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A method for Bottom-up cracks healing via selective and deep microwave heating

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Abstract

The expected life of an asphalt road pavement depends on many factors (fatigue cracking, thermal cracking, etc). Bottom-up cracking is a common mode of hot mix asphalt pavement distress and appears to be critical. In view of this, the objectives of the study presented in this paper were confined into setting up an innovative and non-destructive method to carry out the rehabilitation of the pavement structure. In particular, a new procedure for healing in-depth damaged asphalt pavements is proposed and discussed. This method, based on selective heating, uses appropriate doping and electromagnetic fields in the microwave frequency range in order to induce the self-healing process of the material. Compared to the existing procedures, it allows a deep, selective, adaptive, and not invasive healing. The procedure, numerically validated by multi-physical simulations, can be applied to all solid structures made up of materials wherein the self-healing process can be induced by heating

Keywords: bottom-up cracking, doping, horn antenna, microwave heating, self-healing, conductive materials, present value, pavement rehabilitation.

1. Introduction

In the framework of road infrastructure maintenance, the main goal is the reduction of the occurrence of damages that are for instance cracks and deformations, as well as their repair [1]. Notably, the implementation of targeted and immediate maintenance interventions allows significant savings in terms of management and maintenance costs and times and considerably increases the useful life of the monitored road structure. The detection of surface damages is easier than the one of deep cracks. However, the fatigue cracking generally initiates at the bottom of the hot mix asphalt layer due to repeated and excessive tensile stresses, and gradually propagates up to the surface. Consequently, repairing these latter before they propagate would imply positive outcomes in terms of expected life, agency costs, user costs, and environmental costs.

In this scenario, different methods have been proposed in literature for damages repair. Most of the approaches can be classified into

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two main categories. The first class includes non-thermal methods [1], which aim at repairing cracks by introducing inside the road structure additional rejuvenating materials. Among them, for example nanoparticles, such as nano-clay materials or polymer and rubbers modifiers, can be introduced in the asphalt [2]-[4]. Another possibility is the introduction of micro capsules containing cationic emulsion into the structure [5]-[8]. The use of additive materials induces the healing of asphalt and allows repairing both deep and surface damages in the road structure. However, its use is invasive, as the mechanical and physical properties of the road pavement are modified. Moreover, their insertion in the structure can be based on destructive techniques, which imply, therefore, the interruption of the normal activities carried out through the same structure. Finally, the use of additive materials does not allow having a control on the asphalt healing, as the activation of these particles in presence of cracks is not governable. Indeed, when micro cracks propagate and meet the capsules, the fracture energy at the tip of the crack opens the capsules and releases the healing agent. Then, the self-healing process is activated only in the presence of fractures, so it is impossible to avoid the onset and propagation of the same ones.

The second class of approaches, which may be referred to as thermal, takes advantages from an interesting property of the bitumen, which is the main constituent of the pavement mixture [1]. Indeed, the bitumen is heat-sensitive (namely, thermoplastic), so it changes its physical status as a function of temperature. When its internal temperature increases and reaches a critical threshold (which depends on the considered material), it becomes a viscous liquid and it can self-repair its damages. As a consequence, the bitumen is known to be a self-healing material. The process can start spontaneously in case of sufficiently high temperatures. However, at room temperature, it is very slow. The idea of the thermal approaches is to stimulate the healing process by heating. However, temperature must remain within an acceptable range to avoid changing the properties of the asphalt and therefore making it more sensitive to future stresses.

In the last years, different thermal techniques have been proposed to face the problem of cracking. Heating processes build on information and communication technology and particularly on electromagnetic induction, where electromagnetic radiations penetrate the object (pavement layer), generating electric currents. These latter, in turn, flowing through the resistance of the material, heat it by Joule heating. For instance, the approach in [9] uses the electromagnetic induction and adds to the asphalt mixture electrically conductive particles, usually fibres, in order to improve its electrical conductivity and enhance the self-healing capacity. Similar methods are presented in [10]-[12]. With respect to methods in [2]-[8], the electromagnetic induction-based approach is less invasive. However, it is not selective and allows repairing just the surface damages without implying a deep level of restoration.

It is important to note that electromagnetic induction-based methods and studies differ in terms of main characteristics of the electromagnetic field, geometry of the problem, characteristics of the bituminous mixture to heal, traffic spectrum, and rehabilitation management (see Figure 1).

In terms of main characteristics of the electromagnetic field when operating on the bituminous mixture, the main factors are frequency and power of the electromagnetic sources, number of cycles of application, duty cycle. Based on [Liu et al, 2019] [13] induction heating is optimized using as optimum scheme 55 kHz frequency, 3 kW power and 10% wt of waste steel shavings content.

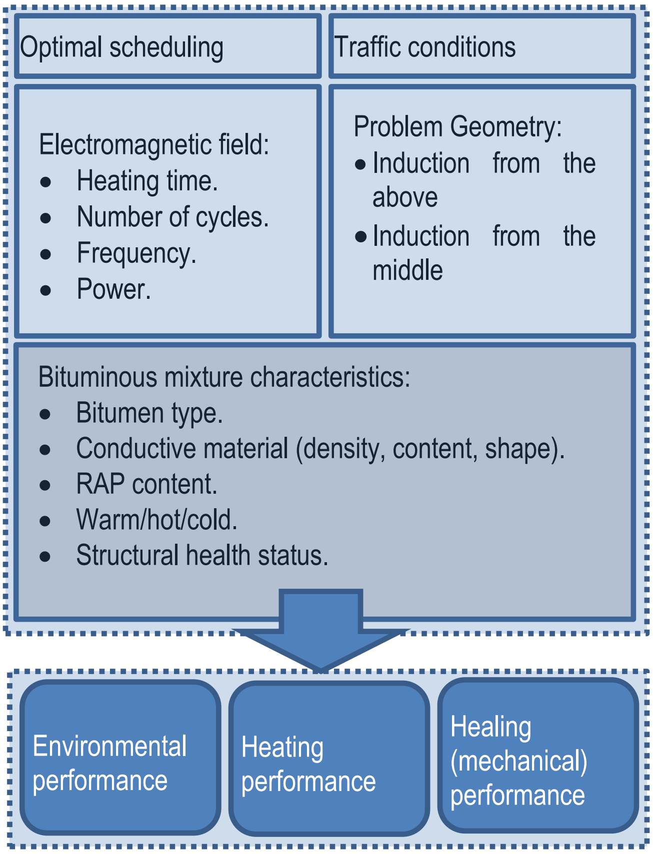


Figure 1. Heating induction: main parameters investigated in the literature

In terms of geometry of the problem and reciprocal position of electromagnetic source and layer to heat and heal, note that usually the source of electromagnetic field is located above the pavement. In contrast, Liu et al [13], incorporated the induction coil underneath the friction course.

For the characteristics of the bituminous mixture to heal, they include bitumen type, conductive material type (e.g., density, content by weight, and shape), reclaimed asphalt pavement (RAP), content and type of bituminous mixture (hot, warm, cold). Note that for bitumen type effects, Vo et al [14], assessed that the healing level of asphalt mixtures increases with a decrease in the binder viscosity. This is consistent with the studies carried out by Gómez-Meijide et al [15], which point out that ageing and RAP content reduce the effectiveness and energy efficiency of induction healing. In contrast, according to Gómez-Meijidea et al [15] the effect of bitumen properties on the induction healing capacity of asphalt mixes mainly depends on bitumen thermal expansion. In other terms, this might indicate that binders with low thermal expansion would result in poor healing performance, as the cracks cannot become completely filled. More precisely, the maximum healing ratio was obtained when the coefficient of thermal expansion (of bitumen) was close to 0.5 mm/°C, being reduced when the coefficient was higher and lower. Furthermore, for conductive materials, Apostolidis et al [16] and Vila-Cortavitarte et al [17] demonstrated that density, type, and quantity of metal wastes greatly affect their possible use as conductive material.

Not only bitumen but also mixture characteristics can affect healing performance. Liu et al [18] carried out a comparative study of the induction healing of Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) finding that the optimal heating temperature of WMA is lower than that of HMA.

For traffic spectrum and flow, note that the level of traffic affects the delays caused by rehabilitation works and [19] pointed out that the induction technology provides better results when maintaining the traffic capacity of the road is difficult and consequently queues are generated.

In terms of rehabilitation management and optimal time to rehabilitate. Based on Garcia et al [20], it has been concluded that the optimal solution is to carry out induction heating at approximately 35% of the lifetime of the material.

The properties and characteristics above imply different heating and healing characteristics, as well as diverse environmental impacts. Importantly, Norambuena-Contrerasa et al [21], observed that the healing level of asphalt mixture reduced with the number of healing cycles.

Unfortunately, the induction methods proposed above do not address the bottom of the asphalt concrete layers where the maximum tensile stresses start under repetitive loadings [22]. Consequently, when the cracks appear at the bottom of the asphalt layers and propagate to the surface of the road pavement the rehabilitation process is not any more effective because it affects just the upper layers. This factor is crucial and highlights the difficulties of the proposed methods in facing the so-called bottom-up fatigue cracking, which is one of the main failure modes in asphalt pavements.

Based on the above, in the study presented in this paper, a new, innovative, and non-destructive thermal method to carry out the rehabilitation of the pavement structure via selective and not invasive microwave heating is introduced and discussed. In particular, the recovery of internal damages at a given height of the structure (i.e., not necessarily at a surface level) for the re-establishment of the normal conditions of use of the solid body of interest, as well as its continuous maintenance during the useful life are addressed. The method takes advantage from the interaction between an electromagnetic field and the asphalt mixture constituting the road, which results in currents induced within the interested materials, as well as in energy absorption. This latter is converted into thermal energy, thus increasing material temperature and triggering the healing process. Unfortunately, the electromagnetic energy absorption is directly proportional to the electrical conductivity of the medium, while the pavement is made up with insulating materials. To overcome such a problem, the proposed method enhances the healing properties of the bitumen by doping it with conductive fibers or fillers, a common practice as in [9]-[12], [23]-[26].

The proposed approach allows solving the bottom-up cracking by inducing a deep heating by means of an electromagnetic applicator, that is a particular type of antenna. In more detail, the selection of the fundamental parameters for the antenna (e.g., frequency, dimension and power) and for the doping (the length and the volume of the fibres), in order to reach the healing temperature and the optimum in term of performance of the treatment, is discussed.

Note that the procedure, herein introduced and numerically validated for road pavements via multi-physical simulations, can be applied to all solid structures made up of materials wherein the self-healing process can be induced by heating.

The remainder of the paper is organized as follows. In Section 2, the general description of the proposed strategy is given. In section 3, a theoretical analysis about the consequences on production management is carried out and discussed. In section 4, an extensive numerical analysis in 3-D realistic scenarios of the proposed technique is illustrated. Finally, conclusions and final remarks follow in Section 5.

2. Healing via microwave heating and appropriate doping

The proposed approach builds on healing the considered pavement at a given depth. This latter is adjustable for the sake of process automation. In more detail, deep (but also surface) cracks can be healed through selective and non-destructive electromagnetic fields (EMF) in the range of microwave frequency. Moreover, the approach builds on the appropriate doping of selected pavement layers by means of conductive fibers. This requires understanding the interaction between the EMF in the range of microwave frequency and the road pavement, and, also how it is possible to change the pavement electrical properties by means of an appropriate doping.

The figure below summarises the method as well as the preliminary analyses required for it. In particular, the boundary conditions and hypotheses concerning the scenario and the treatment parameters are analysed in step 1). In step 2) a multi-physical analysis with recursive optimisation is performed, thus leading to the determination of the optimal parameters (step 3) for the treatment (step 4). Then, both maintenance and rehabilitation scheduling steps follow. Importantly, a real-time assessment of the structural health status could govern the input parameters of the healing process. Furthermore, the feedback from the treated pavement (structural health status after the heating process in step 5) could suggest the best maintenance strategy to follow after the healing treatment (step 6). In the following, we focus our attention on step 2) and 3).

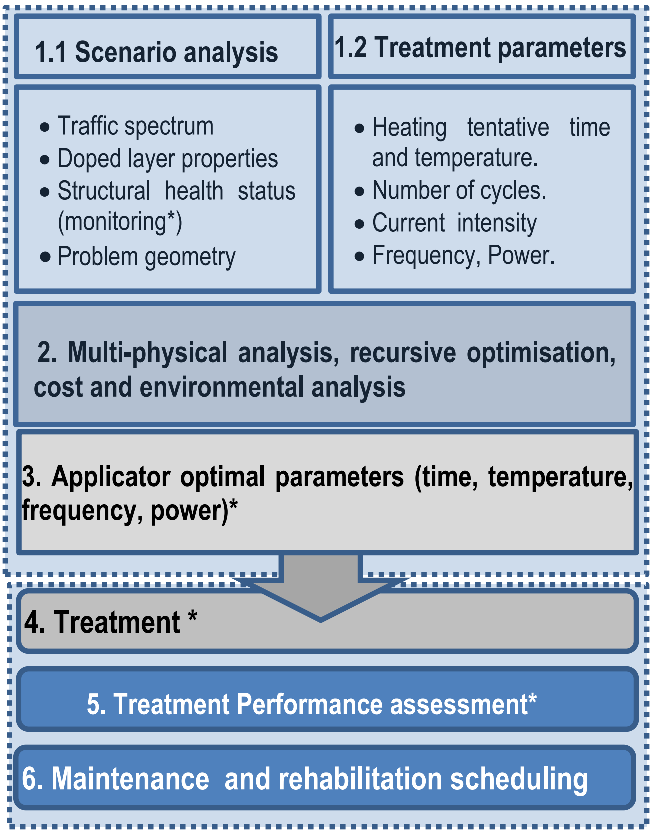


Figure 2. Schematic illustrating the method.

Note. *: compulsory parameters and processes

2.1. *Interaction between EMF and road pavement*

The exposure to EMF in the frequency range of microwaves results in currents induced within the interested materials, as well as in energy absorption and, consequently, in temperature increase. All these effects strictly depend on the material properties and the frequency involved [28].

The currents which are induced inside the medium exposed to EMF are caused by the conduction and polarization mechanisms, which are due to free changes and bounded charges (that are the induced dipoles), respectively. In particular, the current density J can be expressed as:

$$\boldsymbol{J}(\boldsymbol{r},\boldsymbol{w}) = \sigma(\boldsymbol{r},\omega)\boldsymbol{E}(\boldsymbol{r},\omega) \qquad (1)$$

wherein σ denotes the electric conductivity of the considered medium, $\boldsymbol{E}$ is the electric field, $\boldsymbol{r} = (\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ identifies a given position inside the investigated domain, while $\omega = 2\pi f$ being f the considered working frequency. Then, the density current is directly proportional to the amplitude of the electric field as well as to the electrical conductivity of the medium. The higher the conductivity is, the higher the amplitude of $\boldsymbol{J}$ will be.

When the electric current flows in the material, the interaction between charges and material results in the conversion of electricity into heat. Indeed, the current flow transfers energy to moving charges, which, in turn, give it to the material through collisions with the lattice atoms or with the solvent molecules. Finally, through the increase of the intensity of the disordered microscopic motions, an increase of the thermal energy of the system is obtained [28].

In order to quantify the energy absorption, it is useful to introduce the concept of the absorption power ΔW_i for the given volume, which is a measure of the rate at which energy is absorbed by the medium when exposed to the EMF [28]. To this end, let us considerer a mass M filling a volume V. Furthermore, let us assume that this latter can be divided into smaller volumes ΔV_i (i=1,2,..., N). These latter are so little that the electric field inside can be considered uniform and the electromagnetic properties can be supposed constant. The absorption power can be expressed as follows:

$$\Delta W_i(\boldsymbol{r},\omega) = \sigma(\boldsymbol{r},\omega) {E_i}^2(\boldsymbol{r},\omega)\Delta V_i \qquad (2)$$

where E_i is the effective value of the electrical field in ΔV_i. It is important to note that the energy absorption, which produces the heating of a given material, is directly proportional to the electrical conductivity of the materials.

Unfortunately, the electric conductivity of bitumen and aggregates is very low as asphalt concretes are essentially insulators. As a consequence, the energy absorption is negligible and no appreciable temperature increment is induced inside the road pavement. In order to overcome such difficulty and enhance the thermal interaction of the EMF with the asphalt concrete, the herein proposed method targets the conductive doping of the bitumen, as described in the following Subsection.

2.2. *Changing the electrical properties of the road pavement by means of an appropriate doping*

As only a conductive material can be heated effectively by microwaves, the method includes an appropriate doping of the layer wherein the damages/anomalies are expected to start or detected [9]-[12],[25],[26][28],[29]. The procedure due to the doping is selective and adaptive for different contexts. In particular, the procedure is adaptive with respect to the depth wherein the deterioration phenomenon is expected to start (cf. numerical cases in Section 4).

In order to increase the electrical conductivity of asphalt concrete, conductive particles or fillers can be added to mixtures [9]-[12],[25],[26],[27],[29]. Indeed, the temperature-time diagram of asphalt concrete is affected by quantity and characteristics of steel fibres. These are often quantified in terms of percentage by volume content.

Many studies were conducted using different types of additives (carbon fibres, graphite, steel wool, slags, etc.) and many of these consider fibres as the best choice for asphalt concrete. Garcìa et al [23], examined the conductivity of asphalt mortar through the addition of electrically conductive fillers and fibres (graphite and steel wool). In their research, they proved that this material can increase the healing rate and in particular the optimum is achieved with a mixture containing the 8.77% of steel wool (v/v) and sand–bitumen ratio 2.26 (v/v).

Liu et al [11], focused on the electrical conductivity of porous asphalt concretes. The experiments were carried out varying the type and the percentage of steel wool with respect to the total volume of bitumen. The best volume percentages to obtain the minimum resistivity resulted 20%, 12%, and 10% for steel wool type 1, steel wool type 00 and steel wool type 000, respectively. This latter resulted the most efficient among the three fiber types.

Liu et al [11], tested the effects of length of fibers on the resistivity using steel wood type 00 with three different lengths (3.2 mm, 6.4 mm and 9.5 mm). In the examined cases, the best results were obtained using steel wood fibers with initial length of 9.5 mm, while fibers that are too short or too long resulted difficult to blend. Indeed, in the first case fibers would lose into the mixture with no effect on its electrical conductivity, in the second clusters would originate which represent the structure weak point.

Consequently, based on test results [11],[27], 8% steel wool, with an initial length of 9.5 mm was selected as a viable solution. Accordingly, in this paper the deep layer is supposed to be doped with this type and percentage of fibres.

2.3. *On the desired healing temperature*

The optimal healing temperature is just one parameter out of a set of factors that affect time-temperature superposition during healing. Indeed, crack number and dimensions, thermal damage risk, bitumen quantity and percentage, aggregate gradation, and aggregate type govern automation inputs.

As well known, bituminous materials have intrinsic self-healing properties based on the surface energy of the system and diffusion of asphalt molecules from the matrix to the crack surface [28]. Bitumen temperature affects its viscosity and this is crucial because this influences its flowing into the cracks under suitable temperatures. Healing temperatures usually range from 30 °C to 70 °C [30],[31]. They depend on materials and particularly on bitumen type and ageing [21]. For example, for porous asphalt concretes an optimum temperature of 85°C was suggested to obtain the best healing effect with a good stiffness recovery, while higher temperatures could induce swelling and asphalt binder drainage problems [11]. Xiang et al [33] and Tang et al [34] highlighted that the optimal healing temperature is close to the softening point. This latter varies as a function of bitumen type, ranging from 53/65 (for a bitumen 20/30EN) to 39/47 for a bitumen 100/150EN). Importantly, the choice of the type of bitumen mainly depends on weather, layer and traffic. As a matter of fact, the warmer the climate is, the higher the temperature is, the severer the traffic spectrum is, the harder the bitumen should be, the lower its penetration should be (e.g., Bitumen 50/50 EN) and vice-versa (e.g., Bitumen 70/100 EN). As a matter of fact, the softening point of the majority of the asphalt binders used in bottom layers of pavements is close to 50°C [30],[31],[33],[35]. Accordingly, the self-healing temperature has been set at 50°C. By referring to optimal healing times, 31-48 minutes were obtained by Xiang et al [31].

Based on the above it emerges that time and temperature tuning are a function of many variables. Importantly, this fact suggests to set up automated control tuning methods to adjust temperature and time based on scenario analysis. To this end, it may be observed that many methods have been proposed in the literature to assess the structural health status of a pavement. Some of them build on the acoustic signature of a pavement as a means to detect and characterise cracks [36]. Another possibility is to adapt the healing process to the given boundary conditions [37] and to carry out a real-time crack identification as a basis to tune the treatment systems based on ground penetrating radars.

3. Preliminary analysis of method potential in term of production and cost

The method set up in this study (which allowed submitting a national patent request) has some potentials in terms of production effectiveness and savings. In order to quantify the savings related to the application of the method, a theoretical analysis has been here carried out in terms of present values. These are simply the cost of the pavement over its entire life, considering also inflation and interest rates. These predictions build on the formulas developed by Weed, R. M. [38], Praticò et al [39]-[42], in the pursuit of assessing the present value. In practise, the lower the present value is the better the pavement and its management system are. Based on the above it is:

$$PV_0 = C_0 + C_0 \frac{R^T}{1 - R^T} \tag{3}$$

$$\begin{aligned} PV_H = C_0 + C_H \cdot R^T + C_H \cdot R^{T+T\cdot HR^1} \\ + C_H \cdot R^{T+T\cdot HR^1+T\cdot HR^2} \\ + C_H \cdot R^{T+T\cdot HR^1+T\cdot HR^2} + \cdots \end{aligned} \tag{4}$$

where:

1) PV stands for present value (of the costs, as mentioned above).

2) PV_0 refers to the present value associated to a traditional pavement rehabilitated in a traditional way (i.e., reconstructing the asphaltic layers after T years, with T often close to 20).

3) C_0 refers to traditional construction or/and rehabilitation cost.

4) C_H refers to the costs associated with the healing construction and reconstruction process. This is a crucial factor because it pertains to the main variables that affect the spread of automation, i.e., A) technical feasibility; B) costs to automate; C) skills and cost of labour; D) benefits beyond labour cost (superior performance, better quality, etc.); E) regulatory and social acceptance.

5) R is the ratio between 1+INF and 1+INT (where INF is the inflation rate, e.g., 0.04, and INT is the nominal interest rate, e.g., 0.08), HR is the abovementioned Healing Ratio (hopefully close to 1 but realistically lower than 1).

In practice the formulas above provide an estimate of agency costs (or better their present value) during the life of the pavement from its construction (C_0), to its k-th rehabilitation (with k→∞). This latter is going to "cost" $C_0 \cdot R^{kT}$ for a traditional pavement management system (in which the pavement is "reconstructed" after T years).

In contrast, the k-th rehabilitation in the case of the management system proposed in this study (microwave deep rehabilitation) is going to cost $C_H \cdot R^{T+T\cdot HR^1+ ..+T\cdot HR^k}$. This is due to the fact that the healing ratio, i.e., the capability of the proposed method to heal the structure could be lower than 1. Note that it can be demonstrated [42] that for HR=1 and C_H=C_0 the two equations (3)-(4) above are the same. From this discussion it emerges that the proposed method has a potential that depends on two main factors 1) Its cost (C_H), compared to a cost of a traditional reconstruction (C_0). 2) Its ability to heal the pavement (HR·T) compared to the ability of a traditional rehabilitation process (T). Figure 3 illustrates the simulations carried out through the formulas (3)-(4). X-axis refers to years (the range 0-100 was considered). Y-axis refers to the present values of the different scenario considered. Each scenario is identified in terms of the two main variables above discussed, i.e.:

- HR, varying from 1 (the microwave-based treatment perfecty rehabilitates the pavement) to 0.5 (the microwave method gives back to pavement structure half of its last expected life);
- Cost of the healing process (1 or 0.5), where 1 is the cost of the traditional reconstruction option and 0.5 refers to the hypothesis that the microwave-based deep rehabilitation costs half times C_0.

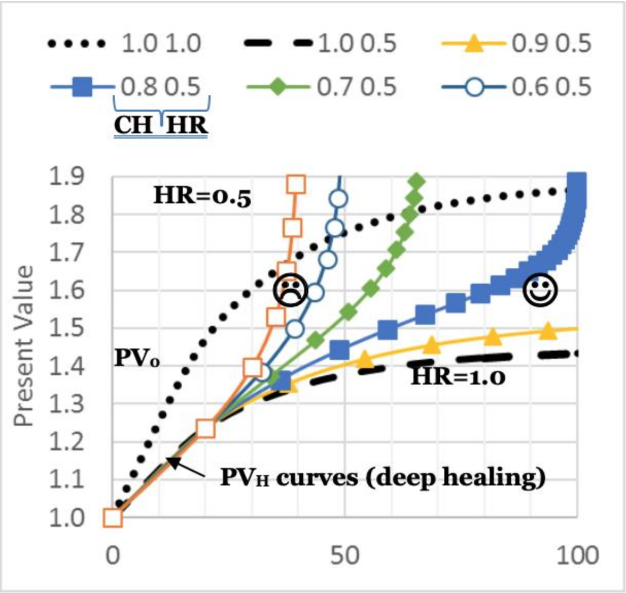


Figure 3. Pointing out management consequences.

In other terms, the curve PV_0 (1.0, 1.0) refers to the traditional pavement management system, where costs range from 1 (construction) to about 1.9 in the first 100 years of life of the pavement (highest curve, dotted). In contrast, the lowest curve (1.0 0.5, dashed) is the one that refers to the microwave method set up in this study, under the hypothesis of a C_H cost of 0.5 times the one of a traditional rehabilitation process. This particular PV_H curve ranges from 1 (construction) to about 1.4 (versus 1.9 for PV_0) in the first 100 years.

Importantly, based on these simulations, values of HR higher than 0.8 have the potential to successfully substitute common rehabilitation processes for much more than 50 years, while lower values (HR=0.5-0.8) would yield quite satisfactory pavement management systems when applied without alternating traditional reconstruction processes. This is a crucial point that calls for further investigations from an experimental standpoint (e.g., laboratory and on-site experiments, for better HR estimates) and from a theoretical and industrial standpoint (e.g., microwave-based thermal changes, hybrid pavement management system strategy, better estimates of method cost after the industrialisation).

Importantly, further benefits are expected for the environment (reduced landfill use, reduced virgin material depletion, and reduced transportation impacts) and for user costs (reduced time delays and congestion due to work zones).

4. Multi-physical analysis

This section illustrates some results of an extensive multi-physical numerical analysis aimed at validating the proposed approach as a non-destructive method to carry out the selective and deep rehabilitation of multi-layered road pavement systems.

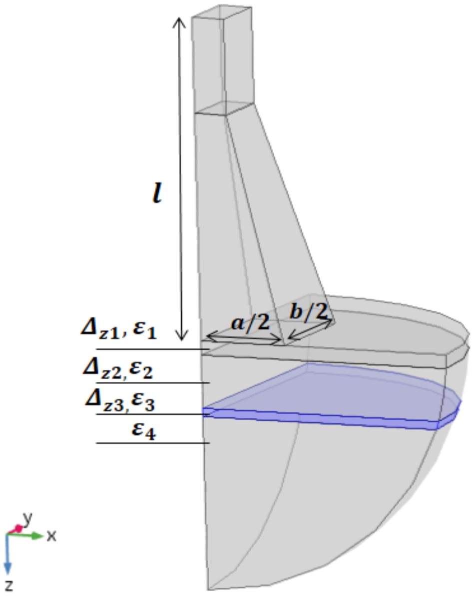
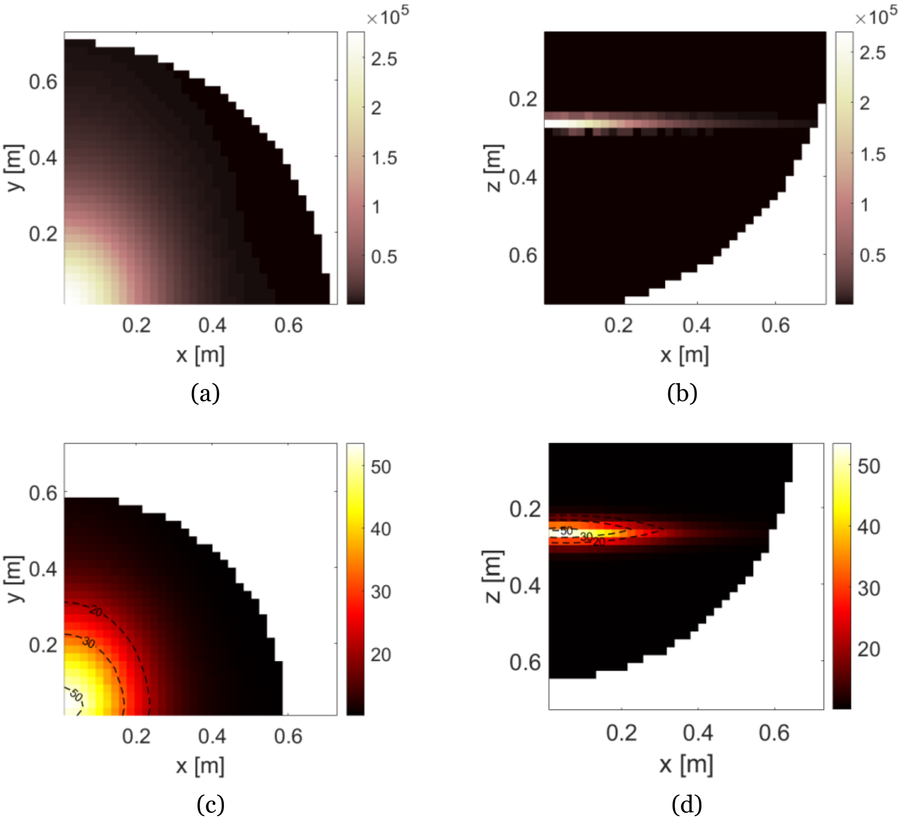


Figure 4. 3-D model of considered scenario.

This section is divided as follows. In Section 4.1, a description of the electromagnetic and thermal model adopted for the road pavement system, while Section 4.2 show the results in terms of absorbed power distributions induced in the internal layers of the pavement systems when a horn antenna is adopted. Finally, the evolution of the temperature distributions with respect to the time, resulting from the applicator designed in Section 4.2, are reported.

It is worth noting that the following analysis involves a singular horn antenna, mostly used in the microwaves range. However, the same analysis can be performed in the case of another antenna or in the case of an antenna array.

4.1. Description of the considered model



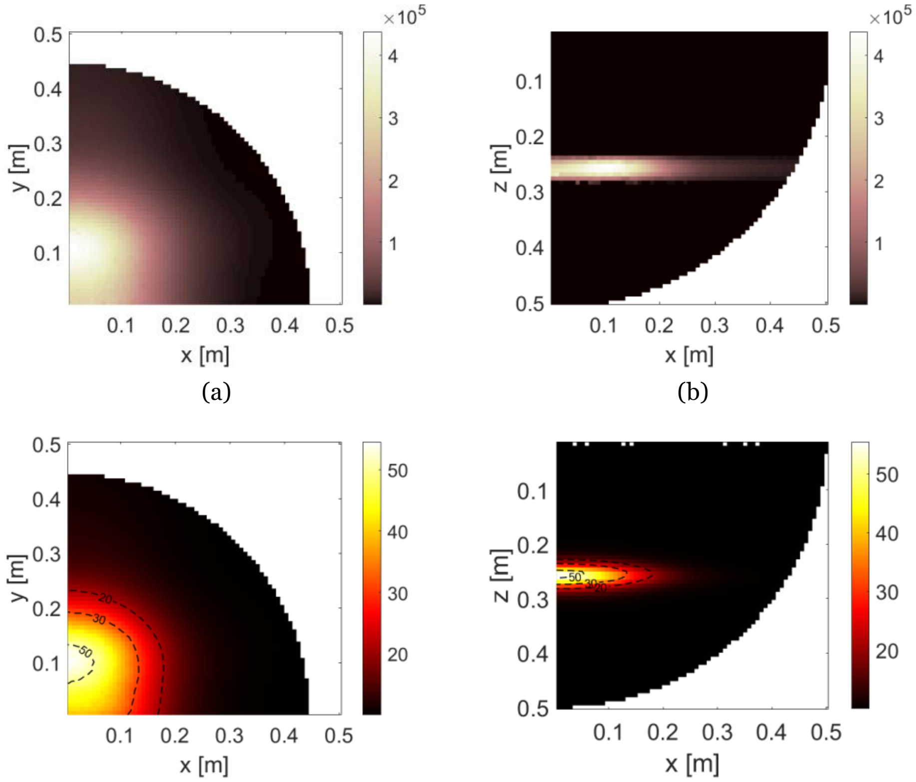
(a) (b) (c) (d)

Figure 5. Microwave healing via 0.4 GHz horn antenna. Absorbed power density $[W/m^3]$ along a cut view on (a) x-y plane at z=0.255 m and (b) x-z plane at y=0m. Temperature distributions [°C] along a cut view on (c) x-y plane at z=0.255m and (d) x-z plane at y=0m.

The considered scenario is a realistic 3-D model of a road pavement. Underlying materials and layers are characterised in terms of geometry, volumetric, electromagnetic parameters, and thermodynamic parameters. In particular, the road model is built by considering the general structure of a flexible road pavement, as shown in Figure 4.

Flexible pavements present a stratified structure in which each layer has a specific role. From the top to the bottom there are bituminous layers (e.g., wearing course which is modelled with a thickness $\Delta_{z1} = 0.05m$, binder course and base course (total thickness $\Delta_{z2} = 0.19m$) and non-bituminous layers (e.g., granular base course and subgrade). Importantly, in order to increase the expected life and postponing the cracking development in wearing courses and overlays, stress absorbing interlayers (still made up with asphalt binders) can be inserted at the bottom of bituminous layers [43]. Accordingly, the method here presented, which can be applicable to both surface and deep layers, includes a stress absorbing layer (with thickness $\Delta_{z3} = 0.03m$) doped in the pursuit of exploiting the EMF heating as described in Section 2.2.

In this study, one of the innovative ideas is to use microwaves to heal in-depth damaged solid structures. It is important to understand how to model the road structure, considering that relative permittivity and conductivity change their values with the scenario under testing as a function of layer characteristics (e.g., air void content), presence of water, EM frequency, and temperatures [44],[45]. Based on these parameters, the healing treatment has to be planned in order to guarantee a sufficient absorption energy to reach the healing temperature in a short time, thus ensuring an optimum time efficiency. Notably, the electromagnetic properties depend on the meteorological conditions in which the treatment is delivered (such as humidity or dryness). For the following numerical analysis, the city of Reggio Calabria (Italy) and the



(a) (b)

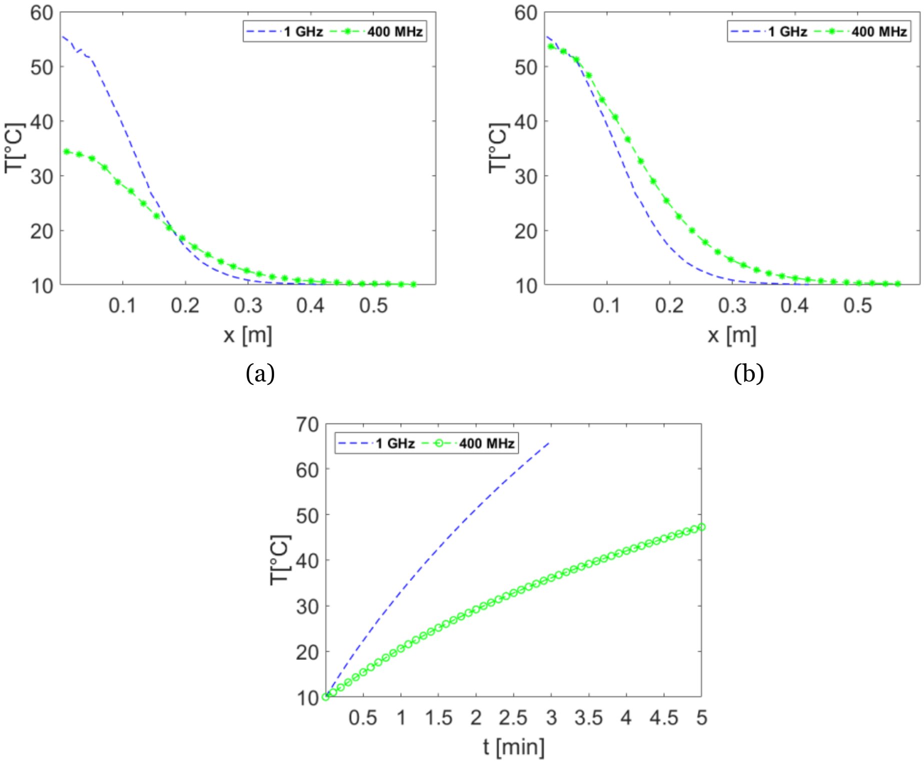
(c) (d)

Figure 6. Microwave healing via 1 GHz horn antenna. Deposed power density $[W/m^3]$ along a cut view on (a) x-y plane at z=0.255m and (b) x-z plane at y=0m. Temperature distributions [°C] along a cut view on (c) x-y plane at z=0.255m and (d) x-z plane at y=0m.

coolest months of winter were considered. Data were gathered from the Italian agency ENEA [46] and pavement temperatures as a function of depth were derived through the formulation given in [47]. Accordingly, as there is no great variation as the depth changes, the initial temperature of the different layers of the pavement has been set at approximately 10°C.

For electromagnetic pavement parameters, note that the electric conductivity is quite low, due to the fact that asphalt concrete is essentially an insulator. On the contrary, the stress absorbing layer (wherein cracks are supposed to start), according to [9]-[12],[25],[26],[27],[29], and supposing to have 8% fibres (on total volume of bitumen), has a conductivity σ of about $0.12\ S/m$. The corresponding relative permittivity ε_r has been chosen according to [45] and, because of the winter period, it has been set ε_1= ε_2= ε_4=5 in every layer except for the doped layer in which ε_3=8.2.

For the EMF applicator, rectangular horn antennas have been selected and supposed to be placed directly on the pavement, neglecting the interposed air. The geometrical antenna parameters are selected according to the technical specifications of some commercial applicators online available [48]. In particular, two different horn antennas were initially considered, circular and pyramidal ones. However, the commercial circular applicators have usually high working frequencies, which affect the performance of the treatment in term of both time and extension of the healing region. Indeed, with respect to the x-axis, the healing region is expected to be extended 0.4 m. This is an important aspect that take into account the average passage area of the wheels and so the most stressed zone in which it is more probable cracks form. For this reason, only pyramidal horn antennas have been considered.



(a) (b)

(c)

Figure 7. Temperature distributions via 1 GHz/400 MHz horn antenna. Temperature distribution [°C] along a cut view on (a) y-z plane (varying x) at the same instant time and (b) at the instant in witch both the antennas reach ≈50°C. Temperature distributions [°C] along a cut view on (c) x=y=0m and z=0.255m.

The pyramidal antenna has a rectangular aperture of dimensions a and b (with $a>b$). In the following numerical analysis, two rectangular horns have been considered. The length l of the first type has been set equal 0.654 m and a=0.582 and b=0.442 m, with a working frequency 1GHz. The second one has l=1.229 m, a=0.837, b=0.604 m and works at 400 MHz [30]. Another important issue for the considered antenna is the power handling capability of the entire system. Both antennas are capable of handling continuous power of the order of 10^4 to 10^7W [49],[50]. However, the considered coax-to-waveguide adapter mainly limits the maximum continuous power supported by horn antennas. In the following, the input power in every case performed was set to 1kW. Of course, if an increased power can be considered, according to the adapter, better results and improved time-temperature performance are expected.

All the results presented have been performed by using a full wave finite element solver. In order to reduce the computation burden, the symmetry of the model has been exploited by simulating only a quarter of the structure pavement-antenna, as shown in Figure 4, and by adopting suitable boundary conditions. Obviously, the achieved results can be replicated to the rest of the domain.

4.2. Numerical Results and discussion

Figure 5 shows the absorbed power density distribution in the different layers of the under-testing scenario, previously described in Section 4.1. These results are achieved by means the use of the pyramidal horn antenna working at the frequency of 400 MHz. In particular, Figure 5-a corresponds to a horizontal cut at z=0.255m, while a vertical cut at y=0m is shown in Figure 5-b. As expected, the power density is focused only into the doped layer, according to its higher

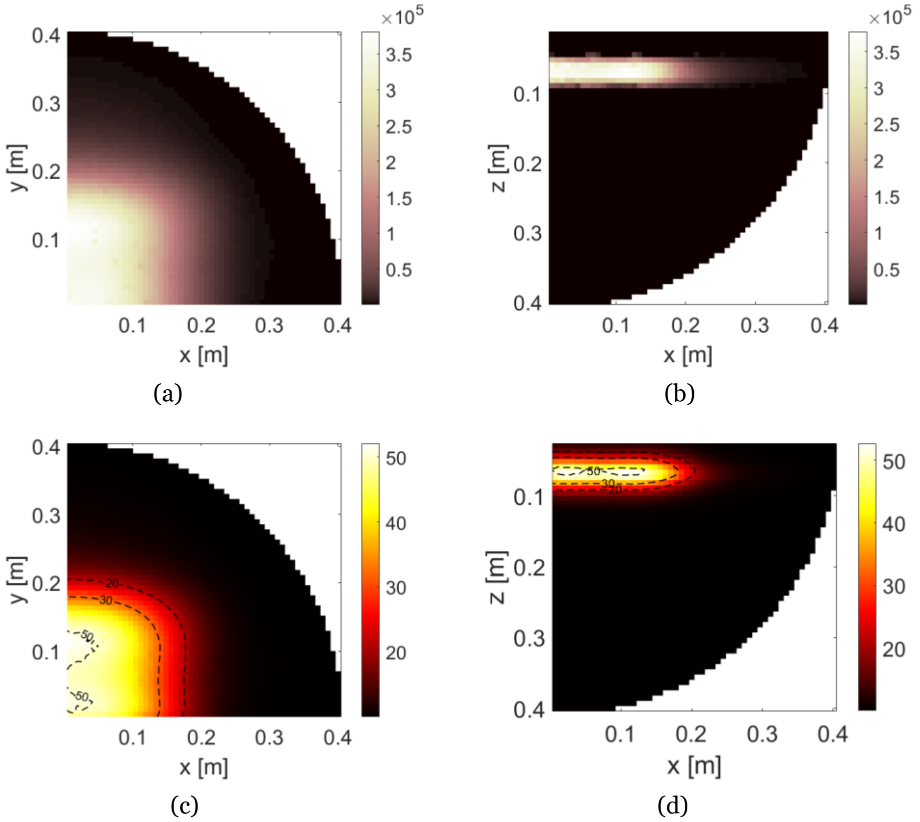


Figure 8. Microwave healing via 1 GHz horn antenna. Deposed power density $[W/m^3]$ along a cut view on (a) x-y plane at z=0.065 m and (b) x-z plane at y=0m. Temperature distributions $[°C]$ along along a cut view on (c) x-y plane at z=0.065m and (d) x-z plane at y=0m.

conductivity. The maximum reached value of absorbed power density is $\approx 2.5 * 10^5$ W/m^3.

As mentioned in Section 2.1, the absorbed power is converted in heat and a temperature increase is induced on the conductive structure. In Figure 5 the temperature values distributions are shown. To qualitatively improve the images, different iso-temperature contours at 20°C, 30°C and 50°C have been superimposed on them. These results confirm that the EM field can induce the road pavement overheat, in a selective way. The healing temperature of 50°C is reached after 226s (about 4 minutes, thus improving the performance with respect to [33]). Obviously changing the input power, we can improve the efficiency of the procedure, but this point in not deal with in this paper because the aim of the present is to offer a validation of the proposed approach.

Given the above, this first case validates the proposed approach, confirms its selectivity and underlines that the procedure is also adaptive in depth, so moving the doped layer we can obtain similar results at different levels. Then, in order to improve the performance both in terms of time, a rectangular pyramidal horn antenna with working frequency of 1GHz has been considered. In Figure 6 both the obtained power density and temperature distributions are shown. These results underline that changing of the working frequency can play a relevant role in the healing treatment.

Again, the absorbed power density is focused only into the doped layer. In particular, its maximum reached value is $\approx 4{*}10^5$ W/m^3. In this case, we can reach the healing temperature of 50°C after 114s, improving the time efficiency of the procedure.

As far as the extension of the healing section of the pavement, as highlighted in Section 4.1, Figures 5 and 6 show that the considered applicators are able to heal a region of about 0.20m. However, in the first example the healing temperature can be reached after 216s, therefore it takes almost twice as much time as the previous case.

In order to quantitatively compare the two antennas, Figure 7 depicts the temperature distributions into the doped layer, varying along the x-axis (fixed y=0m, z=0.255m) and time instant t=226s. As can be seen, working at 1 GHZ allows reaching a higher temperature (Figure 7-a). When both antennas reach the healing temperature, respectively at time instants equal to 114s and 226s, the treated area is quite the same (see Figure 7-b). Figure 7-c shows the temperature change over time in both the antennas. This graph underlines how the heling treatment with the first type is slower than second one.

In order to show the adaptiveness and flexibility of the procedure, a numerical example has been performed by considering a doped layer with a thickness Δ_{z3} below the wearing course with a thickness Δ_{z1}. In this example, the horn antenna working at 1GHz has been considered. The results are shown in Figure 8. As can be seen, the region that can be treated is now greater. However, the time needed to reach the healing temperature is almost the same 138s.

5. Conclusions

In this paper an innovative method for healing damaged solid structures in the pursuit of mitigating the bottom-up cracking phenomenon has been proposed. The method can be applied to heat-sensitive materials and it induces the healing of the material by means of microwave heating at a given depth. In particular, in this paper, the method has been applied to the case of pavements structures. Unlike the other existing ones, this procedure allows obtaining a selective, not invasive, and fast healing. Interestingly, it is also adaptive, as it can induce the healing also in the deeper layers of the road pavement. However, in order to achieve an adaptive and selective treatment, an adequate doping of the layers to treat (typically in the interface between granular base and bituminous base course) is needed. The doping is required in order to increase the electrical conductivity of the asphalt (otherwise near to zero) and it takes place through the insertion of metallic particles (e.g., fibres) in the structure matrix. This allows healing different layers at different heights by dynamically adjusting antenna working parameters.

The method has been tested by means of realistic multi-physical numerical simulations, which consider both the healing of surface and deep layers of a road pavement. In both the cases, the results show that the proposed approach allows reaching in few minutes the healing temperatures, which for the case under investigation have been set up at 50°C. Moreover, the numerical tests have been performed by considering as microwave applicator two different pyramidal horn antennas, working at two different frequencies. In particular, the antenna at 1 GHz is more efficient than the one with an operating frequency of 400 MHz. The first, indeed, leads to benefits in term of time. It is important to note that, with respect to other healing methods proposed in the literature, as the one proposed in [33], the proposed procedure allows drastically reducing the overall treatment time, with inherent advantages in term of management and maintenance costs.

The analyses carried out in terms of present value of agency costs support that this innovative production/construction method has a certain potential from an economic standpoint and paves the way towards its implementation in effective and convenient scenarios where 1) the healing ratio is maximised; 2) microwave-based management costs are reduced.

This paper lays the foundation of the proposed healing procedure. However, further aspects have to be studied yet. In particular, the system antenna-pavement can be further optimized in order to improve the time efficient and enlarge the area under rehabilitation. To this end, future research will focus on the design of an ‘ad hoc’ horn antenna and/or different types of applicators. Moreover, in order to increase the extension of the treatment area, an even more efficient antenna system (for instance an antenna array) could be designed. Another possibility to improve the performance and have a better control of the antenna radiation pattern is the insertion of appropriate dielectric materials inside the antenna [51] and to set up a specific control system (cf., e.g., [52]). This could also allow increasing the amount of electromagnetic field which is transmitted inside the road pavement.

Future research will be devoted also to test the procedure in case of other solid structures, as for instance in [53],[54] and to address from a more comprehensive standpoint the consequences deriving from this innovative microwave-based, deep reconstruction method. Moreover, experimental validation of the proposed method will be surely interesting as future works.

Finally, based on the simulations above, the use of automated control tuning methods to set up applicator and maintenance optimal parameters (by means of before/after scenario monitoring) emerges as a key prospective target.

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