Toward the Design of an Induction Heating System for Asphalt Pavements with the Finite Element Method

Apostolidis, Panos; Liu, Xueyan; Kasbergen, Cor; Scarpas, Athanasios; van de Ven, M.F.C.

DOI
10.3141/2633-16

Publication date
2017

Document Version
Accepted author manuscript

Published in
Transportation Research Record

Citation (APA)
Apostolidis, P., Liu, X., Kasbergen, C., Scarpas, A., & van de Ven, M. F. C. (2017). Toward the Design of an Induction Heating System for Asphalt Pavements with the Finite Element Method. *Transportation Research Record*, *2633*, 136–146. https://doi.org/10.3141/2633-16

Toward Designing an Induction Heating System for Asphalt Pavements by using Finite Element Method

P. Apostolidis[1], X. Liu[1], C. Kasbergen[1], A. Scarpas[1], M. van de Ven[1]

[1] Section of Pavement Engineering
Faculty of Civil Engineering and Geosciences, Delft University of Technology
Stevinweg 1, 2628 CN Delft, the Netherlands
Tel. +31 61 6599128, Email: p.apostolidis@tudelft.nl

Corresponding author:
P. Apostolidis
E-mail: p.apostolidis@tudelft.nl

Total Number of Words

Words in abstract	=	191	words
Words in text:	=	4801	words
Words in references	=	484	words
Figures and Tables (8x250)	=	2000	words equivalent
Total	=	7476	words equivalent

Abstract: Induction technology was introduced to the paving industry to assist pavement operations by heating asphalt layers efficiently from the surface. Many experimental studies have been conducted to investigate the impact of different inductive particles on the heating efficiency of asphalt mixes. However, very limited is the research on quantifying the design, the operational factors and the associated degree of heat generation of induction treatment. In this paper, the hypothesis that different systems of induction coils provoke different levels of heat generation within an inductive asphalt layer was studied. Firstly, a three-dimensional induction heating finite element model was developed to evaluate the design and effect of operational factors for a static single-turn induction coil system. The electrical conductivity values of the material in the inductive asphalt pavement were calibrated with a lab-scale induction device. Also, moving induction systems were analysed considering different operational conditions. The supplied power and the travelling speed of the induction system appeared to be the most influential operational factors for the development of a quick and highly efficient system. The developed model creates an opportunity to imply these analyses in asphalt pavements to optimize the technology in-situ.

1. INTRODUCTION

According to the 2013 European Environment Agency report, the transportation sector is the second most important source of greenhouse gas emissions after the electricity production by fuels with 22.2% with increasing contribution through the last two decades (1). In the same year, the European asphalt industry (EU27) produced about 280 million tonnes of asphalt (2). While its impact is quite small in the transportation sector as a whole, in the past decade the asphalt paving industry has worked hard to reduce the environmental effect of its activities. For this purpose, several state-of-the-art technologies have been developed and one of these is induction heating.

Induction technology was introduced to the paving industry around 2010 to assist construction and maintenance operations by heating pavement layers efficiently from the surface. Initially, it has been used in the Netherlands to prevent ravelling of porous asphalt layers by applying an alternating magnetic field and heating the added inductive particles in the porous asphalt. The advantage of induction heating compared to other commonly used heating methods (e.g., infrared heating) is the quick and effective heat generation at the desired depth and locally around added inductive particles without overheating the mix or the surface (3). As local heating method induction technology can efficiently increase the temperature at the desired depth but it is difficult to predict the thermal profile of the treated asphaltic material during induction.

The addition of inductive particles (i.e., steel fibres, steel slag, etc.) to an asphaltic matrix changes its induction related properties and the mix is transformed from non-inductive to inductive. Addition of inductive particles in asphalt mixes can introduce several advantages, such as enhanced induction heating efficiency locally, reinforcing of mixes and subsequently improve the service life of asphalt pavements. Many studies have been conducted to investigate the effect of inductive particles on structural and non-structural performance of asphalt mixes at meso-scale. Research has in most cases been focused on the development of inductive asphalt mixes at sub-mesoscale. In comparison with mesoscale (10 mm), at sub-mesoscale (1 mm) asphaltic material usually is referred to as a homogeneous matrix in which the inductive particles are distributed forming heterogeneous structures. However, apart from a study in 2016 (4), no research has been conducted to investigate the effect of operational conditions of the induction treatment on asphalt mixes in the field.

First, a summary of the studies conducted to develop inductive asphalt mixes and the contribution of inductive particles on heating effectiveness of asphalt mixes is given.

In 2009, Garcia et al presented a study to reduce the electrical resistivity of an asphalt mortar with five different sizes of mineral particles (<0.120, 0.120-0.250, 0.250-0.50, 0.50-1.00, 1.00-2.00mm, 20 wt% each size) by adding inductive particles with the aim to develop asphaltic materials capable to be heated with induction energy (5, 6). Addition of different types of inductive particles (i.e., graphite and steel wool) was investigated on the basis of the electrical conductivity of the new mixes. They concluded that the conductivity is a function of the volume of the added particles and the sand-bitumen ratio. Also, the conductivity increases faster by adding steel wool than by adding graphite. Similar conclusions were reported for asphalt mortar produced by mixing independently iron powder and steel fibres (7, 8). All above researches confirmed that adding inductive fibres and fillers together a maximum conductivity could be reached without damaging the mechanical properties of asphalt. They observed that, by increasing the volume of inductive particles, the heat generated via induction increased, however after a certain maximum volume, the temperature does not increase anymore.

Initially, the induction technique was used to increase the healing potential of porous asphalt concrete in order to prevent the formation of macro-cracks and delay ravelling. Inductive particles were mixed with the other components of asphalt and with a lab-scale device the inductive particles were heated locally, surrounding bitumen was melting and the micro-cracks were closed preventing the development of macro-cracks. In 2010, porous asphalt concrete mixes with different steel wool fibres (i.e., variation in length and diameter) were investigated in order to evaluate their effectiveness on healing and mechanical response (9). Comparison of different types of inductive fibres showed that the short steel wool fibres with a larger diameter (type 1) provided higher strength than steel wool with longer length and smaller diameter (type 000). In contrary to that higher induction heating efficiency was obtained by adding the type 000 fibres and 10% (by volume of bitumen) of these fibres proved to be the optimum content for the most effective induction treatment.

The effect of steel wool fibres on the mixing of porous asphalt in the laboratory and at industrial scale in an asphalt plant was also evaluated in order to optimize the development of asphalt layers placed in the field (10). Two different mixing processes were tried and it was observed that by changing the mixing cycle a different quality mix was produced. So the mixing process is very important. It was, amongst others, observed that the length of the steel fibres in the porous asphalt concrete reduced by increasing the mixing time, particularly during the first 1.5 minutes of mixing and as a result less clustering was observed. The corrosion sensitivity of fibres in the mix was also investigated in this research and it was found that chloride cannot penetrate inside the mix. Other researchers examined also the possible chloride corrosion damage in asphalt concrete by accelerated chloride migration under a constant electric field (11). It was concluded that the corroded fibres did not degrade the mixes, because the corrosion occurred only at the surface of the fibres exposed to chloride.

Dense asphalt mixes with induction particles were also introduced for induction healing (12, 13). As previously mentioned, changing of the volume and the type of fibres in the mix resulted in different temperatures generated through induction heating. In 2014, an analysis of the volume, length and diameter of steel fibres has been conducted for dense asphalt mixes and the impact on the air-void content, mechanical and induction healing performance was studied (12). It was observed that the mixing process of dense asphalt was strongly influencing the formation of clusters and the final length of fibres was independent of the original length before mixing. The air-void content was affected by increasing the amount of fibres. Higher amounts of fibres caused an inhomogeneous distribution and clusters of fibres leading to a negative impact on the abrasion resistance of asphalt. However, the main conclusion of this research was that the amount, diameter and length of the fibres are the most critical parameters to produce durable dense asphalt. In other research on induction healed dense asphalt (13) the minimum temperature for healing was found to be based on the capillary flow theory. A temperature of 50 ^{o}C initiated bitumen flow to heal cracks. Also, a finite element model was developed for the inductive asphalt mixes in order to predict the time needed to heal micro-cracks considering 85 ^{o}C as a sufficient high healing temperature (4).

Although most of the research on the effectiveness of induction treatment of asphalt mixes has been done at lab-scale, the experimental evaluation of induction heating of asphalt concrete is not only time-consuming but also expensive. Apart from a field study of induction in asphalt pavements in the Netherlands (9), **Fig.1**, the research on induction heating and the associated heat pattern of pavements is limited. Pavement engineers need to avoid undesired delays during operations so the speed of the induction treatment is very important. Because of this fact a special design of induction coils is necessary to generate adequate heat in inductive asphalt, the factors that influence the effectiveness of coil were studied in (9). In this paper the effect of (i) the type of induction coil, (ii) arrangement of coils in an induction system, (iii) operational conditions and (iv) the associated levels of treatment of an induction system for pavement applications are evaluated.

2. THREE-DIMENSIONAL FE MODELING OF INDUCTION SYSTEM

Induction systems have been studied widely in the field of composites manufacturing, such as joint welding of fibre reinforced thermoplastics, by employing advanced experimental and computational tools. In many cases, the involvement of the computational tools for rapid prototyping of induction systems saves additional testing and production costs by providing accurate results for the development of high quality systems. With the computational tools heat transfer simulations, optimization of critical dimensions of coils and studies of heating patterns are among the common prototyping and engineering tasks in order to design systems with the highest possible induction quality (14-17). Nevertheless, an in-depth understanding of the role of induction technology in the pavement industry is required to develop the tools and the materials for uniform and targeted temperature profiles in order to get the desired efficiency.

The effect of induction heating on the temperature of asphalt mixes is normally obtained by utilizing an infrared thermal camera, both in lab- and field- studies. Instead of expensive field testing, multi-physics modelling of electromagnetic heating phenomena provides a quick framework of analysis, particularly suited for the study of complex composite materials such as asphalt mixes. The multi-physics method has proved to be a promising numerical method that can simulate heating phenomena. For this reason, in this paper, the focus is on the development of a computational approach to model induction heating pavement systems with static and continuously moving coils. The impact of operational conditions is also taken into account (i.e., supplied frequency and power, distance between coil and pavement surface, travelling speed, etc.). For this purpose, COMSOL multi-physics finite element tool is used to model a three-dimensional induction system of single-turn coils and an inductive pavement layer in this paper.

A proper model of induction systems should simulate the magnetic field flux distribution around the induction coil and through the asphalt pavement layer and at the same time determine the temperature development in the inductive asphalt pavement. An asphalt pavement and the air domain above the pavement surface were designed in such a way that the induction coils were located in the centre, **Fig. 2.i.** To simplify the response of the heated material, it was assumed to be a homogeneous continuum medium with isotropic properties. Modelling of the induction coil as source of the alternating magnetic field requires a proper design and coil material selection. Most induction coils are made of copper and this was also the selected material in this analysis. Experience has shown that the service life of coils is highly influenced by the shape, the microstructure and the cooling design of coils. However, in this study, overheating phenomena because of improper cooling of the coil are avoided by coupling the magnetic field and heat transfer phenomena directly on the asphalt pavement domain.

2.1 Simulation Conditions of Induction System

The three-dimensional modelling of an induction heating system involves several design, operational and material parameters. Therefore, the induction system model was simulated in three steps: (i) sensitivity analysis of a static single-turn coil, (ii) calibration of material parameters and (iii) analysis of a moving single-turn and two single-turn induction coils.

In the first step, a sensitivity analysis has been conducted by supplying one single-turn induction coil with different supplied power (SP) levels within the range of high frequency induction operations. This analysis has been carried out for different coil geometries, including also variation of the distance between the single-turn coil and the surface of the inductive pavement (i.e., airgap (AG)), to determine the optimum coil characteristics for the development of a prototype induction system. For this step, the values of the effective properties of inductive asphalt were considered to be 1 for magnetic permeability, 100 S/m for electrical conductivity and 6 for electrical permittivity, 1 W/(mK) for thermal conductivity and 920 J/(KgK) for heat capacity (4). However, values of the effective electrical conductivity will be adjusted in the next step of the analysis as part of the effort to calibrate the system. For the operational conditions of the induction coil, SP ranged from 0.1 kV to 1 kV and supplied frequency (SF) from 10 kHz to 100 kHz.

Following the sensitivity analysis of the single-turn induction coil system, calibration of material parameters was conducted for more realistic simulations of induction heating in asphaltic materials. Because of the fact that the values of these parameters vary according to the added inductive particles (volume, shape, individual electro-thermal properties), in the second step an induction model was developed simulating a lab-scale induction heating system with the main purpose to calibrate the effective electrical conductivity values of asphalt mixes. The calibration process involved an iterative process with (i) simulation of heating of a lab-scale induction apparatus and (ii) experimental analysis of induction heating of asphalt using the induction apparatus to determine the appropriate conductivity values of the asphalt mix. Asphalt mix samples with a fixed ratio by weight between steel slag particles (2 mm), filler and bitumen of 2.33:1:0.6 were produced in the lab. The inductive mixes were heated with a lab-scale induction apparatus with SP of 0.55 kV and SF of 65 kHz at 20 ^{o}C. The output data of the induction analyses used to determine material properties of an asphalt pavement layer for the second step of analysis and prototyping the system.

In the third step, a travelling single-turn coil was utilized as prototype coil with the same height and width as the lab-scale device of the second step and the single-turn coil of the first step, respectively. The selected operational conditions for this induction system were 70 kHz and 1 kV. Also a two single-turn induction system was modelled in order to compare the effectiveness of both systems. The horizontal distance (HD) between the two different single-turn coils and their travelling speed (TS) were varied. From previous research (9) it became clear that for pavement engineering purposes a commercial induction system should be capable to travel at approximately 5 km/h, so the efficiency of the system was analysed by increasing steadily the SP at 1 m/s (~ 3.6 km/h).

2.2 Meshing of Induction System

As it is very important that simulation systems have a high accuracy and require reasonable computation time, the domains of the three-dimensional model were meshed with different tetrahedral element sizes. The custom meshes for the induction coil and the surrounding air environment were produced with elements of 0.7 m and 0.03 m maximum and minimum size, respectively. The inductive pavement was meshed with finer elements of 0.15 m and 0.004 m in order to obtain a good resolution of the magnetic density flux distribution. Meshing different geometries with different elements is highly important for fast simulation processes and within certain computational limit, however, the quality is main priority for precise analyses. For this reason, the quality of the custom meshing was tested for each studied domain by reporting the minimum element quality (MEQ) and all the domains show sufficient quality (MEQ>1). **Fig. 2.ii** shows the meshing for the elements of the induction system.

2.3 Multi-physics Governing Equations

In the Cartesian coordinate system, the three-dimensional governing equation of the heat conduction is described by Eq. 1:

$$\rho c_\rho \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{1}$$

where ρ is the mass density of inductive asphalt, k denotes the thermal conductivity, c_p is the heat capacity, T is the temperature, $\mathbf{u}$ is the velocity or travelling speed and Q represents the heat source (kW/m^3).

The thermal convection and the radiation are formulated by the Eq. 2:

$$\mathbf{n} \cdot k \nabla T = h \cdot (T_{sur} - T) \tag{2}$$

where h is the overall convective thermal coefficient and T_{sur} denotes the surrounding temperature.

The thermal diffuse on the top surface of pavement is described in Eq. 3 as:

$$\mathbf{n} \cdot k \nabla T = sigma \cdot em(T_{amb}^4 - T^4) \tag{3}$$

in which T_{amb} is ambient air temperature 20 ^{o}C, sigma is the Stefan-Boltzmann constant of $5.67 \cdot 10^{-8}\ \mathrm{W/m^2K^4}$, **n** is the normal vector and *em* is the surface emissivity of 0.5.

The multi-physics analysis of coupled electromagnetic and heat transfer fields is given by the Eq. 4 as:

$$\rho c_\rho \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + \frac{1}{2} Re(\mathbf{J} \cdot \mathbf{E}^*) + \frac{1}{2} Re(i\omega \mathbf{B} \cdot \mathbf{H}^*) \tag{4}$$

where **E** is electric field intensity, **B** is the magnetic flux density, **H** is the magnetic flux intensity and **J** is the excitation current density is written in Eq. 5 as:

$$\mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} \tag{5}$$

where σ is the effective electrical conductivity of the inductive asphalt – medium, **D** is the electric flux density, j denotes the imaginary unit and ω is the angular frequency.

The governing equation of a single turn induction coil under harmonic transient analysis is written according to Eq. 6 as:

$$I_{coil} = \int_{\partial\Omega} \mathbf{J} \cdot \mathbf{n} \tag{6}$$

For more details about the governing equations of induction heating and coupling electromagnetic and heat transfer phenomena can be found in (4).

3. RESULTS AND MAIN FINDINGS

A total of 673 simulations were run in COMSOL to obtain a solid knowledge about the operational aspects of the induction systems and the temperature development in asphalt pavements. As mentioned before, the analyses developed within a sequential process in which efforts were spent to get information about the most influential factors for a highly efficient system. A schematic flow diagram of the methodology is demonstrated in **Fig. 3** and the main findings of this study are shown below.

3.1 Effect of Design and Operational Conditions on Heating Efficiency

Considering the importance of identifying the main operational factors that influence the efficiency of induction heating, sensitivity analyses were conducted. The sensitivity analyses were performed by varying one parameter while maintaining other parameters constant. The geometry of a single-turn coil (three types of single-turn coils, **Fig. 4**), the AG (airgap), SP (supplied power) and SF (supplied frequency) were the parameters investigated. The efficiency of the induction was measured by determining the temperature at the surface of the pavement after 120 seconds of heating. **Fig. 4** demonstrates the results of these analyses in three-dimensional plots.

The results evidently show that the heating efficiency of induction technology in asphalt is influenced mainly by the SP. Simulations of the system for both AG cases of the coil from the surface of the pavement show the highest efficiency when the system worked at a SP of 1 kV, independently of the coil type. Faster treatment during maintenance operations against crack initiation of asphalt pavements or during construction operations will be possible when higher temperatures at the surface of the pavement are generated during the induction process.

Apart from the SP, it is well known that an induction system with a higher SF provides higher electric field strength and higher heating power but makes the system more expensive (14). In this case, at lower SF, the heating efficiency was higher for the system with 0.025 m coil-pavement distance than the system with a distance of 0.05 m, **Fig. 4**. In the same figure, it is observed that when the coil is closer to the surface the system responses differently resulting in higher temperatures for a higher SF. In particular, systems with AG of 0.05 m and 0.025 m reveal their highest temperature on the surface under 60 kHz and 1kV and under 10 kHz and 1 kV, respectively. Also, the heating efficiency increases when the coil is closer to the pavement. Since the distance between the coil and the pavement surface gives totally different heating responses under the same operational conditions, it becomes clear that prototyping the system is not a straight forward but very complex process and it requires considering all the parameters to design an efficient induction system.

But using the sensitivity analysis at this level, the major operational factors of the system were identified. After completing the material calibration at the subsequent level the TS (travelling speed) will be studied as the crucial factor for using this technology for various heating associated applications in asphalt pavements.

3.2 Effect of Material Conductivity on Heating Efficiency

In case of inductive asphalt mixes, the distribution of inductive particles is related with the mixing time, the mixing load, the amount of particles and the percentages of the other components. In most of the cases, the inductive mixes present clusters of their inductive particles which leads to non-homogenous materials with different electro-thermal properties at different locations of the material. Therefore, highly induction heated spots are created. In order to avoid these phenomena, the distribution of inductive particles considered homogeneous in this paper.

Effective electrical conductivity is the most influential property of a material under induction. Previous researches for the inductive asphalt mixes have been conducted to determine values of conductivity using advanced tools showing significant differences between the values obtained from the experimental and the numerical analyses (4, 8). For this reason, it was deemed important to simulate the lab-scale induction heating and to analyse the effect of conductivity by keeping other material properties constant.

Both experimental and numerical studies have been carried out under 65 kHz, 0.55 kV, 15 mm AG and 20 ^{o}C initial material temperature. Since the optimal conductivity corresponds to optimal heating speed, the electrical conductivity levels were between 0.01 to 1 S/m and the value of the asphalt mix with the closest response for 1 S/m was selected as the one with the most realistic heating response according the experimental results. It is necessary to be noted that every single inductive particle within the asphaltic matrix operates as a heating generator under alternating electromagnetic fields, therefore it made the induction analyses a complicated task since the pavement domain was considered as homogeneous.

3.3 Effect of the Moving Induction System on Heating Efficiency

In this third step of the analysis, two single-turn systems were developed with two single-turn coils and its efficiency was compared with the one single-turn coil system. The temperature distribution and the temperature development in the inductive pavement were evaluated for each induction system.

First, the heat pattern and the temperature development in the inductive pavement with moving systems are predicted. The contour plots of temperature developed after 120 seconds of induction heating under different coil velocities and are presented in **Fig. 5** for both one single-turn and two single-turn coil systems with different horizontal distances (HDs) (0.1 m, 0.2 m and 0.3 m). It can be observed that the maximum generated temperature occurs at the top of the pavement and, in particular, these higher temperature areas are close to the coil's gates where the concentration of magnetic fields is higher. This finding clearly demonstrates the problem of considering the inductive asphalt pavement as a homogeneous domain. The homogeneity approach cannot account for the real magnetic field flux distribution to the inductive particles within the heterogeneous asphaltic matrix and subsequently the generated heat due to Joule's law.

The induction heating efficiency reduced with increasing the speed of the system under given operational conditions both for one and two single-turn coil systems. For different TS, the generated temperature at the surface of the pavement changes as function of the speed. When the induction system operates at lower TS, higher temperatures are generated. The number of single-turn coil utilized for induction can influence also the heating pattern on the surface and inside of the pavement. **Table 1** shows the variation of induction heating efficiency (temperature generated after 120 seconds of induction) of the two different systems and the computed results for the temperature development on the surface of inductive asphalt against time and for different HDs are shown in **Fig. 6.i**.

The impact of the HD of two single-turn coils is studied as well. Taking into account the speed effect on heating efficiency, a sensitivity analysis was performed focusing on HDs and TSs. **Table 1** shows the results of this analysis. Typically in a continuously moving induction system the velocity plays the most crucial role to obtain the desired temperature development. Therefore, this is also obvious in this analysis where the highest induction heating efficiency was reached for 0.02 m/s of speed demonstrating a short influence of the distance of two coils.

High levels of heating efficiency not only on the surface of the pavement but also within the structure should be considered essential for the introduction of this technology for assisting various construction and rehabilitation processes in the asphalt paving industry. Another important observation can be found in **Fig. 6.ii**. It shows that higher temperature generated mostly in depth of 0.3 m from the pavement surface. Further from the surface, the temperature becomes constant and doesn't increase anymore. This temperature gradient propagation inside the pavement shows the advantage of induction heating technology as a pavement treatment to ameliorate initiation of the top-down and bottom-up cracking in pavement layers with optimized thicknesses for induction purposes up till 0.3 m depth. Since the higher temperature field generated in this pavement is on a surface layer of thickness less than 0.3 m, this thickness can be treated as the optimized the inductive layer.

In conclusion, modelling of moving induction heating systems provides an excellent tool for the design of prototype machines capable to assist pavement operations with the desired heating profile and TS. Increasing the SP in parallel with reducing the AG gives an increase of induction heating efficiency. For example, **Fig. 7** demonstrates that a system with SP of 4 kV provides a surface temperature of 65 ^{o}C, 68 ^{o}C and 70 ^{o}C for a system moving with a speed of 1 m/s and AG of 0.025 m, 0.015 m and 0.005 m, respectively. For this given set of operational conditions, the highest heating efficiency was obtained mainly by controlling the SP in relation to the moving speed of the system.

4. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the results of the reported study, the three-dimensional FEM induction heating modelling shows great potential to design first induction prototypes of expensive advanced engineering set-ups for lab- and field-scale pavement applications. Important findings of the described research are:

- The first step sensitivity analysis demonstrated the impact of the operational factors for the induction heating efficiency, namely:
    - Supplied power and airgap affected mainly the induction heating efficiency for all the types of single-turn coils.
    - Supplied frequency of the magnetic field showed relatively high influence at AG of 0.05m and little influence at AG of 0.025m.
    - The type of the coil also plays a crucial role for the temperature generation at the surface of an inductive asphalt pavement.
- Analysis of the temperature generation of a homogenous domain which represents a highly complex and heterogeneous material as inductive asphalt concrete is evidently a difficult task. In the second step of this study, the values of electrical conductivity were calibrated by simulating induction heating of a lab-scale induction apparatus and the calibrated values were used for the modelling.
- The studies on moving induction coil systems showed that the travelling speed is a very crucial factor for a quick and reliable induction heating operation on asphalt pavements. Increasing the supplied power, the number of single-turn coils and the horizontal distance between them (HD) resulted in a higher induction heating

efficiency which in turn resulted in a more reliable moving induction system for pavement applications.

Studies on the temperature dependence of the material properties deserve priority for further investigation on the electromagnetic and the heat transfer performance of asphaltic materials. The developed multi-physics model creates an opportunity to apply these analyses in inductive asphalt pavements. A large-scale prototype is required to recalibrate the results of the moving system as described and designed in this paper. This will improve the modelling and will in the end optimize the processes in-situ.

REFERENCES

(1) Greenhouse Gas Emissions (source: EEA)
(2) eurobitume.eu/bitumen/facts-and-stats.
(3) Lupi, S., M. Forzan, A. Aliferov. *Induction and Direct Resistance Heating: Theory and Numerical Modeling*. Springer International Publishing, Switzerland, 2015.
(4) Apostolidis, P., X. Liu, T. Scarpas, M. van de Ven, G. van Bochove. Investigation of Induction Heating in Asphalt Mortar: Numerical Approach. Presented at 95nd Annual Meeting Transportation Research Board, Washington D.C., 2016.
(5) Garcia, A., E. Schlangen, N. van de Ven, Q. Liu. Electrical Conductivity of Asphalt Mortar containing Conductive Fibers and Fillers. *Construction and Building Materials 23*, 2009, pp. 3175-3181.
(6) Garcia, A., E. Schlangen, M. van de Ven, D. van Vliet. Induction Healing of Asphalt Mastic and Porous Asphalt Concrete. *Materials and Structures 44*, 2011, pp. 499-508.
(7) Apostolidis, P., X. Liu, T. Scarpas, G. van Bochove, M. van de Ven. Towards an Experimental Protocol for the Study of Induction Heating in Asphalt Mastics. Presented at 95nd Annual Meeting Transportation Research Board, Washington D.C., 2016.
(8) Apostolidis, P., X. Liu,. T. Scarpas, G. van Bochove, M. van de Ven. Advanced Experimental Evaluation of Asphalt Mortar for Induction Healing Purposes. Presented at 95nd Annual Meeting Transportation Research Board, Washington D.C., 2016.
(9) Liu, Q., E. Schlangen, M. van de Ven. Induction Heating of Electrically Conductive Porous Asphalt Concrete. *Transportation Research Record 2305*, TRB, Washington, D.C.,2012, pp. 95-101.
(10) Garcia, A., E. Schlangen, M. van de Ven, G. van Bochove. Optimization of Composition and Mixing Process of a Self-healing Porous Asphalt. *Construction and Building Materials 30*, 2012, pp. 59-65.
(11) Apostolidis, P., X. Liu, T. Scarpas, M. van de Ven, G. van Bochove. (2016). Evaluation of Chloride Induced Damage in Stone Mastic Asphalt Mixes Suitable for Induction Heating. Proc. Functional Pavement Design - Erkens et al. (Eds.), Taylor & Francis Group, London, ISBN978-1-138-02924-8.
(12) Garcia, A., J. Norambuena-Contreras, M. Bueno, M.N. Partl. Influence of Steel Wool Fibers on the Mechanical, Thermal and Healing Properties of Dense Asphalt Concrete. *Journal of Testing and Evaluation 42*, 5, 2014, pp. 1107-1118.
(13) Garcia, A., M. Bueno, J. Norambuena-Contreras, M.N. Partl. Induction Healing of Dense Asphalt Concrete. *Construction and Building Materials 49*, 2013, pp. 1-7.
(14) Gong, I., R. Hagel, R. Unbehauen. Applying 3-D FEM to Evaluate Induction Heating of a Slab. Presented at 2nd International Conference on Computation in Electromagnetics, 1994, pp. 203-206.
(15) Di Barba, P., A. Savini, F. Dughiero, S. Lupi. Optimal Shape Design of Devices and Systems for Induction-heating: Methodologies and Applications. *International Journal for*

Computation and Mathematics in Electrical and Electronic Engineering 22, 1, 2003, pp. 111-122.
(16) Dughiero, F., M. Forzan, S. Lupi, M. Tasca. Numerical and Experimental Analysis of an Electro-Thermal Coupled Problem for Transverse Flux Induction Heating Equipment. *IEEE Transactions on Magnetics 34,* 5, 1998, pp. 3106-3109.
(17) Boadi, A., Y. Tsuchida, T. Todaka, M. Enokizono. Designing of Suitable Construction of High Frequency Induction Heating Coil by Using Finite-Element Method. *IEEE Transactions on Magnetics 4*, 10, 2005, pp. 4048-4050.

LIST OF TABLES AND FIGURES

TABLE 1 Variation of induction heating efficiency of the two different induction systems at different TS

TS (m/s)	Temperature (degC)			
	One single-turn coil	Two single-turn coils		
		HD: 0,1 m	HD: 0,2 m	HD: 0,3 m
0,02	85,27	128	130,90	141,8
0,04	54,03	76	77,79	80,87
0,06	51,45	61	59,01	61,07
0,08	38,29	49	49,43	50,06
0,1	34,44	43	43,75	45,33

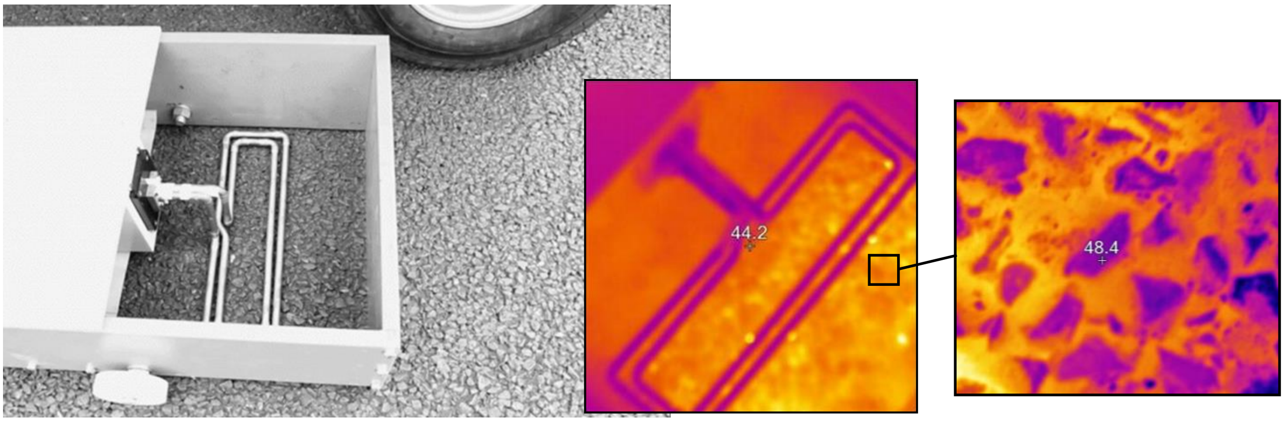


FIGURE 1 Induction heating of motorway A58 in the Netherlands (June 2014)

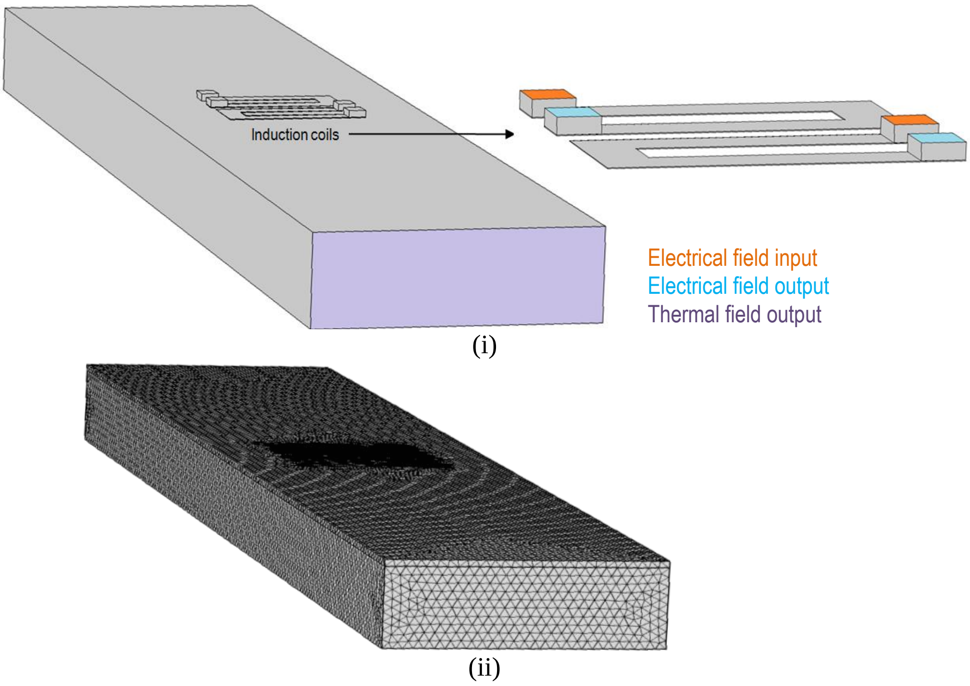


FIGURE 2 (i) Three-dimensional geometry and (ii) mesh of induction heating system

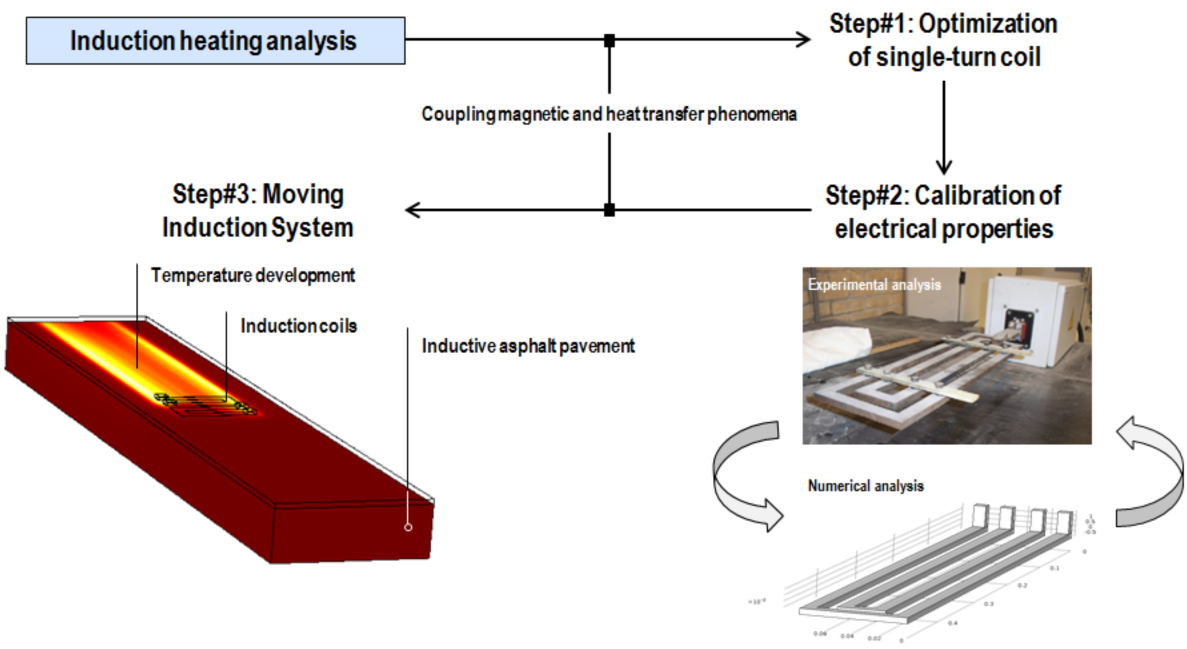
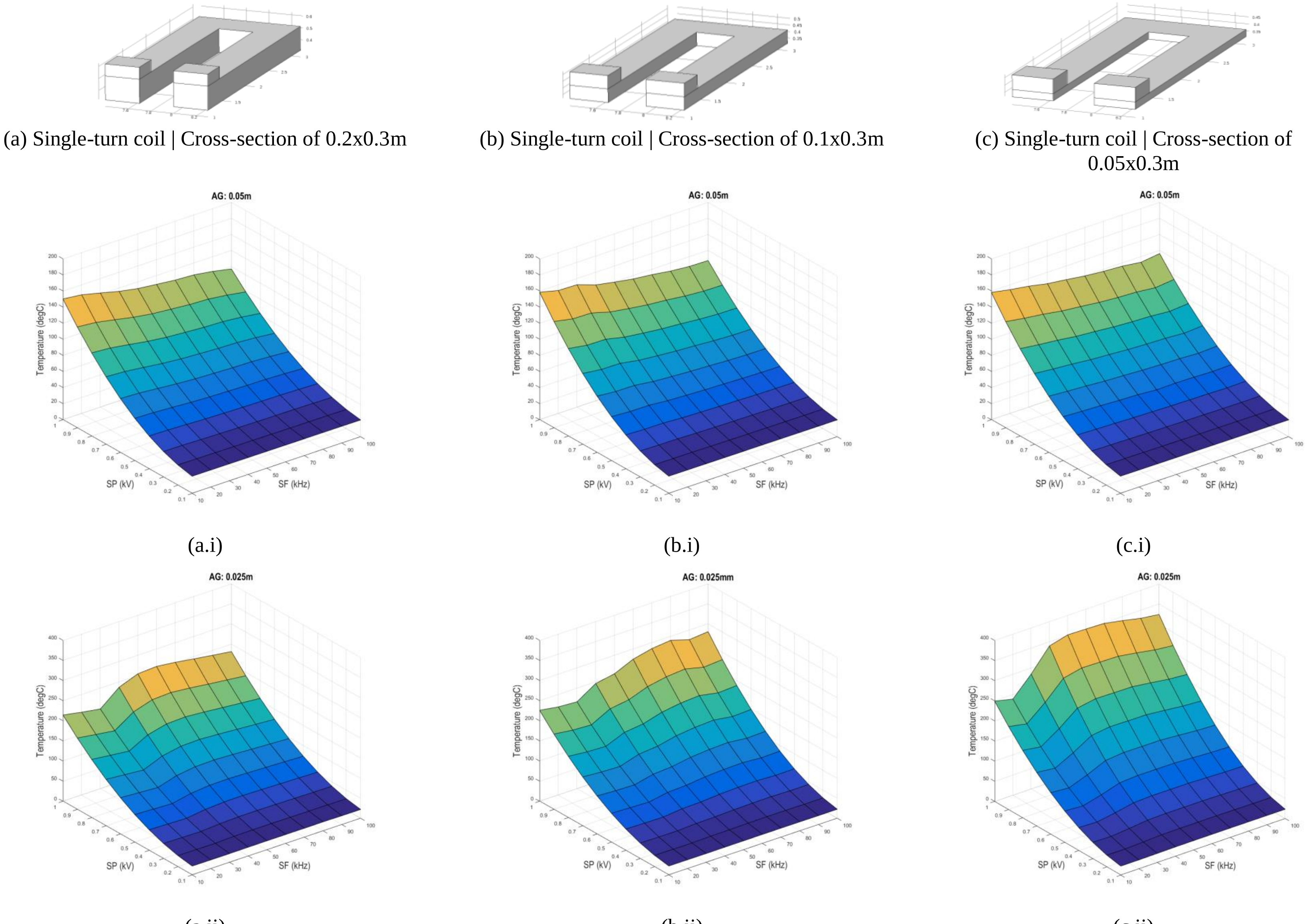


FIGURE 3 Methodology for induction heating analysis



(a) Single-turn coil | Cross-section of 0.2x0.3m

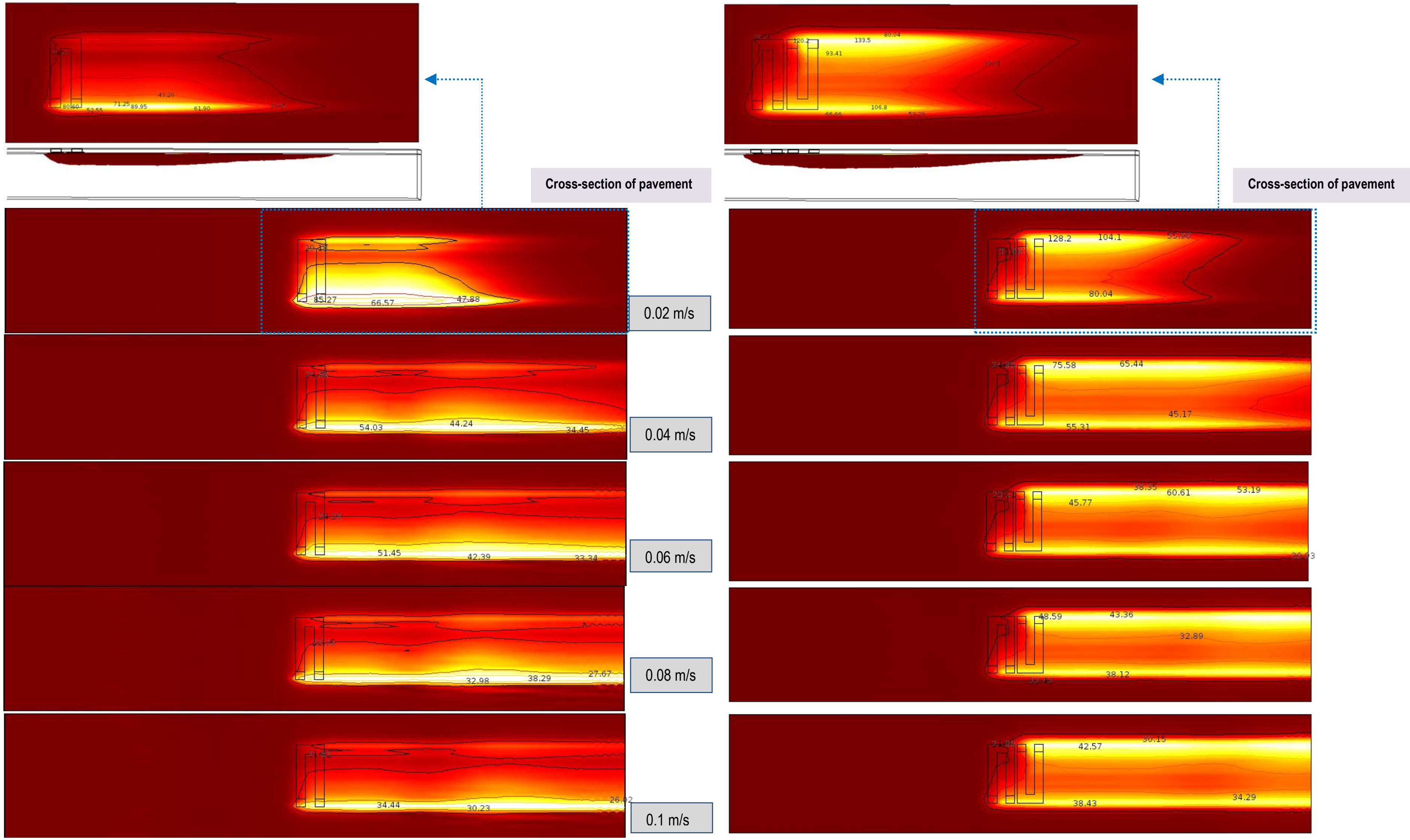
(b) Single-turn coil | Cross-section of 0.1x0.3m

(c) Single-turn coil | Cross-section of 0.05x0.3m

(a.i) (b.i) (c.i)

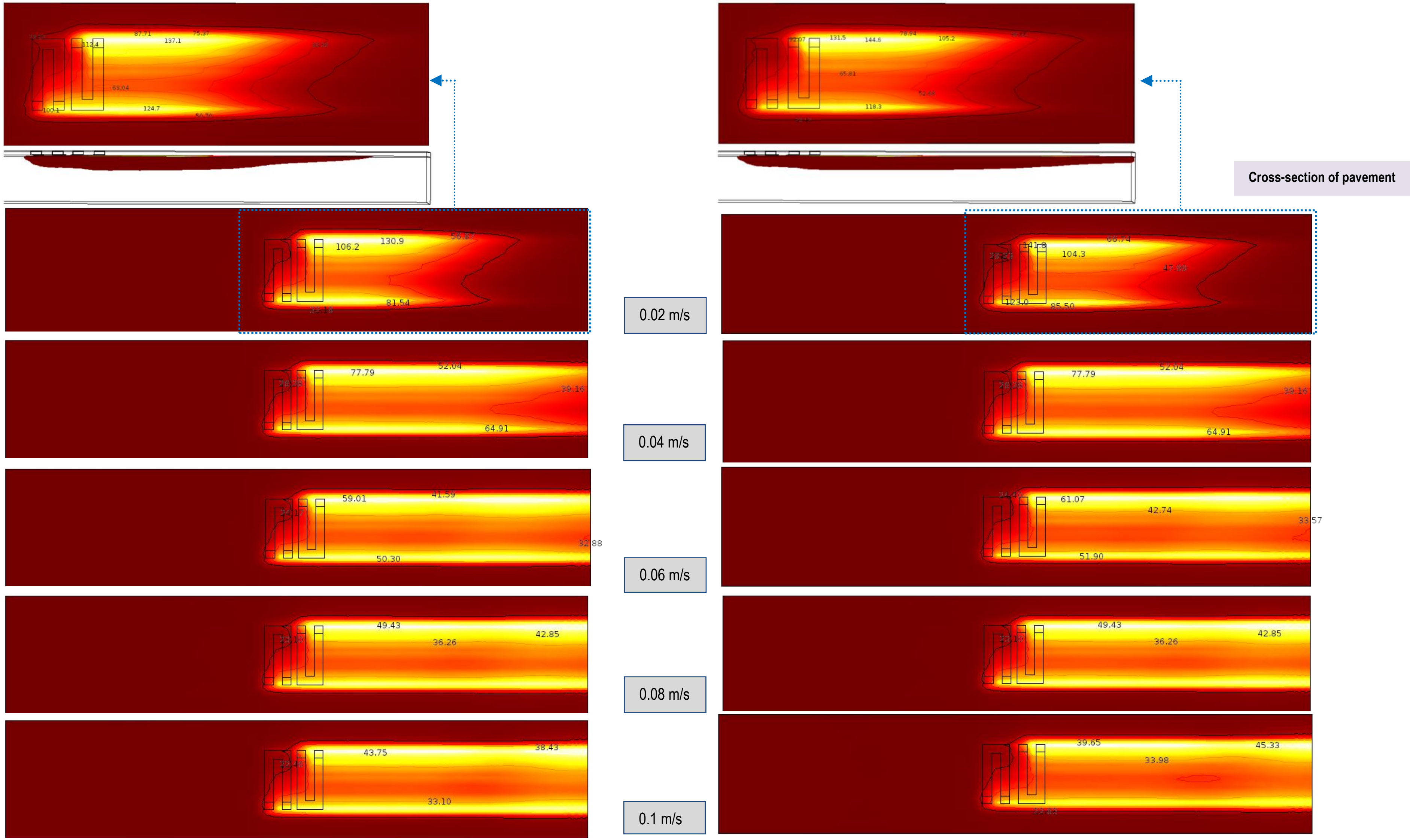
(a.ii) (b.ii) (c.ii)

FIGURE 4 Variation of induction heating efficiency for different types of one single-turn coils



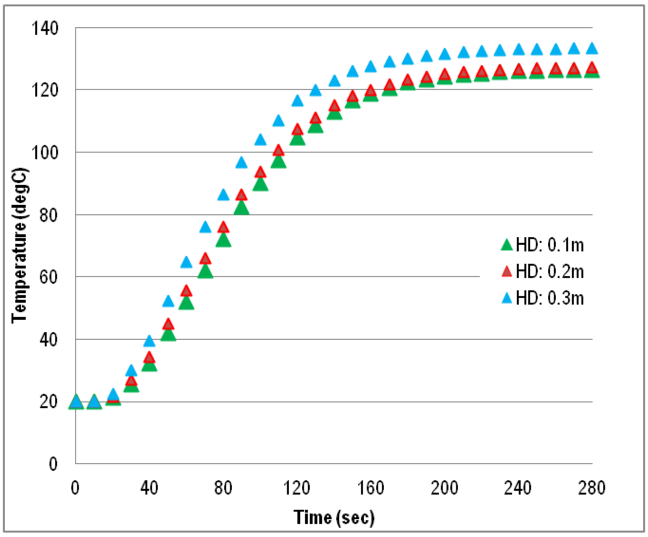
(i) one single-turn coil (ii) two single-turn coils | HD: 0.1 m

FIGURE 5 Thermal field distribution of different induction system at different HD and TS (continue →)

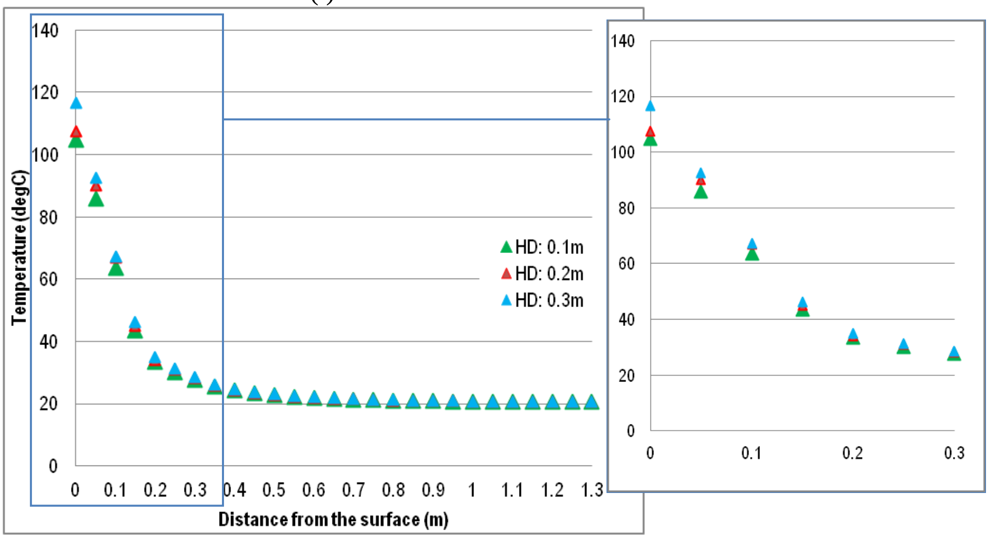


(iii) two single-turn coils | HD: 0.2 m

(iv) two single-turn coils | HD: 0.3 m



(i)



(ii)

FIGURE 6 (i) Surface temperature development of an asphalt pavement and (ii) temperature distribution in asphalt pavement after 120 seconds of induction for different HDs

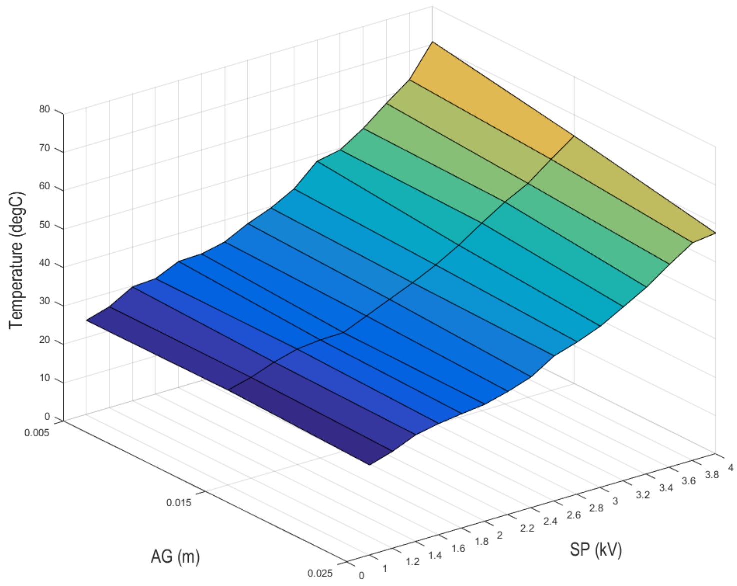


FIGURE 7 Variation of induction heating efficiency of the induction two single-turn coil system, TS: 1 m/s