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- Design, Manufacturing, Specification, Management, Construction, Evaluation, Rehabilitation
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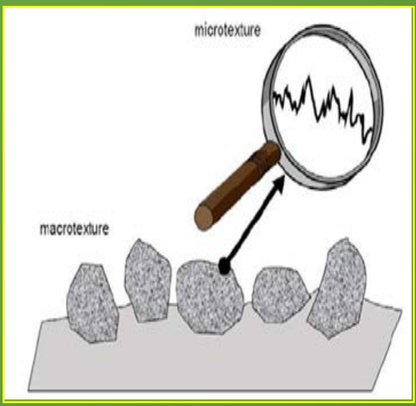

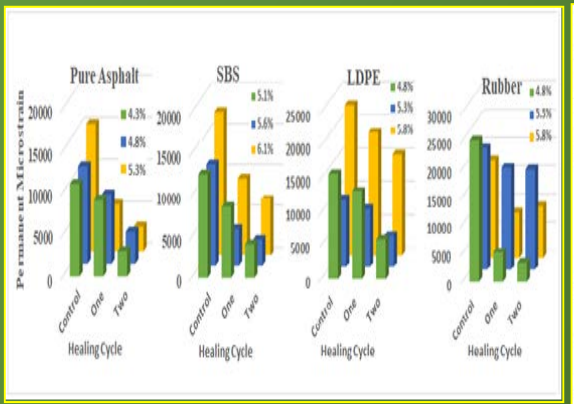

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MONITORING AND SELF-HEALING OF SURFACE-INITIATED CRACKS IN GAP-GRADED ASPHALT PAVEMENTS

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ABSTRACT

Top-down cracking (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 which are less accessible and cost more to repair. 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 were used to promote induction heating when applying microwaves. This research shows the self-healing results of TDC on gap-graded asphalt concrete for very thin layers (AC-VTL) and open-graded porous asphalt (PA) after microwaves exposure. These mixtures were tested with diverse types, sizes and proportions of metallic additions (steel wool, steel filing and metallic powder, all of them from industrial waste). Three types of studies were performed: 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 a waste product, with reduced times and applied energies compared to the reference mixtures without additions. Results validate the use of ultrasounds for monitoring the crack depth.

Keywords: Top-down cracking (TDC), Self-healing, Metallic filler, Microwave, Crack depth, Non-destructive testing (NDT), Ultrasound, Pavement maintenance

INTRODUCTION

Gap-graded asphalt concrete for very thin layers (AC-VTL) is commonly used for high-volume and high-speed wearing courses of pavements. It offers enhanced surface characteristics even with thin thicknesses (2-3 cm). Similarly, the use of open-graded porous asphalt (PA) for permeable friction courses allows vehicles to operate at high speed on wet pavements. Both types of asphalt mixtures offer safer driving and less rolling noise than traditional dense asphalt concrete (AC). However, they have a more heterogeneous internal structure and higher void content (usually more than 12% for AC-VTL and 20% for PA), which makes them more susceptible to cracking.

Adequate monitoring and timely treatment of surface-initiated cracks with top-down propagation (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 long-lasting 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., 2011).

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 and 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 AC-VTL (also known in European Standards as BBTM [“Béton bitumineux très mince”]) have not been analysed.

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, our study sought after an optimal addition in reduced proportions from industrial waste that would allow significant energy saving and achieve a complete self-healing of TDC.

MATERIALS

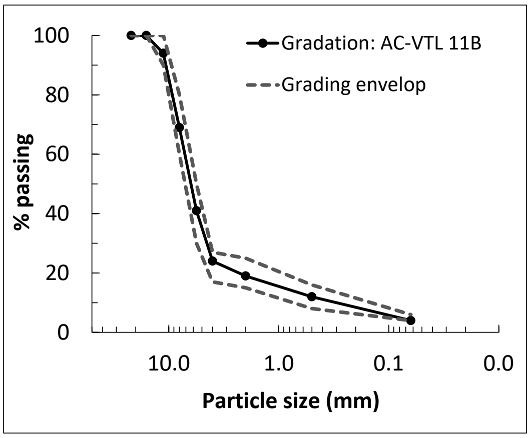
Cylindrical and slab specimens of both types of hot mix asphalt (HMA) were compacted at the laboratory: AC-VTL 11B PMB 25/55-65 with a bitumen content of 5% (by total weight of mixture) and PA 11 PMB 25/55-65 with 4.5% of the same type of polymer-modified bitumen. All the aggregate fractions came from massive phonolite (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 proportions (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. Both mixtures were produced following the Spanish road specifications [PG-3] (Spanish Ministry of Infrastructures, 2014).

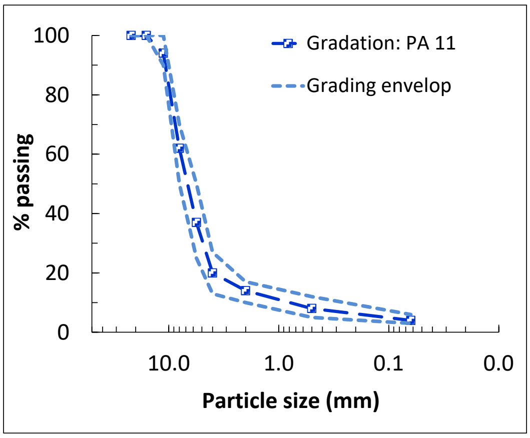
. Percentages of steel addition (by total weight of mixture).

Type of mixture (HMA)	Type of metallic addition						
	Ref	**SW10**	**SW5**	**SF1/2**	**SF0.5/1**	**SPC0.063/0.5**	**SPC<0.063**
AC-VTL 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]



a)



b)

Aggregate gradation and specified grading envelope for both gap-graded mixtures: a) AC-VTL 11B PMB 25/55-65; b) PA 11 PMB 25/55-65.

METHOD

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 (300x300x60 mm), compacted by 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).

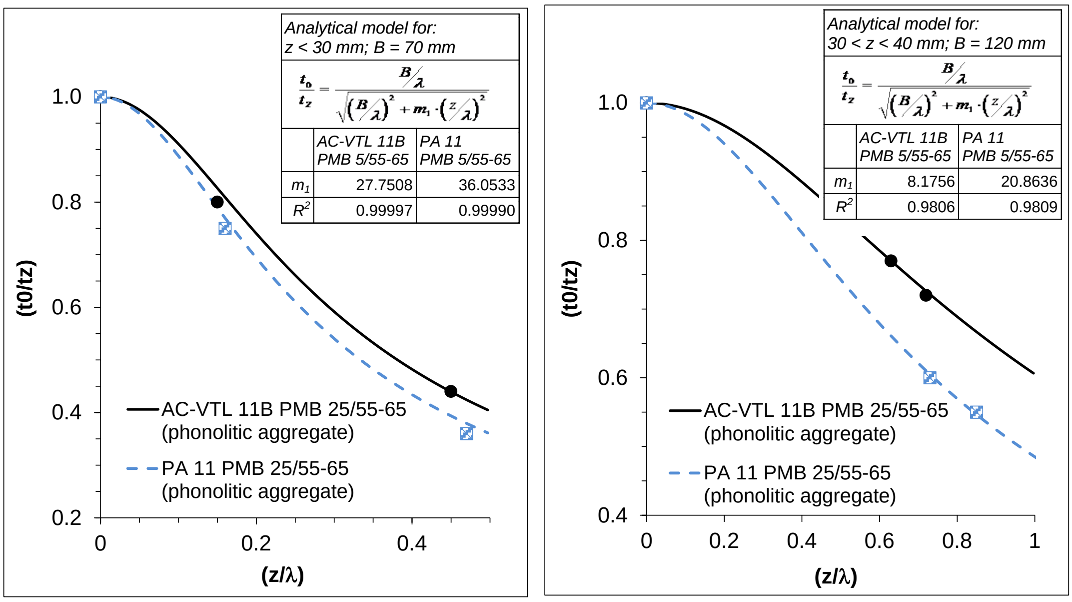
Once characterized, each cylindrical specimen was cut into two halves in order to measure the temperatures inside of each compacted specimen after microwave exposure. The slab specimens were divided into three prismatic samples. A total of 70 test samples were obtained: 58 from cylindrical specimens and 12 from slab specimens.

The different test samples were previously conditioned in a heater-refrigerator at 15 ºC (±0.1 °C) during 4 hours, 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 the binder (67 ºC). 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 (300x300x60 mm), different prismatic beam samples were obtained to measure the evolution of the crack depth after microwave exposure (300x110x60 mm and 300x80x60 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 ºC) 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 10±1 mm (according to the maximum size of aggregate), and with a 4-5 mm slot between notch faces. The net initial crack depths (subtracting the notch depth) ranged between 18±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. (2011 and 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).



a) b)

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). [(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].

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 ºC. Figure 2 shows the functions of the calibrated models for both HMA, at T = 20 °C with measurement baseline (B = linear distance between transducers) 70 and 120 mm.

Before exposure, all the prismatic samples were placed in an oven for acclimatization (4 hours at 20 ºC). 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).

a) b)

Prismatic sample of AC-VTL 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) Aspect of the same crack, completely closed in its entire depth, after an exposure time to microwaves of 110 s (starting temperature 20 ºC).

RESULTS AND DISCUSSION

Engineering properties of the mixtures

The mixtures with steel additions complied with the specifications for roads ($V_m \geq 12\%$ for AC-VTL; $V_m \geq 20\%$ for PA; ITSR ≥ 90% for AC-VTL; PL ≤ 20-25% for PA; see 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-VTL PMB 25/55-65	$D_{max,V}$ (g/cm^3)	2.54	2.54	2.54	2.54	2.54	2.54	2.54
	$D_{b,SSD}$ (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
	ITSd (MPa)							0.884
	ITSw (MPa)							0.817
	ITSR (%)							92.36
PA 11 PMB 25/55-65	$D_{max,V}$ (g/cm^3)	2.56	2.56	2.56	2.56	2.56	2.56	2.56
	$D_{b,SSD}$ (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

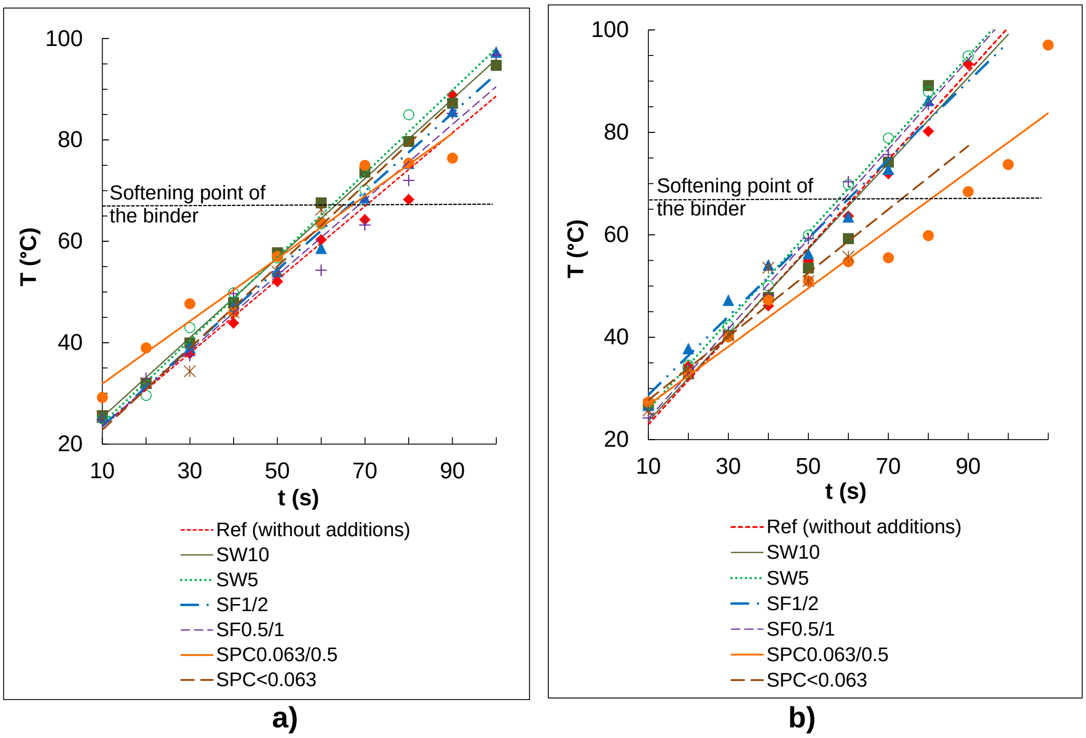
(Ref) Reference mixture without additions; (SW10) Steel wool of length 10 mm; (SW5) Steel wool of 5 mm; (SF1/2) Steel filing of size 1-2 mm; (SF0.5/1) Steel filing 0.5-1 mm; (SPC0.063/0.5) Steel filing with corundum powder of size 0.063-0.5 mm; (SPC<0.063) Steel and corundum powder less than 0.063 mm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

Effect of the steel addition 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 (R2) of the fitting varied between 0.958 and 0.997, for AC-VTL 11B; and 0.907-0.998 for PA 11.

After examining the results, the following observations are presented:

- The filler used to substitute the mineral powder (SPC<0.063mm) offered good results with AC-VTL 11B mixtures (5.5% of this addition), taking into account that the content is between half and a third part of the SPC0.063/0.5 addition. The metallic filler reduced exposure time by 7.6% in AC-VTL 11B mixtures. Nevertheless, the performance was irregular in the case of porous mixtures (PA 11) [4.5% of addition], being less efficient than the control specimens. On the contrary, the PA 11 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.
- 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%].
- 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.



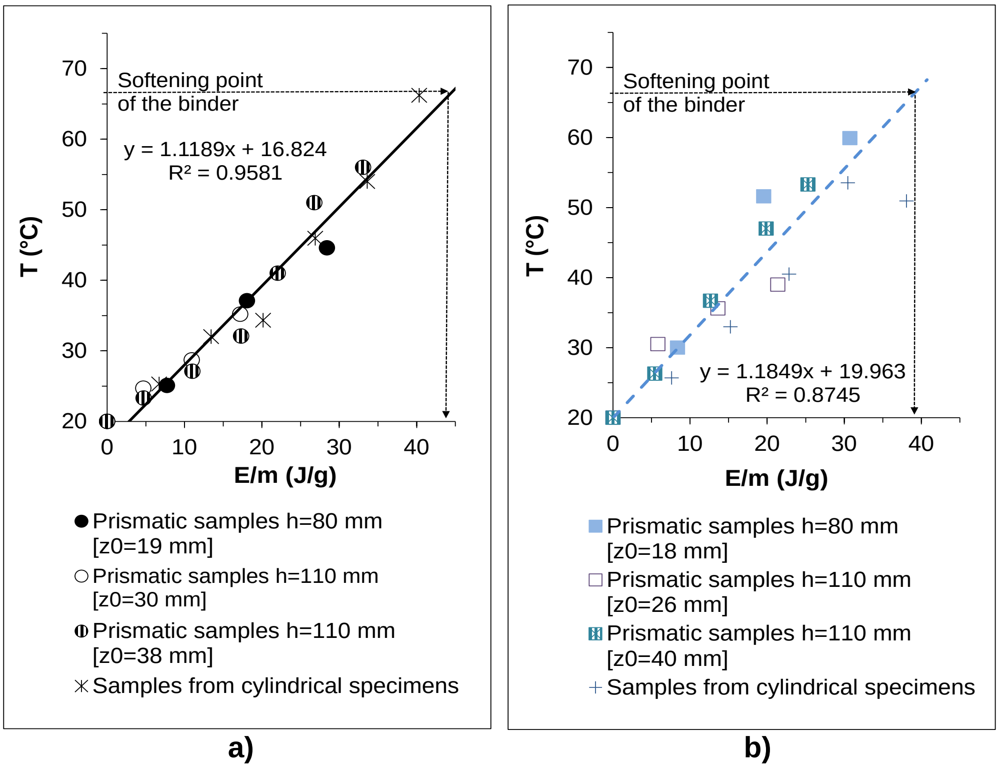
Comparison of the effect of the type and size of the metallic addition on the heating speed: a) AC-VTL 11B PMB 25/55-65; b) PA 11 PMB 25/55-65.

To summarize, the optimal addition for AC-VTL 11B, considering both practical applications 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 11 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 mixtures.

Effect of the microwave energy on the 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 1.1 (ºC·g)/J for AC-VTL 11B; and 1.2 (ºC·g)/J for PA 11. The model obtained with AC-VTL 11B offers better fit (R2=0.96) compared to the other material (R2=0.88 for PA 11).



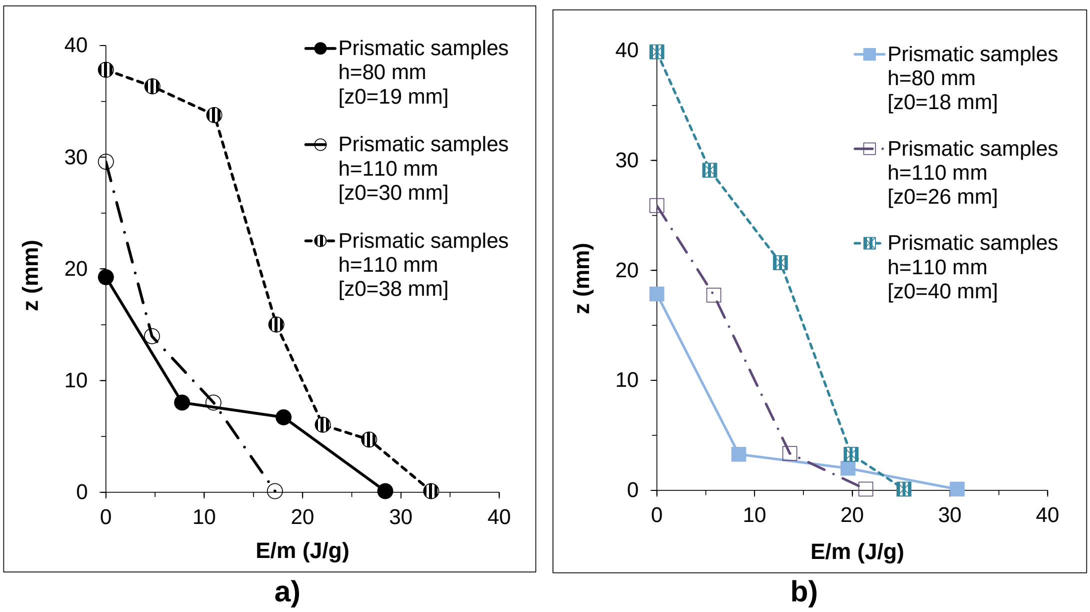
Temperatures vs. specific energy supplied by microwaves on both types of HMA with steel filler (SPC<0.063 mm): a) AC-VTL 11B PMB 25/55-65; b) PA 11 PMB 25/55-65.

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 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 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 seconds), starting off at a room temperature of 20 °C. These times are equivalent to a specific energy between 17.2 and 33.1 Joules/gram (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.



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 ºC and different initial crack depths (z_0): a) AC-VTL 11B PMB 25/55-65; b) PA 11 PMB 25/55-65.

CONCLUSIONS

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

- The use of microwaves has proved to be an efficient way of controlled, quick heating for both types of gap-graded 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-VTL, 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.
- However, 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 1.1-1.2 (ºC·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 33 J/g, 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 the 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 (a life-cycle assessment would determine the benefits of using this waste material); 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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