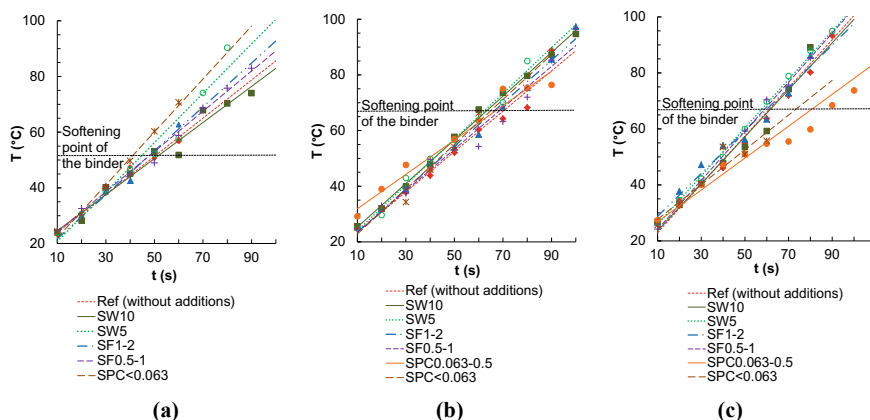


Fig. 4 Comparison of the effect of the type and size of the metallic addition on the heating speed: **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

- The intermediate size additions (steel filings $0.5 < \# < 2$ mm) offer an intermediate thermal efficiency between steel wool fibres and the finest filings, which is due to the fact that they were also used with intermediate proportions.

To summarize, the optimal addition for AC-S and BBTM, considering both practical applications (easier mix formulation and mixing) and thermal efficiency, is the metallic filler (SPC < 0.063 mm) because distribution is far more homogeneous and avoids clump formation as occurs in the case of steel wool fibres, making compaction difficult. The addition of metallic filler implies significant benefits: simple production and dosage control of the mixtures; excellent homogenization and compaction with the habitual production formula used for each mixture type with similar final properties; it offers greater energy efficiency to microwaves as the smaller particles facilitate heat generated by Joule effect; furthermore, the powdery particles prevent the accumulation of charges that ionize the air, avoiding electric arcs when microwaves are applied; and finally, this filler yields environmental advantages by using up waste metal produced in the industry.

However, the best addition for PA mixtures is 5 mm steel fibres. This is because the fibres increase electric connectivity between aggregates, which counters the isolation effect produced by the high levels of porosity of PA.

4.3 Effect of Microwave Energy on Temperature

With the aim of comparing the results obtained from the different specimens (cylindrical and prismatic), the temperature was indicated as a function of the energy supplied per unit of mass (specific energy, E/m). The fitted functions were estimated by linear regression with the experimental values (Fig. 5) and can therefore be applied regardless of the mass of the mixture and the power output of the microwave device.

The analysis of these models show that the rate of temperature increase vs. the specific energy may be considered roughly constant in each HMA (Fig. 5), being $0.9\text{ }^{\circ}\text{C}/(\text{J/g})$ for AC-S mixtures; $1.1\text{ }(^{\circ}\text{C g})/\text{J}$ for BBTM; and $1.2\text{ }(^{\circ}\text{C g})/\text{J}$ for PA. The model obtained with BBTM offers better fit ($R^2 = 0.96$) compared to the other materials ($R^2 = 0.74$ for AC-S; $R^2 = 0.88$ for PA 11).

4.4 Monitoring of the Crack Depth

The last phase of the study made it possible to systematically study the reduction in depth of the cracks generated in the laboratory on the prismatic samples after microwave exposure. This enabled verification of the practical effectiveness of the

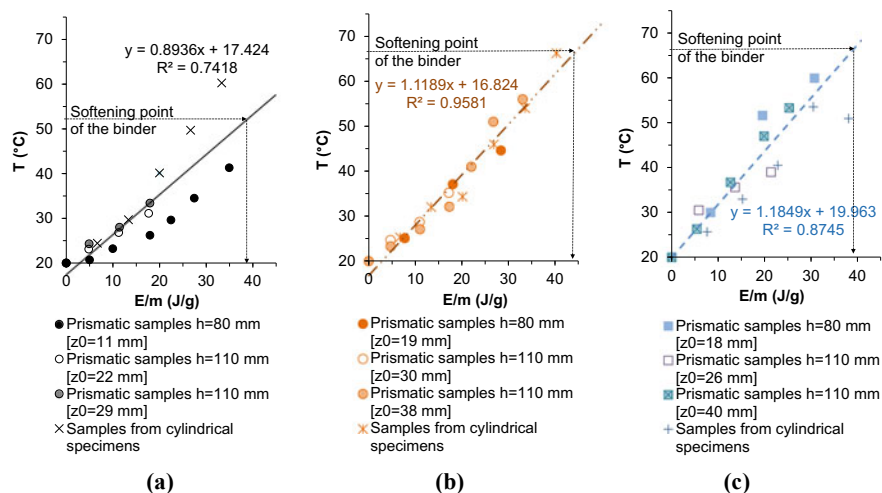


Fig. 5 Temperatures vs. specific energy supplied by microwaves on each type of HMA with steel filler ($\text{SPC} < 0.063$ mm): **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

method and the chosen addition. In order to monitor the cracks, the previously mentioned ultrasound technique was employed. The crack depth (z) following each interval of microwave treatment was expressed according to the specific energy (E/m) supplied.

The ultrasound results show a reduction of the crack depth with the applied specific energy. This proves that the healing begins at the crack tip, where the opening is smaller, and spreads towards the surface until self-healing completion. As the experimental points demonstrate in Fig. 6, effective and complete closure was verified throughout the macro-cracks previously produced in the laboratory, including

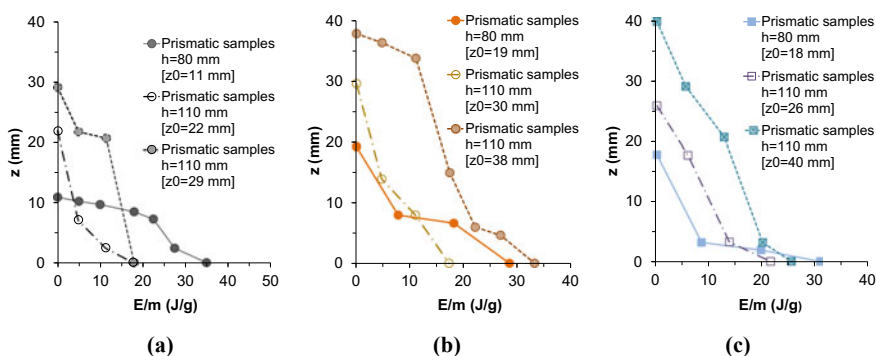


Fig. 6 Evolution of the crack depth with the microwaves specific energy on prismatic beams with steel filler ($\text{SPC} < 0.063$ mm) from an initial temperature of 20°C and different initial crack depths (z_0): **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

the deepest cracks (40 mm). In no event was the initial notch closed, confirming that this methodology is ineffective with wide cracks ($>4\text{--}5$ mm), with crack faces excessively polished and with severed aggregates. This suggests that the pavement maintenance must be periodical in order to avoid excessive deterioration.

In the laboratory, cracks up to 40 mm deep were completely self-healed after a brief microwave exposure (between 110 and 210 s), starting off at a room temperature of 20°C . These times are equivalent to a specific energy between 17.2 and 35.0 J/g (depending on the type of HMA and crack depth). This fact demonstrates the effectiveness of microwaves for self-healing of surface-initiated macro-cracks with both types of mixtures with metallic filler. Furthermore, the crack depth measurement method by ultrasounds proved to be efficient, reasonably precise, cost effective and manageable.

5 Conclusions

Based on the results of this experimental research, the following conclusions can be drawn:

- Microwaves have proved to be an efficient way of controlled, quick heating for the three types of asphalt mixtures with metallic additions and requiring simple, safe, compact, affordable and low power equipment.
- The smaller particles (steel filings $\#<0.063$ mm) proved to be the optimal addition for AC-S and BBTM, taking into account practical use and thermal efficiency (heating speed with lower energy consumption). Furthermore, mixing and proportioning control proves easier and the mixture is more homogeneous and compactable. Standard formulations may be used, final characteristics of the mixtures are similar, heating energy efficiency is improved and electric arcs are avoided.
- On the contrary, the PA mixtures have shown better performance with short steel fibres (5 mm) because the fibres increase electric connectivity between aggregates in these high-porosity mixtures.
- The temperature increase rate with regard to the specific energy is approximately linear and proved to be approximately 1.0°C g/J .
- In the laboratory complete self-healing of surface-initiated cracks of up to 40 mm in prismatic specimens with metallic filler was achieved. The energy per unit of mass required is low (between 17 and 35 J/g, depending on the HMA type and starting at room temperature of 20°C), and consequently a short exposure time is necessary (between 110 and 210 s with the laboratory prismatic specimens).
- The experimental results proved that healing starts at the crack tip and spreads towards the pavement surface till healing completion, providing the cracks are not excessively wide ($<4\text{--}5$ mm), and that the sides are not too polished nor the aggregates severed. This suggests that pavement maintenance must be periodical in order to avoid excessive deterioration.

- The use of ultrasounds for depth measurement of top-down cracks has proved to be efficient, relatively precise, cost effective and manageable.
- The proposed self-sealing technique allows not only longer service life of the pavement but also reduces rehabilitation costs. Furthermore, there are numerous environmental advantages: recovery and reuse of metal waste from industry; and prevention of new waste from milling of cracked surface layers. The time saving aspect of these procedures is noteworthy when compared to the standard pavement rehabilitation methods, allowing quick re-opening of traffic and reduced energy consumption and emissions.

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