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Christiane Raab *Editor*

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

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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

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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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 (Franesqui 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 macrocracks 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/cm^3.

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

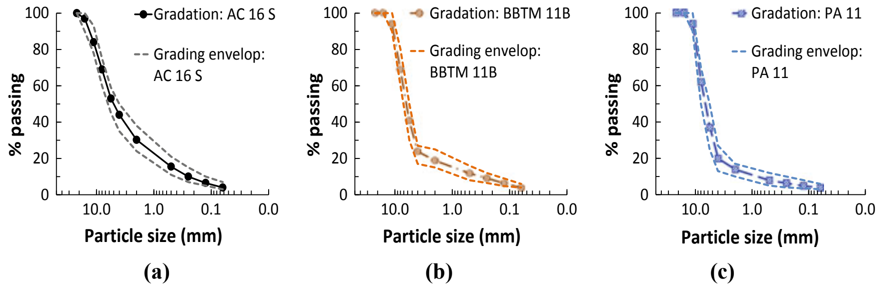

Fig. 1 Aggregate gradation and specified grading envelope for the three types of mixtures: **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

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).

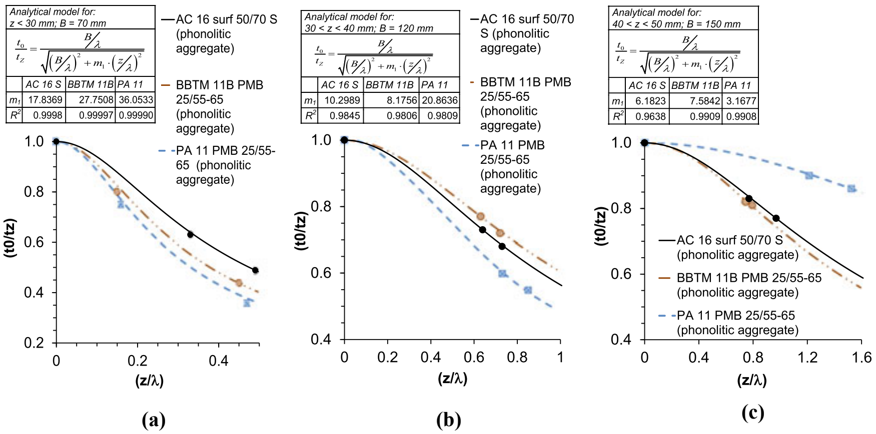

Fig. 2 Calibrated functions used to predict crack depth using ultrasounds at 20 °C: **a** For cracks up to 30 mm depth (B = 70 mm); **b** For cracks from 30 to 40 mm (B = 120 mm); **c** For cracks from 40 to 50 mm (B = 150 mm). [(t0/tz) transmission time ratio on the non-cracked HMA surface (z = 0) and on the same specimen with crack depth (z); (λ) Ultrasound wavelength; (B) distance between transducers]

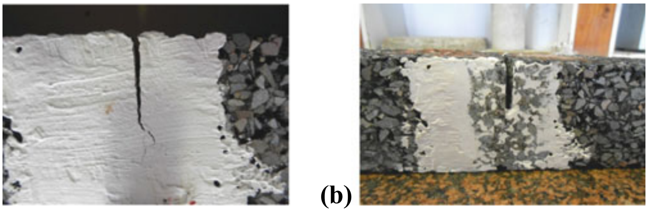

Fig. 3 Prismatic sample of BBTM 11B PMB 25/55-65 with metallic filler (SPC<0.063 mm) and height 80 mm: **a** Net initial crack depth of 19 ± 1 mm, excluding the notch; **b** Detail of the same crack, completely closed in its entire depth, after an exposure time to microwaves of 110 s (starting temperature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

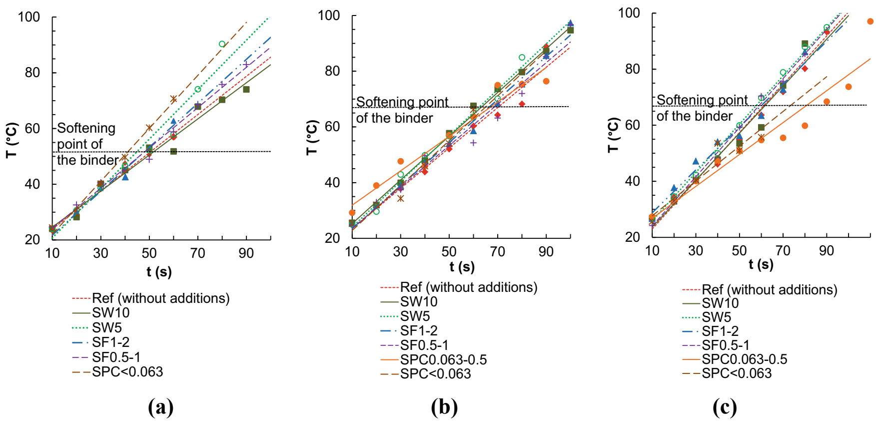

Fig. 4 Comparison of the effect of the type and size of the metallic addition on the heating speed: **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

- 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 °C/(J/g) for AC-S mixtures; 1.1 (°C g)/J for BBTM; and 1.2 (°C g)/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

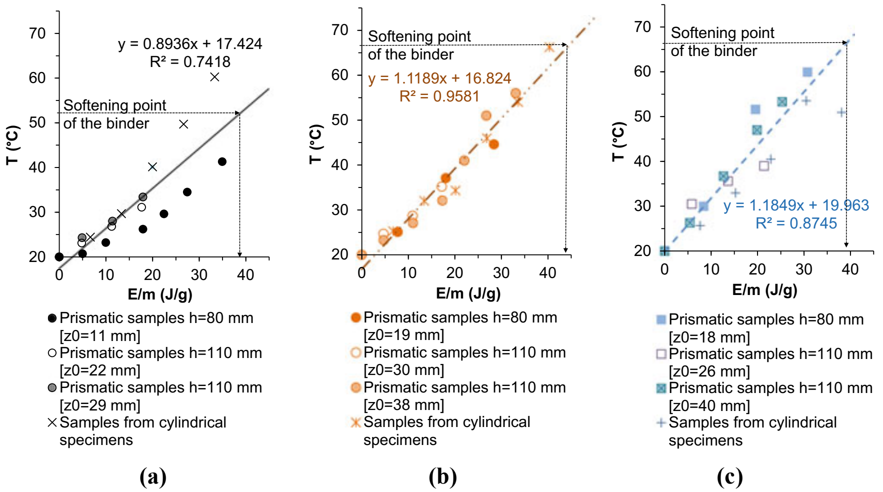

Fig. 5 Temperatures vs. specific energy supplied by microwaves on each type of HMA with steel filler (SPC<0.063 mm): **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

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

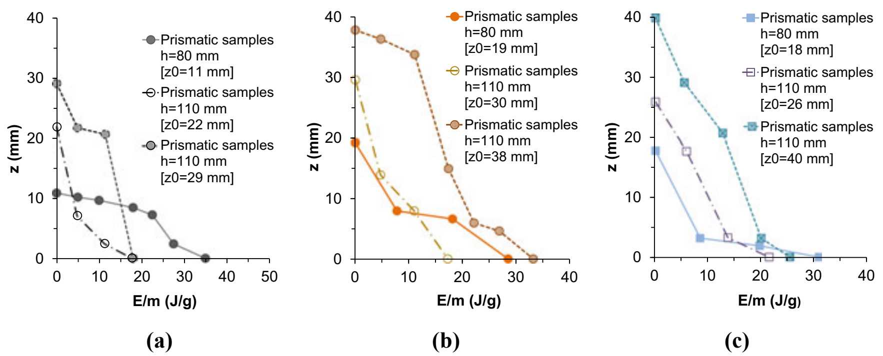

Fig. 6 Evolution of the crack depth with the microwaves specific energy on prismatic beams with steel filler (SPC<0.063 mm) from an initial temperature of 20 °C and different initial crack depths (z_0): **a** AC 16 surf 50/70 S; **b** BBTM 11B PMB 25/55-65; **c** PA 11 PMB 25/55-65

the deepest cracks (40 mm). In no event was the initial notch closed, confirming that this methodology is ineffective with wide cracks (>4–5 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 (<4–5 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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