EXPERIMENTAL AND NUMERICAL INVESTIGATION OF INDUCTION HEATING IN ASPHALT MIXES

THESIS

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by

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Considering the importance of the need of mitigating the energy consumption and the corresponding emission of CO₂, the construction industry is focusing to develop novel materials with enhanced durability and new functionalities. State-of-the-art techniques have been adopted from the infrastructure industry in order to transform construction and maintenance processes to sustainable and eco-friendly.

Asphalt mixture is a material widely used in the construction industry mainly for transportation infrastructure. During hot summers and long resting periods, asphalt mixtures can partially recover their mechanical properties such as strength and stiffness. This inherent property of asphalt mixtures is termed self-healing and has important impact on the service life of asphalt pavements. If the healing process could be sped up, pavements with longer lifespan could be built.

The last few years, a lot of effort has been spent to develop innovative techniques in order to trigger the healing capability of asphalt mixtures. Induction heating is a technique via which asphalt pavements can be heated locally and mechanical properties can be recovered. The approach of using the induction heating technique to speed up the healing process is named induction healing. Induction healing approach requires the development of asphalt mixtures with electrically conductive additives and an electromagnetic source in order to increase the temperature of material.

This thesis is aimed at developing insight into the induction heating technique and how the asphalt mixes at different levels are influenced from the additives. Control of the rheological, electrical, thermal and mechanical properties of asphalt mastic and mortar are among the key research objectives. For this, experimental and numerical methods have been used.
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Introduction and Literature Review

In this Chapter, some research background of induction healing in asphalt mixes and literature review are given. In the end, the research approach together with the methodology of this study are presented. In order to avoid the misunderstanding of the different healing mechanism, in this study, the term of "self-healing" refers to autonomous non-assisted healing and "healing" means assisted healing.
1.1. INTRODUCTION
Self healing of asphalt mixtures is known for many years (1-4) by pavement engineers. It implies that the asphalt pavement is expected to repair itself during hot summers and long rest periods. However, due to traffic on road, self healing does not take place completely in the field condition. For this reason, a lot of research is focusing on the development of new techniques which can assist asphalt pavement to be healed. Both the healing types, non-assisted healing and assisted healing, result to extending the service life of the asphalt pavement (5).

1.2. TECHNIQUES FOR INDUCED ASPHALT HEALING
Recent years, several innovative techniques have been developed in order to trigger the healing capability of asphalt mixtures. Among others, the techniques of healing of asphalt concrete mixture by utilizing of microcapsules and by induction heating are two main techniques that have been reported in this literature review.

1.2.1 HEALING OF ASPHALT CONCRETE BY MEANS OF MICROCAPSULES
The healing concept by means of microcapsules is illustrated in Figure 1.1. It can be seen that the microcapsules filled with a healing agent are embedded in an asphalt concrete mixture. An approaching crack breaks the embedded microcapsules, releasing the healing agent into the crack plane through capillary action and heals it. One of another innovative ideas was incorporating the rejuvenating additives in capsules inside the asphalt mixture (7, 13). When the stress applied on capsules reaches a certain critical value, the capsules break and rejuvenators inside the capsules are released to restore the original properties of the bitumen.

Figure 1.1: Microcapsules concept on asphalt healing
Garcia et al. (7) reported a method of making capsules made of porous stone with the rejuvenator additives embedded inside and surrounded by a hard, impermeable shell. The shell must be able to sustain the stresses imposed during mixing with the aggregate and the high temperature encountered during the mixing process, but they should not be so strong that they would never break when required. The core material used was porous sand with size between 1.0 and 1.7 mm. The sand had a highly porous structure and 87% absorption capacity. Two types of rejuvenator were used, both of which were dense aromatic oils from two different sources. The walls of the capsules were formed of cement bonded by epoxy resin. The process consisted of the following steps:

- The sand was mixed with a rejuvenator and heated up to 105 °C for 1 h.
- A vacuum was used then for 30 min to force the oil to penetrate into the voids in the sand particles.
- The process was repeated twice in order to ensure that air was removed.
- In order to produce the shell, the epoxy resin was mixed with the sand (already now containing the rejuvenator) until all grains were uniformly coated with a layer of epoxy resin.
- The coated sand was added to cement in the presence of steel balls in a container. The cement was bound to the epoxy resin surrounding the sand, so forming a shell around the porous sand.
- The material was then sieved in order to use it in the asphalt mixture as a replacement of material of the same size.
- The fresh capsules were cured for 8 h at 35 °C.
- Epoxy resin was added to cover the capsule surface.
- Capsules were cured for 8 h at room temperature under continuous horizontal movement (400 revolution per minute) in order to avoid cluster formation.

The capsules tendency for breaking when used in a porous asphalt mixture (a commonly used asphalt type in the Netherlands) was checked. Samples of the mixture were prepared using gyratory compactor with specimen diameter of 100 mm, saw cut after compaction to a height of 50 mm and the indirect tensile strength was determined at 5 °C. It was found that 4% of the capsules were destroyed during mixing process and the capsules reduced the stiffness of the asphalt mixture (7).

As a part of the same research at Delft University of Technology, four types of rejuvenators were encapsulated inside porous asphalt, and the performance of the mixtures was evaluated. The release mechanisms of the capsules were investigated. The effect of the capsules on the porous asphalt mixture was examined under the microscope after the asphalt samples were broken in indirect tensile tests (8).

One issue that was not clearly demonstrated in the literature for this technique is the effectiveness of the rejuvenator oil to heal the asphalt pavement at typical pavement service temperatures. Typically, rejuvenators have been used in hot mix recycling. It is known that the extent of rejuvenation achieved is controlled by diffusion kinetics (time and temperature of the
interaction between the bitumen and the rejuvenators). When encapsulation is used as a technique for self-healing, such interaction would happen at ambient (or pavement service) temperature. There was no investigation in the literature on how the rejuvenator additives would react with bitumen at such low temperature. This low temperature would affect the efficiency of the rejuvenator additive to a great extent. Another major issue is how to ensure that the capsules will not break during the construction process, releasing the encapsulated oil into the mixture at early stage and reducing the asphalts’ stiffness and deformation resistance.

1.2.2 HEALING OF ASPHALT CONCRETE BY MEANS OF INDUCTION HEATING

The self-healing rate of asphalt increases rapidly and cracks close much faster at higher temperatures. The main concept in the induction heating technique is the production of asphalt mixtures that can be heated in site using induction energy (8, 9, 13). Local heating inside the mixture by means of induction energy has been used to repair the binder and recover the properties of the mixture. Figure 1.2 shows the basic concept of induction heating as a method to improve mixture healing (13). This method is considered as assisted healing technique, because it needs human interaction to heal the material.

The concept in induction heating is that, when an alternating electrical current is applied across a conductive coil, an alternating magnetic field with the same frequency is created (9). When a magnetically and electrically susceptible material is located within the magnetic field, an electric current will be generated automatically inside the material. Bitumen and aggregate are not electrically conductive materials; however, adding electrically conductive particles to the mixture becomes conductive (6, 9).

Figure 1.2: Induction heating concept on asphalt healing
Conductive asphalt has been defined as the mixture of bitumen, aggregates and additives, such as electrically conductive and magnetically susceptible components (6). Earlier trials were made to make an electrically conductive road for de-icing purposes in 1950s (16). Wu et al. (17) developed electrically conductive asphalt using carbon black, graphite and/or carbon fibre as fillers. The effect of filler type, filler content and mixed fillers on the resistivity of the asphalt were evaluated. However, it was found that increasing the amount of conductive filler caused degradation of the mixture strength and workability.

The increase of electrical conductivity of asphalt mixes is explained based on the percolation threshold theory, by Garcia et al. (7), see Figure 1.3. It can be seen in Figure 1.3 that the transformation of an asphalt mix to a material with high electrical conductivity is a process divided in four phases, the insulated phase, the transition phase, the conductive phase and excess of fibers phase. As it can been seen, in the beginning of adding steel fibers, these are well distributed but remain isolated from each other and it is difficult to let electrons flow within the mass of the mix. If more fibers are mixed with the traditional constituents of asphalt mixes, the conductivity increases significantly because more conductive paths are formed. Further adding more fibre, it did not improve the electrical conductivity of the asphalt mixes.

Figure 1.3: Volume resistivity versus volume content of steel fiber schematic (left) and volume resistivity experiments (right) (6)

The electrical conductivity of asphalt mortar (asphalt binder, sand and mineral filler) containing graphite and steel wool was evaluated by Garcia et al. (6) and an optimum volume of conductive additives were determined, see Figure 1.4.a. Also it was found that it is more effective to reach the target conductivity with conductive fibres rather than with conductive fillers. In case of adding steel fibers, when the fibre content exceeds the optimum value, clusters of fibres start to appear in the mixture; smaller amounts of fibre may not be effective with the mixture being non-conductivity. Moreover, it was found that the sand–bitumen ratio is a key factor in the design of the conductive
asphalt mixes, see Figure 1.4.b, where an optimum volume of conductive fibre exists for each sand-bitumen ratio.

![Graph](image1.png)

![Graph](image2.png)

Figure 1.4: Volume resistivity versus conductive particles-bitumen ratio for asphalt mortar system (left) and volume resistivity for various sand-bitumen ratios and different percentages of steel fibers (right) (6)

Previous research indicated that asphalt mortar with conductive additives can be heated in a very short time by using the induction heating technology (9). Samples with different sand/bitumen ratios, different contents of steel wool fibre and/or graphite were heated for different times. The relationship between heating time, sand/bitumen ratio and temperature at different ratios of fibre and/or filler were demonstrated in Figure 1.5. It was found that there is an optimum ratio of sand/bitumen, above which the heating rate does not increase (9).

Liu et al. (14) prepared electrically conductive porous asphalt by adding steel fibres and steel wool to asphalt mixtures. The effect of volume content of the steel fibres and steel wool on the indirect tensile strength, electrical conductivity and heating rate of porous asphalt were investigated. It was proven that porous asphalt mixtures containing steel wool were easily heated by induction heating. It was reported that porous asphalt containing long steel wool with small diameter had better conductivity than short steel fibres with a greater diameter. Steel fibres with a short length and large diameter had a better reinforcing effect on the mixture than steel wool. 10% by volume of bitumen of steel wool was proposed as an optimal content in porous asphalt to obtain good conductivity, high induction heating rate without reducing the indirect tensile strength.

The first field section with conductive asphalt was constructed in the Netherlands in 2010. Laboratory trials were conducted to optimise the design of the asphalt mixture (10). Conductive fibres (steel wool) were added to the mixture at three levels (2%, 4% and 6%). The fibres were chopped and had diameters of between 0.0088 mm and 0.0127 mm. Indirect tensile strength tests indicated that the volume of fibres did not increase the mechanical resistance of the asphalt mixtures. Different proportions of steel wool at different mixing times were evaluated to define the possibility of fibre cluster formation in the mixture. This was done both in the laboratory and in the asphalt mixing plant. At 2% steel wool, no clusters appeared in the mixture. In the laboratory, samples containing 6% steel wool fibres had high volumes of clusters and could not be tested for indirect tensile strength. It was found that during the first 1.5 min in the laboratory mixing, fibres
reduced their length more than 70%. Longer mixing times caused shorter fibres and smaller amounts of fibre clusters.

![Graphs showing temperature vs. sand/bitumen ratio for different heating times and proportions.](image)

Figure 1.5: Induction heating efficiency at three different heating times for asphalt mortar with different conductive additive proportions and different sand-bitumen ratios (from the top left to the bottom right): Steel wool content 8.76%, Steel wool content 6.54%, Steel wool content 5.83%, Steel wool content 6.54%+graphite content 14.67% (6)

The outcomes of this first field section were evaluated in 2013 (11), two years after its construction. Experiments were conducted on the drilled field cores to study their mechanical, heating and healing properties and the results coincided with those on the laboratory made samples. The field cores appeared enhanced durability with increased induction heating capacity because of the reinforcement of porous asphalt concrete with steel wool and the improvement in the healing properties.

Garcia et al. (12) evaluated the effect of steel wool on dense graded asphalt mixtures. The evaluated parameters of the fibres included two different lengths, four different proportions and four different diameters (12). The fibre content varied from 0% to 6% by binder volume (approximately 0 to 2% of total mixture weight). The influences of fibres on the air voids content, the electrical and thermal conductivities and the maximum temperature reached after a fixed time of induction heating were evaluated. It was found that steel wool fibres were damaged during the mixing and compaction processes. Increasing the volume of steel wool fibres in the asphalt mixtures can cause an increase in the air voids content in the mixture. The thermal conductivity of dense mixtures was reduced with an increase in the air voids content and was reduced with an
increase in the volume of steel fibres in the mixture. The steel fibre parameters did not affect the thermal conductivity of the asphalt, due to the small volume of fibres used in the mixture. The electrical conductivity of the asphalt increased with the amount of fibres in the mixture. The maximum temperature reached after 1 min of heating was 90 °C. The induction heating rates of the asphalt mixtures were found to be dependent on the volume and diameter of steel wool fibres, and there was no clear relation between the heating rates and either the air voids content, the thermal conductivity or the electrical resistivity of the mixture. It was concluded that the time needed for induction heating for dense graded asphalt mixtures is too high compared to results obtained in the Netherlands with porous asphalt and that a lot of work needed to improve the technique before it becomes practical (12).

Menozzi et al. (15) evaluated the use of induction heating to heal fatigue damaged dense graded asphalt samples. The asphalt mixture samples contained one source of fibre, which was steel with a diameter of between 0.6 to 1.4 mm, that was introduced at 6% by volume of the mixture. The bitumen used was 70/100 penetration grade and the mixture evaluated was a dense graded mixture. Induction heating was found to be suitable for healing the damage up to a certain level (defined by the number of loading cycles in their work). Beyond this level, induction heating could not heal the sample. There is a maximum temperature suitable for healing the asphalt sample. Increasing the temperature during induction heating can degrade the bitumen, which can affect its capacity for healing the mixture.

1.3. **APPROACH AND METHODOLOGY OF THE THESIS**

It is evident that nowadays the transportation infrastructure around the world attracts more and more attention due to increasing growth and environmental impact. Within this framework, the asphalt paving industry is continually exploring technological improvements with the aim to enhance the pavement performance and increase energy efficiency of construction and maintenance processes. In the recent years many green technologies appeared, with the example of induction heating technique to attract more and more attention. This technique could find many applications such as preventive maintenance technique and heating technique during pavement construction.

The objective of the experimental work of this thesis is studying the influence of iron powder as filler-sized additive on the induction heating and healing of asphalt mixes. The main reason of selecting iron powder as conductive additive is to produce induction heated asphalt mixes with well dispersion of additives avoiding in parallel addition of big amounts of steel fibres which leads to clusters and mechanical degradation. It is believed that iron powder will contribute to improve the electro-thermal properties and consequently the induction heating efficiency by supporting all the possible conductive pathways to be reached. A schematic depiction of the conductive asphalt mixture with steel fibers and iron powder is given in Figure 1.6. Moreover, the induction heating technique is investigating by developing numerical models.
This thesis is organized in such a way that allows focusing on problems and issues related to a given material scale. In doing so, it provides an in-depth understanding of all the factors for the development of asphalt mixes at different scales and finally to produce asphalt concrete mixture with improved mechanical properties and capable to be heated with the induction heating technique. Here, the studied asphalt mixture is Stone Mastic Asphalt (SMA) and its composition is given in Table 1.1.

About SMA mixtures, the last years these type of mixtures have been established in the Netherlands as noise-reduction solution on the pavement surface on the local and urban communities. Particularly, these apart from good durability and rutting resistance are characterized with good absorptive properties because of their stone skeleton. However, SMA mixtures need regular maintenance, otherwise the structural and noise reduction performance drop enormously (18). Nowadays, Heijmans proposes a new SMA product for thin noise reduction layers, the SMA Microflex Type B (Table 1.1), which fulfills the Dutch noise reduction standards by decreasing noise up to 2.5 dB (A) and in parallel is suitable for maintenance with the induction heating technique.
Table 1.1: Composition of Stone Mastic Asphalt (Microflex Type B)

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Aggregate weight % retained</th>
<th>Cumulative aggregate weight % retained</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0-5.6</td>
<td>4.20</td>
<td>4.20</td>
<td>42.00</td>
</tr>
<tr>
<td>5.6-4.0</td>
<td>33.30</td>
<td>37.50</td>
<td>333.00</td>
</tr>
<tr>
<td>4.0-2.0</td>
<td>40.00</td>
<td>77.50</td>
<td>400.00</td>
</tr>
<tr>
<td>2.0-0.5</td>
<td>5.10</td>
<td>82.60</td>
<td>51.00</td>
</tr>
<tr>
<td>0.5-0.18</td>
<td>2.00</td>
<td>84.60</td>
<td>20.00</td>
</tr>
<tr>
<td>0.18-0.125</td>
<td>5.50</td>
<td>90.10</td>
<td>55.00</td>
</tr>
<tr>
<td>0.125-0.063</td>
<td>1.40</td>
<td>91.50</td>
<td>14.00</td>
</tr>
<tr>
<td>&lt;0.063</td>
<td>8.50</td>
<td>100.00</td>
<td>85.00</td>
</tr>
</tbody>
</table>

Substituted part of <0.063 is 0%
Iron powder after substitution of <0.063
New <0.063

Bitumen SBS Cariphalte XS (% of Weight of mixture) 6 60.00
(% of Volume of bitumen) 0 0.00

Total weight (g) 1060.00

In this thesis, the theoretical background of induction heating is presented in Chapter 2. The physical properties of the mineral fillers and iron powder are investigated in Chapter 3. The effect of the combination of the iron powder and the conventional mineral fillers on the electro-thermal-mechanical properties of conductive asphalt mastic is examined in Chapter 4. Examination of different combinations of the electrically conductive additives on the induction heating efficiency and the mechanical response of asphalt mortars are presented in Chapter 5. Finally, in Chapter 6, 3D finite element meshes are generated by using X-ray images and utilized for calibration of the model parameters and to perform a more realistic simulation of the asphalt mixture induction healing process. The current thesis structure and the research methodology utilized in this thesis are given Figure 1.7.
Figure 1.7: Outline of the thesis
REFERENCES

Theoretical Background of Induction Heating

Induction heating is a complex phenomenon that combines the electromagnetic and heat transfer theory, and has immediate relationship with the metallurgical properties of materials. This state-of-the-art technique has been proposed to be used as a maintenance method in order to heal asphalt pavements. In the present Chapter, the theoretical background of phenomena behind the induction heating technique is presented.
2.1 INTRODUCTION

Induction heating is a complex phenomenon that combines the electromagnetic and heat transfer theory, and has been applied widely in the metallurgical and semiconductor industry for bonding, hardening or softening of metals or conductive materials (1-3). However, nowadays this technique is used in the pavement industry as a maintenance technique, see Figure 2.1. Due to the fact that timely and efficient maintenance of asphalt road layers is critical, preventive maintenance treatments can extend the life of asphalt pavements at a lower cost than reactive maintenance. Hence, repairing the asphalt pavement via induction heating can provide a quick method for maintenance, without the need for extra construction materials.

It is well known that asphalt mixes are non-conductive materials, but when conductive particles are added, such as steel fibers or iron powder, the electromagnetic properties can be enhanced and mixes become suitable for induction heating. The asphalt mixtures can be heated locally under a time-variable magnetic field. Specifically, when an alternating electric current is applied to an induction coil, a time-variable magnetic field is generated on this. According to Faraday's law, this magnetic field induces currents (eddy currents) in the additives within the mixture, such as steel fibers, and they are heated up based on the principles of the Joule law, see Figure 2.1.c. The generated heat in the additives increases locally the temperature of the asphalt mortar rather than heating the stone aggregates. Through the temperature rise the bitumen is melting, the micro-cracks are healed and the mechanical properties are recovered. This mechanism is known as induction healing of asphalt mixtures.

The rate and the efficiency of heating of the asphalt mix is also dependent on the frequency of the magnetic field, the effective electrical, thermal properties and the magnetic permeability of asphalt mixtures. In the present Chapter, the theoretical background of phenomena behind the induction heating technique is presented (4-10).
Theoretical Background of Induction Heating

2.2 THEORETICAL BACKGROUND

2.2.1 FUNDAMENTALS OF ELECTROMAGNETIC FIELD PHENOMENA

MAXWELL EQUATIONS
Maxwell’s equations describe the electromagnetic field phenomena by involving four different field variables: the electric flux density vector $\mathbf{D}$ [C/m$^2$] or [As/m$^2$], the magnetic flux density vector $\mathbf{B}$ [A/m], the electric field intensity vector $\mathbf{E}$ [V/m] and the magnetic field intensity vector $\mathbf{H}$ [A/m$^2$]. These are given in the following equations 2.1, 2.2, 2.3 and 2.4:
Theoretical Background of Induction Heating

(2.1) which is known as Faraday’s law and describes that the induced currents in the asphalt mixture with conductive additives have the same frequency, but the opposite direction as the supplied electric current by the induction coil.

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

which is known as Ampere’s law in which \( \mathbf{J} \) is the current density. This equation (2.2) describes that the applied alternating electric current on induction coil will produce in its surrounding area an alternating magnetic field with the same frequency as the induction coil current.

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]  \hspace{1cm} (2.2)

which is known as Gauss’s electric field law and \( \rho \) is the free volume charge density [C/m\(^3\)] or [As/m\(^3\)].

\[ \nabla \cdot \mathbf{D} = \rho \]  \hspace{1cm} (2.3)

which is known as Gauss magnetic field law.

The differential equation

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (2.4)

which is known as Gauss magnetic field law.

The differential equation

\[ \nabla \times \mathbf{J} = -\frac{\partial \rho}{\partial t} \]  \hspace{1cm} (2.5)

represents the conservation of charges at any point and it is known as the equation of continuity.

The magnetic field intensity \( \mathbf{H} \) plays the most crucial role on induction heating and depends on the current flowing in the induction coil, the coil geometry and the distance from the coil to the asphalt mix.

**Constitutive Equations of Electromagnetic Field**

The constitutive equations contribute to the connection of field quantities using the parameters of materials in the field propagation. To define the constitutive relationship between the different field vectors, the asphalt mixture’s equations are assumed linear, homogeneous and isotropic, and are added to form the complete system.

The relationship between the electric flux and field intensity is

\[ \mathbf{D} = \varepsilon_0 \varepsilon_r \cdot \mathbf{E} = \varepsilon \cdot \mathbf{E} \]  \hspace{1cm} (2.6)
wherein $\varepsilon$ is the electrical permittivity ([F/m] or [As/m]) of the asphalt mixture with conductive additives. The permittivity is the product of the electrical permittivity of vacuum $\varepsilon_0$ (8.854$\cdot10^{-12}$ As/Vm) and the relative electrical permittivity ($\varepsilon_r$). The last one describes the ability of a material to conduct the electric field better than vacuum or air and it is one for conductive materials.

Similarly with the relationship (2.7), the relation between the magnetic flux and field intensity is

$$\mathbf{B} = \mu_0 \cdot \mu_r \cdot \mathbf{H} = \mu \cdot \mathbf{H}$$ \hspace{0.5cm} (2.7)

where $\mu$ is the magnetic permeability [H/m] or [Vs/A]. The permeability of vacuum is constant with a value $\mu_0$ = $4\pi \cdot 10^{-7}$ Vs/Am. The relative magnetic permeability $\mu_r$ describes the ability of a material to conduct the magnetic flux better than a vacuum or air and has a remarkable impact on all basic induction heating phenomena, coil calculation and computation of electromagnetic field distribution.

Concerning the association of current density with the electric field density, this is expressed as

$$\mathbf{J} = \sigma \cdot \mathbf{E} = \frac{1}{\rho_E} \cdot \mathbf{E}$$ \hspace{0.5cm} (2.8)

in which $\sigma$ is the electrical conductivity [S/m] or [A/Vm] and $\rho_E$ is electrical resistivity [Ωm] or [Vm/A]. The above equation is known as the continuum form of Ohm’s law. If the medium is homogeneous, then

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon}$$ \hspace{0.5cm} (2.9)

Combining the equation of continuity and Ohm’s law,

$$\nabla \cdot \sigma \mathbf{E} + \frac{\partial \rho}{\partial t} = 0$$ \hspace{0.5cm} (2.10)

Therefore,

$$\frac{\partial \rho}{\partial t} + \sigma \frac{\rho}{\varepsilon} = 0$$ \hspace{0.5cm} (2.11)

The charge density of any time is

$$\rho = \rho_0 e^{-\frac{t}{\tau}}$$ \hspace{0.5cm} (2.12)

here $\tau = \frac{\varepsilon}{\sigma}$ is the relaxation time of the medium.
**Boundary Conditions**

Maxwell’s and constitutive equations of the medium describe the vector quantities of the electromagnetic field in space. So the above field equations apply throughout the site, including the interfaces between media propagation.

The relations between the discontinuity exhibited by field quantities and changes in load distribution or streams are called boundary conditions. The boundary conditions due to this discontinuity cannot be extracted from the differential form of Maxwell’s equations while there is no problem with the complete corresponding form. Assume the general case of two materials as shown in Figure 2.2.

It is believed that loads are distributed on the boundary surface with density $\rho$, Cb/m$^2$ and can create surface currents flow. The boundary conditions on the quantities of the electromagnetic field are:

\[
\hat{n} \times (E_1 - E_2) = 0 \quad (2.13)
\]

\[
\hat{n} \times (D_1 - D_2) = \rho \quad (2.14)
\]

\[
\hat{n} \times (H_1 - H_2) = J_s \quad (2.15)
\]

\[
\hat{n} \times (B_1 - B_2) = 0 \quad (2.16)
\]
The theoretical background of Induction Heating

Figure 2.2: Boundary conditions of field vectors (a) tangential components of E and H and (b) perpendicular components of B and D (5)

The boundary conditions can be described in words as:

- Expression 2.13 describes the continuity of tangential component of electric field intensity \( E \) across the interface of medium 1 and 2.
- The perpendicular component of magnetic field intensity \( D \) is discontinuous for a quantity equal to surface load density \( J \) on surface \( S \) (equation 2.14).
- According to the tangential component of magnetic field intensity \( H \) is discontinuous across the interfacing mediums with a quantity of current density \( J \) on surface \( S \) (equation 2.15).
- Expression 2.15 indicates that the perpendicular component of magnetic induction \( B \) is continuous across the interface of medium 1 and 2.

**DIFFUSION EQUATIONS**

The equations of Maxwell represent a system of coupled first-order differential equations and they can be reduced to two second-order equations. These equations with boundary conditions and constitutive relations describe the properties of the electric and magnetic field in media. After taking into consideration the energy and momentum of the electromagnetic field and their interaction in media, see Appendix A&B, the magnetic flux \( B \) can be expressed by a vector potential \( A \) as:
\[ \mathbf{B} = \nabla \times \mathbf{A} \]  \hspace{1cm} (2.16)

wherein \( \mathbf{A} \) is the magnetic vector potential. Based on the Faraday's law from Maxwell's equations

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\frac{\partial}{\partial t} (\nabla \times \mathbf{A}) = -\nabla \times \frac{\partial \mathbf{A}}{\partial t} \]  \hspace{1cm} (2.17)

Otherwise,

\[ \nabla \times (\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t}) = 0 \]  \hspace{1cm} (2.18)

Due to the fact that

\[ \nabla \times (\nabla \varphi) = 0 \]  \hspace{1cm} (2.19)

then,

\[ \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \varphi \]  \hspace{1cm} (2.20)

Multiplication of the electric field with the electrical conductivity \( \sigma \) gives

\[ \mathbf{J} = \sigma \mathbf{E} = -\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla \varphi = -\sigma \frac{\partial \mathbf{A}}{\partial t} + \mathbf{J}_s \]  \hspace{1cm} (2.21)

in which \( \mathbf{J}_s \) is the current density source in the induction coil. Assuming that the simplification of divergence of a curl is zero and the displacement current is negligible in a material with high electrical conductivity

\[ \nabla \times \mathbf{H} = \mathbf{J} \]  \hspace{1cm} (2.22)

Results in

\[ \nabla \times \frac{1}{\mu} \mathbf{B} = \mathbf{J} \]  \hspace{1cm} (2.23)

Substituting equations, the diffusion equation is

\[ \sigma \frac{\partial \mathbf{A}}{\partial t} - \frac{1}{\mu} \nabla^2 \mathbf{A} = \mathbf{J}_s \]  \hspace{1cm} (2.24)
In the case of working with sinusoidal current excitation, and sinusoidal eddy current as well, a time-harmonic electromagnetic field is introduced

\[ i\omega \sigma A - \frac{1}{\mu} \nabla^2 A = J_s \]  

(2.25)

In the electrically conductive asphalt mix is an induced current density denoted by \( J_{\text{eddy}} \). The equation for the asphalt mixture is

\[ i\omega \sigma A - \frac{1}{\mu} \nabla^2 A = 0 \]  

(2.26)

where

\[-i\omega \sigma A = J_{\text{eddy}}\]  

(2.27)

**SKIN EFFECT AND SKIN DEPTH**

The skin effect is the phenomenon of non-uniform current distribution within the asphalt mix cross-section when an alternating current flows through. A time-varying magnetic field is accompanied by a time-varying induced electric field, which in turn creates secondary time-varying currents (eddy currents) and a secondary magnetic field. It is known that the eddy currents produce an opposite magnetic flux to external flux. Here, the total flux is reduced. When the surface is induced by alternating electromagnetic field, the current penetration of current from the surface to bottom of mix is called skin depth and varies because of material properties. The higher electrical conductivity and/or higher the magnetic permeability leads to higher current density on the surface of the asphalt mix.

Taking into account that the asphalt mixes is linear, isotropic, homogeneous and charge free \( (\rho=0) \), the equations of Maxwell can also be reduced to two second order differential equations in electric field intensity vector \( \mathbf{E} \) [V/m] and magnetic field intensity vector \( \mathbf{H} \) [A/m²].

\[ \nabla \times \nabla \times \mathbf{E} = -\mu \frac{\partial (\nabla \times \mathbf{H})}{\partial t} = -\mu \frac{\partial}{\partial t} (\sigma + \varepsilon \frac{\partial}{\partial t}) \mathbf{E} \]  

(2.28)

\[ \nabla \times \nabla \times \mathbf{H} = (\sigma + \varepsilon \frac{\partial}{\partial t}) \nabla \times \mathbf{E} = -\mu \frac{\partial}{\partial t} (\sigma + \varepsilon \frac{\partial}{\partial t}) \mathbf{H} \]  

(2.29)

In practice, the generators produce time harmonic magnetic fields. Hence, the harmonic solutions are assumed and the equation

\[ \nabla \times \nabla \times \mathbf{a} = \nabla (\nabla \cdot \mathbf{a}) - \nabla^2 \mathbf{a} \]  

(2.30)
is utilized with the properties $\nabla \cdot \mathbf{H} = 0$ and $\nabla \cdot \mathbf{E} = 0$. Especially, the above steps lead to second order homogeneous wave equations based on $\frac{\partial \mathbf{E}}{\partial x} \rightarrow -i\omega \mathbf{E}$ and $\frac{\partial^2 \mathbf{E}}{\partial x^2} \rightarrow -\omega \mathbf{E}$

$$\nabla^2 \mathbf{E} - \gamma^2 \mathbf{E} = 0$$  \hspace{1cm} (2.31)

Similarly,

$$\nabla^2 \mathbf{H} - \gamma^2 \mathbf{H} = 0$$  \hspace{1cm} (2.32)

wherein $\gamma^2 = i\omega \mu (\sigma + i\omega \varepsilon)$ and $\gamma$ is the propagation constant of the medium and is defined as

$$\gamma = \alpha + i\beta = i\omega \sqrt{\mu \varepsilon (1 - \frac{i\sigma}{\omega \varepsilon})}$$  \hspace{1cm} (2.33)

where

$$\alpha = \omega \sqrt{\frac{\mu \varepsilon}{2} \left( \sqrt{1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}} - 1 \right)}$$  \hspace{1cm} (2.34)

$$\beta = \omega \sqrt{\frac{\mu \varepsilon}{2} \left( \sqrt{1 + \frac{\sigma^2}{\omega^2 \varepsilon^2}} - 1 \right)}$$  \hspace{1cm} (2.35)

The solution of $\nabla^2 \mathbf{H} - \gamma^2 \mathbf{H} = 0$ is determined after taking into account that it represents a uniform electric wave propagation in the positive $z$-direction

$$E_x(z, t) = \text{Re} \left[ E_0 e^{-a z} e^{-i\beta z} e^{-i\omega t} \right] = E_0 e^{-az} \cos (\omega t - \beta z)$$  \hspace{1cm} (2.36)

The above means that during the travelling of an electric or magnetic wave in a conductive distributed medium, the amplitude of the wave starts to be attenuated exponentially by $e^{-a z}$, with attenuate constant $a$ [Np/m]. Generally speaking, when the electromagnetic waves reach the surface in a conductive medium, a current will start to flow within the surface and decreasing exponentially towards the interior of the material, see Figure 2.3.
For a good conductor ($\sigma >> \varepsilon \omega$)

\[
\gamma = \sqrt{i \mu \omega \sigma} = \frac{1 + i}{\sqrt{2}} \sqrt{\mu \omega \sigma} = (1 + i) \sqrt{\mu \omega f \sigma}
\]  

(2.37)

The skin depth or depth of penetration is denoted as the distance for which the amplitude of a plane wave decreases a factor $e^{-1}=0.368$. Consequently, it becomes

\[
\delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\mu \omega f \sigma}}
\]

(2.38)

The skin depth is inversely proportional to the square root of frequency, permeability and conductivity. Therefore, a good conductor such as copper has low skin depth. Moreover, iron, as a ferromagnetic material and is 7 times less conductive than copper and appears to have nearly 10,000 times greater permeability. This electromagnetic property of iron reduces the skin depth of the material to about 1/38 that of copper. The total current in a conductor is

\[
l = \int_{-\infty}^{0} j dy = \frac{I_s}{a} = \frac{I_s \delta}{\sqrt{2}} e^{-i \frac{\pi}{4}}
\]

(2.39)

In the case of the skin effect, the frequency plays a crucial role and is one of the most important parameters in induction heating applications.

### 2.2.2 Fundamentals of Heat Transfer Phenomena

Heat transfer occurs in three different modes, conduction, convection and radiation. With regards to the heat conduction mode, the constitutive equation of the Fourier law is given by
Theoretical Background of Induction Heating

\[ q_{\text{cond}} = -k \nabla T \]

(2.40)

where \( k \) is the thermal conductivity tensor of the asphalt mix \([\text{W/}(\text{m}\cdot\text{C})]\), \( T \) is the temperature \([\text{C}]\) and \( q_{\text{cond}} \) is the heat flux by conduction.

The heat convection from the surface of the mix to the ambient fluid or gas can be defined by the following equation 2.41

\[ q_{\text{conv}} = h (T_s - T_\infty)^a \]

(2.41)

where \( h \) is the convection surface heat transfer coefficient \([\text{W}/(\text{m}^2\cdot\text{C})]\), \( T_s \) is the surface temperature \([\text{C}]\), \( T_\infty \) is the ambient temperature \([\text{C}]\) and \( q_{\text{conv}} \) is the heat flux density by convection \([\text{W/m}^2]\).

Moreover, heat losses transferred from the hot conductive asphalt mix due to the electromagnetic radiation is known as thermal radiation and is described by equation 2.42

\[ q_{\text{rad}} = \sigma m [(T_s)^4 - (T_\infty)^4] \]

(2.42)

where \( \sigma \) is the Stefan-Boltzmann constant \((\sigma = 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4)\) and \( m \) is the emissivity of the surface.

The temperature distribution in a medium is governed by the heat conduction equation

\[ \rho c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \]

(2.43)

where \( \rho \) is the density, \( c \) is the specific heat capacity, \( k \) is the thermal conductivity and \( Q \) the energy generated in the material per unit volume and time. The scalar material parameters determining the rate of change of temperature are the mass density \( \rho \) and the specific heat capacity \( c \).
REFERENCES


Characterization of Fine Particles: Mineral Fillers and Fine Additives

Conventional asphalt mixes contain asphalt binder, aggregate and mineral fillers, all of which are components with resistivity values between $10^8$ to $10^{12} \, \Omega \mu$ and negligible magnetic characteristics. However, for the development of asphalt mixes with induction healing functions the fine particles (mineral fillers and conductive fines) play a significant role in term of improvement of the thermal, electrical and magnetic properties of mixes. Herein, three types of fines were utilized for making asphalt mixes. The first two are the conventional mineral fillers e.g. a weak limestone (WL) and a produced filler (PR). The PR filler represents the filler particles in aggregates to have (fraction less than <0.063 mm). The third fine is the iron powder (IP). The scope of this Chapter is to study the physical properties of the mineral fillers and iron powder such as their shape, chemical composition, size distribution and density. The effect of the combination of the iron powder and the conventional mineral fillers on the electro-thermo-mechanical properties of conductive asphalt mastic will be examined in Chapter 4.
3.1 **INTRODUCTION**

It is well recognized that mineral fillers play an important role in the properties of mastics and hot-mix asphalt (HMA) mixtures. Better understanding of the effects of fillers on the properties of mastics and HMA mixtures is crucial to good mix design and high performance of HMA mixtures. By adding the electrically conductive filler into asphalt mixtures, it is capable of transforming a nonconductive material to a material with lower electrical resistivity. In this way, asphalt mixes become electrical conductive, dielectric or magnetically susceptible materials.

For the transformation of an insulator to a conductor, graphite powder, carbon black and aluminum chips are widely utilized. Fibers such as steel, carbon fibers and steel wool are another category of additives for the same purpose. Moreover, materials which can be characterized with high magnetic permeability are cobalt, nickel and iron.

In general, fillers in asphalt mixes are fine powders with a particle size distribution in the range of 0-100μm. They can be materials such as calcium carbonate, carbon black, industrial wastes such as fly ash from power stations. Other common fillers include silica, kaolin, mica, cement, feldspar and diatomite.

Fillers in asphalt are used to increase stiffness, reduce rutting (permanent deformation), increase mixture density and decrease the cost of asphalt mixtures. However, more filler in asphalt mixtures can also lead to asphalt pavement cracking or fatigue failure when the asphalt stiffness is increased too much. Too less filler amount can lead to drainage of bitumen from the asphalt mixture (1, 2).

The most frequently used filler in asphalt is limestone (calcium carbonate), which is derived from the consolidation of micro-organism during the formation of the earth’s crust. Limestone is the general term for rocks where calcite, a form of calcium carbonate, is the predominant mineral. Limestone may also contain a proportion of magnesium carbonate, dolomite, silica, clays, iron oxides and organic materials.

Other materials commonly used as fillers in asphalt include Portland Cement and hydrated lime, which have well documented properties with regard to mixture durability and reduced potential for moisture damage in asphalt (3). Additionally, recycled filler in the form of so-called “baghouse” fines is frequently used. The performance of baghouse fines was the subject of several key studies (1, 2) on the behavior of filler in asphalt. Kavussi and Hicks (4) proposed that in order to provide satisfactory properties in the finished asphalt, filler should:

- Not show adverse chemical reactions with bitumen
- Not possess high porous particles which may lead to excessive stiffening through selective adsorption of bitumen
- Contain a dense (well graded) Particle Size Distribution

In this research, three types of fines were utilized for making induction heated asphalt mixes. WL and PR fillers are mineral fines and they have approximately the same mineralogical characteristics, but different physical parameters, such as particle size, shape, specific surface area and density. Moreover, iron powder (IP), which is an alloy of iron and silicon, was used as filler additive. The commercial name of this powder is ferrosilicon (FeSi3.5Cr4.5). Table 3.1 summarizes the
properties of iron powder such as size of grains and chemical composition according to the manufacturer.

<table>
<thead>
<tr>
<th>Powder Grading</th>
<th>Powder composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{10} , [\mu m]$</td>
<td>$D_{50} , [\mu m]$</td>
</tr>
<tr>
<td>7.37</td>
<td>15.96</td>
</tr>
</tbody>
</table>

In the following sections, the physical properties such as the density, shape and specific surface area of the mineral fillers and iron powder are presented.

### 3.2 EXPERIMENTAL METHODS

#### 3.2.1 FINE PARTICLES DENSITY

The particle density of fillers is calculated by using the principle of Archimedes:

$$\rho_{\text{particle}} = \frac{m_{\text{particle}}}{V_{\text{particle}}} \quad (3.1)$$

where $m_{\text{particle}}$ represents the mass of particles and $V_{\text{particle}}$ the volume of particles. For normal asphalt fillers, the range is mostly relatively narrow from 2.65 to 2.75 g/cm$^3$ as most fillers are derived from natural aggregates.

For the purpose of density analysis of fines of mixture, the Ultrapycnometer device at the Department of Geosciences of TU Delft was used with deviation for the results of 0.005% at 27°C. After the determination of the weight and the volume of filler by the Ultrapycnometer, the density was derived as the ratio of weight and volume. The results derived from Ultrapycnometer are presented in Table 3.2.

<table>
<thead>
<tr>
<th>Density [kg/cm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler, weak limestone (WL)</td>
</tr>
<tr>
<td>Filler, produced limestone (PL)</td>
</tr>
<tr>
<td>Iron powder (IP)</td>
</tr>
</tbody>
</table>

It can be observed that the iron powder has a density (7.507 g/cm$^3$) that is less than that expected for pure iron (7.86 g/cm$^3$) since it has oxygen, chromium, silicon and carbon contents, which can reduce the density of the iron powder.
3.2.2 PARTICLES SHAPE

The particle shape of fillers is investigated by using microscopy, due to the small particle sizes. In asphalt filler studies, Scanning Electron Microscopy has been used to investigate the particle shapes of fillers.

Scanning electron microscopy (SEM) is one of the most commonly used techniques in materials science because of its capability to capture excellent resolution images. SEM instrumentation and a schematic of standard SEM set up are shown in Figure 3.1. An electron beam is produced (200 eV-50 keV) and the electrons are deflected by scanning coils in a regular pattern onto the sample surface. Consequently, this rastering area on the sample surface is the main cause of the magnification of the images.

![SEM set-up and operation principle](image)

Figure 3.1: SEM set-up and operation principle: JEOL JsMM 6500F SEM set-up (a) and schematic diagram of SEM (b) [5]

Figure 3.2 shows the images captured by SEM from the fines, fillers WL, PL and iron powder (IP). The shape and texture of different fine particles are illustrated, with the magnification scale set at 2000 times. The study of the microstructure morphology of fines was performed at ambient temperature.
3.2.3 SPECIFIC SURFACE AREA

Surface characteristics of a material refer to the crucial properties of the surface, such as surface area, surface roughness and pore size. The specific surface area represents the ratio of particle’s surface area to its mass. There are different methods for the determination of the specific surface area such as the Particle Size Distribution, the gas adsorption experiments and the calorimetry technique.

One of the techniques for acquiring information concerning the surface areas is the BET (after Brunauer, Emmett and Teller) method. This method is based on the isothermal adsorption of gas molecules on the surface of the fine part. The gas molecules create a monolayer and the specific surface area is measured based on the size and the amount of the adsorbed gas molecules. The advantage of this and all the gas sorption techniques is the accuracy of the measurement. It takes into account the surface texture, shape of particles and the external pores of the surface.

The BET equation is given in the formula:
where $V$ is the volume of gas adsorbed at pressure $p$, $V_{\text{mono}}$ is the volume of gas corresponding to one monolayer, $\varphi$ is the ratio of pressure of gas and pressure at saturation ($\frac{p}{p_s}$) and $c$ is a constant:

$$ c = e^{\left(\frac{E_1-E_L}{RT}\right)} $$  \hspace{1cm} (3.3)

where $E_1$ is the heat of adsorption for the first layer and $E_L$ is the heat for the second and higher layers.

Figure 3.3 shows a plot with vertical axis $\frac{\varphi}{V(1-\varphi)}$ horizontal axis $\varphi$ and slope $A = \frac{(c-1)}{cV_{\text{mono}}}$. The interception $I$ of the vertical axis and the slope $A$ are used to calculate the monolayer adsorbed gas quantity $V_{\text{mono}}$ and the BET constant $c$. These quantities are determined using the following equations 3.4&3.5:

$$ V_{\text{mono}} = \frac{1}{A + I} \hspace{1cm} (3.4) $$

$$ c = 1 + \frac{A}{I} \hspace{1cm} (3.5) $$

Figure 3.3: The BET plot and schematic of adsorption of fine particles

The total surface area $S_{\text{total}}$ and the specific surface area $S_{\text{BET}}$ are given by:
\[ S_{\text{total}} = \frac{V_{\text{mono}} N s}{V} \]  
\[ S_{\text{BET}} = \frac{S_{\text{total}}}{a} \]

where \( V_{\text{mono}} \) is in units of volume which are also the units of the molar volume of the adsorbed gas. \( N \) is Avogadro’s number, \( s \) the adsorption cross section of the adsorbing species, \( V \) the molar volume of the adsorbate gas and \( a \) is the mass of the solid sample or adsorbent.

For the BET specific surface area determination, the analysis was performed with a Gemini VII 2390p analyzer. The three samples were tested twice and the results indicate also the standard error. These samples were dried at a temperature of 105 °C for at least 1 hour and the BET equipment was calibrated using a glass powder standard reference material (Lot:7-30-863-23) with a specific surface area of 5.1 ± 0.3 m^2/gr. The results derived from BET are presented in Table 3.3.

<table>
<thead>
<tr>
<th></th>
<th>Specific surface area (m^2/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler, weak limestone (WL)</td>
<td>10.2650 ± 0.0312</td>
</tr>
<tr>
<td>Filler, produced limestone (PL)</td>
<td>1.9765 ± 0.0055</td>
</tr>
<tr>
<td>Iron powder (IP)</td>
<td>1.0066 ± 0.0056</td>
</tr>
</tbody>
</table>

It is well known that the particle size and the shape can influence mixture properties, including rheological, mechanical, electrical and thermal properties (5-10). Iron powder (IP), in this thesis is used for enhancing the electro-thermal properties of our asphalt mixes, demonstrates small particle size in conjunction with very small surface area (1.0066 m^2/g).
REFERENCES

Experimental Evaluation of Asphalt Mastic for Induction Heating Purposes

The induction heating technique requires the modification of asphalt mixtures with conductive additives, such as steel fibers and iron powder, in order to make possible their heating by means of an alternating electromagnetic field. The generated eddy currents on asphalt mixtures increase locally the temperature and hence the asphalt pavement can be repaired by means of bitumen remelting. In this chapter, the impact of filler-sized particles such as mineral fillers and iron powder with different physical properties and at various concentrations was examined in terms to evaluate the mastics produced for induction heating applications. Iron powder as filler-sized additive improves the electro-thermal properties of asphalt mastics. These properties can be controlled at desired levels when iron powder is added at specific volumetric proportions. Moreover, the workability of the conductive asphalt mastics is maintained by adjusting the concentration of filler-sized particles within the mixtures. The main goal of this part of the research is to study the influence of fine particles on conductive asphalt mastics performance in terms of manufacturing durable asphalt mixes with enhanced induction heating capabilities.
4.1 INTRODUCTION

Today, the rapid growth of transportation infrastructure around the world and the increasing attention to more environmental friendly solutions for the construction and maintenance of pavements lead to the asphalt paving industry to explore novel technological improvements. With the impending European and global regulations on greenhouse gas emissions, fumes and energy conservation, a lot of effort is on developing sustainable asphalt mixes with non-structural properties by integrating new functionalities without losing their durability (1-3). One of these non-structural functionalities is induction self healing. Induction self healing asphalt mixes has been attracted considerable attention as novel materials capable to restore their mechanical properties under induction energy input (4-10).

To study the new asphalt mixtures for induction heating, it is important to have in-depth understanding of the interaction between the conductive additives and other asphalt components. Because of the fact that the improved macroscopic response of an asphalt pavement has a direct link with the durability of the bonding components in the asphalt mixtures, much research is focused on the behavior of asphalt mastics (binder and filler-sized particles, see Figure 4.1) and mortars (binder, filler-sized particles and sand). Particularly, the influence of filler-to-binder interaction on mastic performance (11-12) and the volumetric concentration of different types of fillers (13) are studied at mastic level. On the other hand, asphalt mortars have been studied extensively in (14-15). To develop conductive asphalt mixtures suitable for induction heating, many efforts were concentrated on adding steel fibers as additives to improve the durability of mixtures and to increase the induction heating efficiency. However, mixtures with steel fibers require a strong mixing effort and longer mixing time in order to disperse steel fibers uniformly. Moreover, the longer steel fibers easily produce clusters inside the asphalt mixtures, causing inhomogeneity which will reduce significantly the mechanical response (9, 10). It is very important that the filler-sized conductive particles are well dispersed into the mixture in order to provide sufficient isotropic properties to the materials.

Figure 4.1: Conductive asphalt mastic with main constituents and the related additive
The main objective of this Chapter is experimental investigation of the interaction between induction facilitating additives and the traditional asphalt components. Initially, characterization of mineral filler and the additive is required before the development of asphalt mastics. To study in detail the micro-morphology of different asphalt mastics. Scanning Electron Microscopy (SEM) was utilized. Moreover, the electrical and thermal properties of different mastics are examined by using a digital Multimeter and the CTherm TCi analyzer, respectively. Furthermore, the rheological properties are studied at the linear and non-linear viscoelastic range, by means of time and frequency domain analyses. At the next level of discretization of asphalt mortar, the analyzed asphalt mastics are used as matrix. Steel fibers and sand are added in order to determine the induction heating efficiency of mortars. The framework of the experimental study is illustrated in Figure 4.2.

![Research diagram of investigation](image)

**Figure 4.2: Research diagram of investigation**

### 4.2 Preparation and Composition of Asphalt Mastics

The sequence of adding individual component into the asphalt mastic, the mixing temperature and the mixing time are very important parameters for the preparation of an asphalt mastic. The mixing procedure for the conductive mastics was based on the method outlined by Cooley et al. (16). The preparation procedure before mixing is summarized below:

- Determine the specific gravity of the filler and bitumen.
- Dry filler to constant mass at 105 °C.
- Calculate the mass of bitumen and filler needed.
- Place 0.5 litre of bitumen in an oven at 180 °C.
- Weigh the correct quantity of bitumen and filler.

Addition of iron powder to the mastic affects the volumetric properties by increasing the skeleton structure of asphalt mastic and consequently of the asphalt mixture. For this reason, two methods for mastic addition were explored. The first one is by adding iron powder with replacing an equivalent volumetric amount of mineral fillers and the other one is without replacing the mineral fillers. The compositions of the different conductive asphalt mastics (MA_F()_P()) are given in Table
4.1. The notation MA indicates mastic, F represents filler, P represents iron powder. The values between brackets indicate the corresponding volume of the components. The composition of original asphalt mastics is described by the following relation:

\[ V_{\text{mastic}} = V_{\text{bit}} + V_{\text{f}} \]  \hspace{1cm} (4.1)

where \( V_{\text{f}} \) is the volume of filler and \( V_{\text{bit}} \) is the volume of bitumen.

Table 4.1: Mastic composition by weight without the additives

<table>
<thead>
<tr>
<th>Component</th>
<th>Density (kg/m(^3))</th>
<th>Percentage (% w/w)</th>
<th>Mass (gr)</th>
<th>Cum. Mass (gr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler WL</td>
<td>2781</td>
<td>50.4</td>
<td>50.40</td>
<td>50.40</td>
</tr>
<tr>
<td>Filler PR</td>
<td>2699</td>
<td>7.1</td>
<td>7.10</td>
<td>57.50</td>
</tr>
<tr>
<td>Bitumen SBS Cariphalte XS</td>
<td>1030</td>
<td>42.5</td>
<td>42.50</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Following the mixing process and considering the importance of having repeatable and reliable experimental measurements, polymer modified bitumen SBS was firstly poured into the drum at 180\(^\circ\)C and fillers, mineral filler WL and PR and iron powder IP (7507 kg/m\(^3\)), were placed on the drum and mixed together at 105 \(^\circ\)C.

The concentration of fines in the different mastics, with densities determined by the Helium Pycnometer, is illustrated in Table 4.2 and 4.3.

Table 4.2: Composition of different asphalt mastics, by volume

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [g/cm(^3)]</th>
<th>Filler WL fraction (%) + Filler PR fraction (%)</th>
<th>Powder IP fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA_F100_P0</td>
<td>1.5936</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>MA_F75_P25</td>
<td>1.9565</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>MA_F50_P50</td>
<td>2.2432</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>MA_F25_P75</td>
<td>2.4551</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>MA_F0_P100</td>
<td>2.7955</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>MA_F100_P25</td>
<td>2.3610</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>MA_F100_P50</td>
<td>3.0055</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>

MA: asphalt mastic, F: filler, P: iron powder
Table 4.3: Composition of different asphalt mastics, volume

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density [g/cm³]</th>
<th>Filler WL fraction (%) + Filler PR fraction (%)</th>
<th>Powder IP fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA_F100_P0</td>
<td>1.5936</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>MA_F95_P5</td>
<td>1.6456</td>
<td>95</td>
<td>5</td>
</tr>
<tr>
<td>MA_F90_P10</td>
<td>1.6829</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>MA_F85_P15</td>
<td>1.7301</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>MA_F80_P20</td>
<td>1.8437</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>MA_F75_P25</td>
<td>1.9565</td>
<td>75</td>
<td>25</td>
</tr>
</tbody>
</table>

MA: asphalt mastic, F: filler, P: iron powder

4.3 EXPERIMENTAL METHODS

4.3.1 SEM IMAGING OF ASPHALT MASTICS

Micrographs of the conductive asphalt mastics are captured using a scanning electron microscope (SEM). The micrographs are obtained from a JEOL JSMM 6500F, see Figure 4.3.b, using an electron beam energy of 15 keV and beam current of approx. 100 pA. The backscattered electron image mode (BSE) is selected for the images acquisition.

Aluminum cylinders with a height of 18 mm and a diameter of 31 mm are used as sample-substrates for SEM scanning, see Figure 4.3.a. A thin film of mastic is applied on a glass plate at 140 °C in order to form a very smooth area at one side after which the sample is stored at room temperature for 24 hours. Then, the sample is gently cut and placed on the aluminum cylinders. The study of micro-morphology of conductive asphalt mastic is performed in the environmental mode.

Figure 4.3: (a) Aluminum cylinder and (b) the scanning electron microscope

The study of the microstructural morphology of an asphalt mastic is presented in Figures 4.4 and 4.5. The influence of different additives’ contents as described in Tables 4.2 & 4.3 is investigated. The big grey particles represent the mineral fillers and the brightest parts of the images are the iron powder (IP) which is homogeneously distributed in the bituminous matrix.
Figure 4.4: BSE micrographs of asphalt mastic at two different magnification levels

Figure 4.5: SEM BSE images of asphalt mastics with iron powder
Figure 4.6: SEM BSE images of asphalt mastic systems demonstrating the influence of substitution on the micro-morphology: (1) MA_F100_P0, (2) MA_F100_P25, (3) MA_F100_P50, (4) MA_F75_P25 and (5) MA_F50_P50

By comparing images 3 and 5 in Figure 4.6, it is obvious that the conductive asphalt mastics without substituting the mineral filler - see image 3 - appear to have a surface morphology with less dark space than asphalt mastics produced with substituting mineral filler with iron powder, see image 5. The spacing among the filler-sized particles is reducing with increasing the amount of iron powder without substituting relative volumetric amount of mineral filler, see images 1 to 3. Qualitative observation of conductive asphalt mastics surfaces with SEM shows that the morphology of asphalt mastics after adding iron powder has a direct link with the volumetric concentration of filler-sized particles – iron powder and mineral fillers. It should be noted that the current micro-morphological results agree with the rheological results of conductive asphalt mastics which will be explained in the Frequency Sweep Test subsection of the current Chapter.

4.3.2 **Electrical Properties of Asphalt Mastics**

After mixing the components, the hot conductive asphalt mastic is poured in a silicon-rubber mould to obtain rectangular samples with dimension 125 × 20 × 25 mm. Electrical resistivity is determined with the two-electrode method at room temperature of 20 °C. The specimens are cut at the short ends in order to avoid the problem of binder concentration at the surface and to have better contact with the electrodes. The electrodes are made of copper, placed in the right and left sides of the moulds and with the samples inside the mould the electrical volumetric resistance is measured using a digital Multimeter, see Figure 4.7.
The geometry, the electrical resistivity and the permittivity of the material are the only parameters that influence resistance and capacitance. The potential difference between the electrodes and the total charge of them do not play a role in this material property. Therefore, the electrical resistivity was obtained from the Ohm’s second-law:

\[ \rho = \frac{RS}{L} \]  

where \( \rho \) is the electrical resistivity, measured in \( \Omega \cdot m \), \( L \) is the electrode distance, measured in mm, \( S \) is the electrode conductive area measured in \( \text{mm}^2 \) and \( R \) is the measured resistance, in \( \Omega \).

From the capacitance data, the electrical permittivity is offered from the following equation:

\[ C = \varepsilon_r \varepsilon_0 \frac{S}{L} \]  

where \( \varepsilon_r \) is the relative static permittivity of the material or dielectric constant \( (\varepsilon_r = \varepsilon/\varepsilon_0, \varepsilon_r = 1 \text{ for vacuum}) \), \( \varepsilon_0 \) is the electric constant \( (=8.854 \times 10^{-12} \text{ Fm}^{-1}) \), \( S \) is the electrode conductive area measured in \( \text{mm}^2 \), distance \( L \) between the two electrodes and \( C \) is the measured capacitance, measured in mF.

In the experimental measurements, the electric field was considered constant and the contact resistance between the electrodes and the asphalt mastics was considered zero. The results which are given in the Figure 4.8 are the average of three measurements.

The electrical resistivity decreases with increasing iron powder content with or without replacing an equivalent proportion of mineral filler, see Figure 4.8.a.1 and 4.8.a.2. In Figure 4.8.a.1, a reduction of the electrical resistivity is observed when iron powder is mixed proportionally within the asphalt mastic by substituting mineral filler. Moreover, Figure 4.8.a.2 shows that the resistivity was also reduced after adding extra iron powder into the asphalt mastic matrix. The reason of this decrease of the electrical resistivity can be explained by the percolation threshold theory. The percolation threshold was reached when the shorter conductive pathways were formed by the higher amount of iron powder in the asphalt mastic. The conductive asphalt mastic
MA_F85_P15 represents the mastic at the percolation threshold position and adding more iron powder hardly reduces the electrical resistivity further.

Concerning the electrical permittivity of asphalt mastics – otherwise the ability of material to store electrical energy, this appears increase after adding iron powder. For the mastic MA_F85_P15, the electrical permittivity shows a maximum value, and in case of adding more iron powder no considerable impact was observed.

The conductive asphalt mastics without replacing of mineral fillers with iron powder show a lower electrical resistivity than those developed after replacing, see Figure 4.9.a. This observation happens because the filler-sized particles form a highly density skeleton with very short spacing between the particles when extra iron powder is added in the asphalt mastic. On the other hand, asphalt mastics produced without substitution of mineral fine particles show a higher permittivity than mastics which were developed after substituting part of mineral filler with powder, Figure 4.9.b.

Figure 4.8: Effect of the volume content of fine additives on; (a.1 & a.2) the electrical resistivity and (b.1 & b.2) relative permittivity of asphalt mastics
4.3.3 **THERMAL PROPERTIES OF ASPHALT MASTICS**

Thermal conductivity measurements were performed by using the C-Therm TCi thermal analyzer, see Figure 4.10. The sensor is based on the Modified Transient Plane Source Method (21, 22) to determine the thermal resistivity and effusivity of the material.

The prepared specimen for this test must have a diameter of around 17 mm to cover the entire sensor. The sensor is heated up by a small current and its responses are monitored while in contact with the specimen. The thermal resistivity and effusivity of the specimen were measured and obtained directly from the sensor. From the inverse of the resistivity the thermal conductivity was obtained. Using the effusivity concept other thermal properties such as heat capacity and diffusivity can be derived. The effusivity is given by:

\[
Effusivity = \sqrt{k \cdot \rho \cdot c_p}
\]  

(4.4)

where \(k\) is the thermal conductivity [W/m-K], \(\rho\) is the density [kg/m\(^3\)] and \(c_p\) is the heat capacity [J/kg-K]. The thermal conductivity is defined from Fourier’s law as:

\[
q = -k \cdot \frac{dT}{dx}
\]  

(4.5)

where \(q\) is the heat flux (the amount of thermal energy flowing through a unit area per unit time), \(\frac{dT}{dx}\) is the temperature gradient and \(k\) is the coefficient of thermal conductivity, often called thermal conductivity. Heating, reading and cooling were repeated 6 times per specimen to obtain an average reading.
The thermal conductivity and heat capacity of asphalt mastics produced with and without substituting part of the filler with the iron powder are presented in Figure 4.11.

Figure 4.10: C-Therm TCi – thermal analyzer

Figure 4.11: Effect of the volume content of fine additives on; (a.1&a.2) the thermal conductivity and (b.1&b.2) heat capacity of asphalt mastics
It was found that the thermal conductivity of asphalt mastic increased after adding iron powder. This increasing tendency can be explained by the thermal properties of iron powder which is added into the asphalt mastic. It is known that the thermal conductivity of iron powder is considerably higher than the conductivity of the other asphalt components. Hence the increase of the amount of iron powder leads to an increase of the effective thermal conductivity of the conductive asphalt mastic. This can be seen in Figure 4.11.a.1&a.2 showing that the thermal conductivity of sample MA_F85_P15, which represents the conductive asphalt mastic at the electrical percolation threshold, was 0.56 W/mK is higher than the thermal conductivity of pure asphalt mastic sample MA_F100_P0 which was 0.487 W/mK. On the other hand, Figure 4.11.b.1&b.2 demonstrates a reduction of the heat capacity of asphalt mastics when iron powder is added.

Finally, the produced conductive asphalt mastics without substitution of mineral filler-sized particles had a higher thermal conductivity and lower heat capacity, see Figure 4.12. At higher filler-sized particles concentration, the interaction among the particles is increasing within the asphalt mastics. Thus, the spacing among the particles and the coating role of asphalt binder around the particles reduces having as consequence this thermal observation for the conductive asphalt mastics.

![Graph](image-url)

**Figure 4.12:** Effect of developing asphalt mastics with and without substitution of mineral filler with iron powder on (a) thermal conductivity and (b) heat capacity

### 4.3.4 Rheological Properties of Asphalt Mastics

A Dynamic Shear Rheometer (DSR) was used to evaluate the rheological properties of asphalt mixes in the linear and non-linear range.

#### 4.3.4.1 Stress and Frequency Sweep Test

The stress sweep test was conducted in order to identify the linear viscoelastic range (LVR), which is defined as the level where $G^*$ decreases to 90% of the original $G^*$ value. This is characterized as the 10% stiffness reduction criterion. Afterwards, frequency sweep tests were carried out and the complex modulus and phase angle were obtained. They were used to build-up the master curves of
complex modulus and phase angle for each asphalt mastic system. The theoretical background of the rheological analysis of asphalt mix is presented in Appendix D.

A stress sweep was first conducted to determine the linear viscoelastic limit behavior for bitumen. Analyses were performed from -10 °C to 60 °C with a shear stress range from 0.01 to 10 Pa and at 1 Hz. The complex shear modulus $G^*$ versus stress/strain plot was used to determine the linear viscoelastic region (LVE). The test frequency was run on 8 mm parallel plates with a 2 mm gap for asphalt mastics at all the testing temperatures. The sample was allowed to equilibrate temperature for 10 minutes (within +/- 0.1 °C tolerance).

The linear viscoelastic range (LVR) is demonstrated by the relationship between the complex shear modulus $G^*$ versus shear stress and shear strain. The linear viscoelastic limit was defined as the level where $G^*$ decreases to 90% of the original $G^*$ value. From the data, it can been seen that the linear behavior is evident in the strain window below 0.1 %. Another observation is the remarkable impact of the temperature on the modulus. Figure 4.13 shows that when the temperature increases, the complex modulus decreases enormously. Appendix F contains all the results of amplitude sweep tests for asphalt mastic systems.

![Figure 4.13: Amplitude sweep results of SBS polymer modified bitumen at different temperatures](image)

Before the frequency sweep tests, the stress sweep test was conducted from -10 °C to 60 °C with a shear stress range from 0.01 to 10 Pa and at 1 Hz in order to identify the linear viscoelastic range (LVR). The LVR is characterized as the 10% stiffness reduction criterion and was used to filter the linear and non-linear viscoelastic region. Afterwards, the frequency sweep test was carried out over a temperature range from -10 °C to 60 °C. At a reference temperature of 30 °C, the master curves as given in Figure 4.14 show the rheological behavior for all the conductive asphalt mastics. The test stress sweep and frequency sweep were run on 8 mm parallel plates with a 2 mm gap for asphalt mastics at all the testing temperatures.

It can be observed that the asphalt mastic without adding iron powder is obviously much stiffer than the conductive mastics produced after replacing mineral filler with iron powder. This happens due to the fact that iron powder is spherical and finer particle than the other mineral fillers and is easily rolling under shear stress when is added in the mastic by replacing mineral filler. However,
the asphalt mastics appear to have a higher complex modulus and lower phase angle when iron powder is added without replacing the mineral filler. The reducing visco-elastic properties at higher concentrations of filler-sized particles and when particles are added without substitution are linked with the interaction of particle-particle. Increasing the concentration of filler-sized particles leads to lower the spacing among the particles and asphalt mastics with higher viscosity and higher stiffness are obtained. Consequently, the lower workability of mastic during mixing process is resulted.

Figure 4.14: (a) Complex modulus and (b) phase angle mastercurves for various mastic systems produced with and without substitution part of filler with iron powder
4.3.4.2 **MULTIPLE STRESS CREEP RECOVERY TEST**

The presence of the elastic response of an asphalt mix is defined by determining the percent recovery and non-recoverable compliance of the materials. The non-recoverable creep compliance defines the resistance of bitumen or asphalt mixture to permanent deformation under repeated loading. Permanent deformation is a non-linear phenomenon and therefore linear viscoelastic properties are not likely to correlate with it. Hence, the MSCR test was developed for measuring properties beyond the linear viscoelastic range (18-20). The good correlation between asphalt binder and pavement performance was the reason to adapt this method in pavement engineering (20).

According to AASHTO TP 70-10 (Appendix E), the conductive asphalt mastics are loaded at a constant stress for 1 s and then allowed to recover for 9 s. Ten creep and recovery cycles are run at 0.1 kPa creep stress followed by ten more cycles at 3.2 kPa creep stress. The stress and strain are recorded at least every 0.1 seconds for the creep cycle and at least every 0.45 seconds for the recovery cycle during the test. Multiple stress creep and recovery tests were carried out at 64 °C. The tests were performed with the parallel plate geometry with diameter 25 mm and 1 mm gap. The sample was allowed to equilibrate temperature for 10 minutes (within +/- 0.1 °C tolerance). It should be noticed that the test described above is normally done on pure binders, so the results are only for comparison the different mastics under the given loading conditions.

![Figure 4.15: Schematic representation of MSCR test loading sequence showing only two stress levels (for illustration) (20)](image)

Multiple stress creep and recovery tests were carried out at 64 °C. The tests were performed on parallel plate geometry with diameter 25 mm and 1 mm gap. The sample was allowed to equilibrate temperature for 10 minutes (within +/- 0.1 °C tolerance).

The percentage of recovery and the non-recoverable creep compliance of conductive asphalt mastics were determined at two different stress levels. At low stress level, the percent recovery of the conductive asphalt mastics experienced a slight reduction from 97.5% to 95% for MA_F100_P0 and MA_F0_P100 respectively, see Figure 4.16.a. This slight reduction indicates that the conductive asphalt mastics can recover a lower portion of the total strain at the end of each loading-unloading
cycle for lower load level. Similarly, reduction of the percentage recovery shows the same tendency for the higher stress level for the same mastics. The conductive asphalt mastics demonstrate reduction of the percent recovery both at low and high stress levels when iron powder was added without replacing the amount of mineral filler. Moreover, the non-recoverable compliances of conductive asphalt mastics are illustrated in Figure 4.16.b. It can be observed that significant decrease of the creep compliance is found in case of producing conductive asphalt mastics by adding iron powder (MA_F100_P25). However, conductive asphalt mastics produced by replacing mineral filler appear a significant increase at 0.1 kPa stress level when 25% of iron powder is added. The creep compliance shows similar performance for both low and high stress level like the percent recovery response of mastics.

Figure 4.16: (a) Recovery (%) and (b) non-recoverable creep compliance (kPa⁻¹)
4.4 CONCLUSIONS

The main scope of the part of thesis was to examine the impact of iron powder on electrical, thermal and rheological properties of asphalt mastic. For this reason, various asphalt mastics were produced with different concentrations of fines and the key findings are the followings:

- The increase of the amount of iron powder leads to improve the effective electrical properties of asphalt mastics. These properties appear higher values for mastics produced without substitution of mineral filler.
- The values of thermal conductivity and heat capacity of asphalt mastics increase and reduce respectively when iron powder is added. Particularly, when extra iron powder is added within the asphalt mastics – without replacing part of mineral filler – the mastics have their highest thermal conductivity and lowest heat capacity.
- The workability of the conductive asphalt mastics can be adjusted at any level by controlling the concentration of filler-sized particles within the mixes. However, apart from the volumetric concentration of fines, it also should be taken into account the particle to particle interaction and consequently their shape and size in order to control properly the visco-elastic properties of mastics.
REFERENCES


Asphalt mortar consists of bitumen, filler, and sand, and can be modified by adding induction heating additives. The structure, composition and performance of asphalt mortars with these additives have direct influence on the mechanical and induction heating performance of asphalt mixes and asphalt pavements. The main goal of the current Chapter is to investigate the improved induction heating and healing capacity of asphalt mortar, as a highly desirable engineering property, by means of adding electrically conductive additives (e.g. iron powder and steel fibers). Examination of different combinations of these additives on the induction heating efficiency and the mechanical response of asphalt mortars are presented.
5.1 **INTRODUCTION**

There are various techniques that can be applied to restore the mechanical characteristics of mixtures during their lifespan (1). Induction heating technique is one of these. Previous research indicated that asphalt mixtures, with the addition of conductive additives, such as steel fibers, can be heated in a very short time by using the induction heating technology (7-10). However, the distribution of steel fibers within mixtures appears to have a direct relation with the volumetric and mechanical properties (11-18) of asphalt mixtures and it was observed that the characteristics of steel fibers – diameter and length - are affected by the mixing and compaction processes (19). It is very important to develop conductive asphalt mixtures with well dispersed conductive particles to provide sufficient isotropic properties to the materials. For this reason, filler-sized conductive additives can be added into asphalt mixtures as alternatives to study the influence of different combinations of additives on the mechanical response of asphalt mixtures and the induction heating and healing efficiency and the mechanical response of asphalt mixtures.

During the induction heating, the asphalt mortar of conductive asphalt concrete is heated locally without heating the stone aggregates. For this reason, the asphalt mortar with conductive additives is selected to be studied in this research. The effect of different volumes of steel fibers and iron powder on the electrical and thermal properties is evaluated by using a digital Multimeter and CTherm thermal sensor, respectively. After the electro-thermal investigation, the tensile strength and fatigue performance of conductive asphalt mortars are studied. The induction heating and healing capacity of conductive asphalt mortars is investigated as well. The current experimental study covers the structural and non-structural performance of conductive asphalt mortars which are developed for induction healing purposes and the findings provide a good indication of the impact of additives on these materials.

![Image](image_url)

**Figure 5.1:** Research diagram for the investigation
5.2 Preparation and Composition of Asphalt Mortar

The original asphalt mortar without electrically conductive additives consists of sand (2697 kg/m³), weak limestone (WL) filler (2781 kg/m³), produced limestone (PR) filler (2699 kg/m³) and SBS modified bitumen (1030 kg/m³). The weight percentage of these components in the original asphalt mortar is 33%, 5%, 34% and 28% m/m for mineral filler WL, PR, sand and bitumen, respectively.

For the development of conductive asphalt mortar, iron powder (7507 kg/m³) was added as a filler-sized additive after substituting the equivalent volumetric part of mineral fillers - WL mineral filler and PR mineral filler - in order to avoid volumetric degradation. Steel fibers (7756 kg/m³) are mixed with the other components without replacing any of them added as a volume percentage of bitumen. In this investigation, the conductive asphalt mortars are prepared with different volume percentages of iron powder 5%, 10%, 15%, 20% and 25%) and the amount of steel fiber by volume of bitumen is kept constant (4%). The compositions of the different conductive asphalt mortars (MA_F(P)_P()) are given on Table 5.1. The notation MA indicates asphalt mortar, F represents filler, P represents iron powder. The values in the brackets indicate the corresponding volume of the components.

Table 5.1: Composition of different conductive asphalt mortars

<table>
<thead>
<tr>
<th>Type of Asphalt Mortar</th>
<th>Bitumen (% m/m)</th>
<th>Sand (% m/m)</th>
<th>Mineral filler WL (% m/m)</th>
<th>Mineral filler PR (% m/m)</th>
<th>Iron powder (% m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA_F100_P0</td>
<td>28.00</td>
<td>34.00</td>
<td>33.00</td>
<td>5.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MA_F95_P5</td>
<td>28.00</td>
<td>34.00</td>
<td>31.35</td>
<td>4.75</td>
<td>5.15</td>
</tr>
<tr>
<td>MA_F90_P10</td>
<td>28.00</td>
<td>34.00</td>
<td>29.70</td>
<td>4.50</td>
<td>10.30</td>
</tr>
<tr>
<td>MA_F85_P15</td>
<td>28.00</td>
<td>34.00</td>
<td>28.05</td>
<td>4.25</td>
<td>15.45</td>
</tr>
<tr>
<td>MA_F80_P10</td>
<td>28.00</td>
<td>34.00</td>
<td>26.40</td>
<td>4.00</td>
<td>20.60</td>
</tr>
<tr>
<td>MA_F75_P25</td>
<td>28.00</td>
<td>34.00</td>
<td>24.75</td>
<td>3.75</td>
<td>25.75</td>
</tr>
</tbody>
</table>

MA: asphalt mortar, F: mineral filler, P: iron powder, steel fiber (volume of bitumen): 4%

5.3 Experimental Methods

5.3.1 Electrical Resistivity of Asphalt Mortars

The protocol of electrical resistivity measurements was the same with those in Chapter 4. The change of the electrical resistivity of an asphalt mortar with steel fibers, but without iron powder is shown in Figure 5.2a. The conductive paths formed by steel fibers develop and lead to a gradual decrease of the resistivity above 2% volume of fibers. It is clear that the increase of the volume of steel fibers reduces the resistivity or increases the electrical conductivity of asphalt mortar. The optimum steel fibers content reached when no longer increases the electrical conductivity by adding more than 6.4% of steel fibers. For adding iron powder in the mortars with constant steel fibers content, it was selected asphalt mortar with 4% of steel fibers as a conductive mortar with amount of steel fibers beyond the percolation threshold.
The combination of steel fibers and iron powder further improves considerably the electrical conductivity of the asphalt mortar, see Figure 5.2. It can be seen that, by choosing asphalt mortar with 4% of steel fibers and adding the iron powder stepwise in parallel with the reduction of mineral filler, the replacement of mineral filler with iron powder decreases the electrical resistivity of the asphalt mortar further. The optimum combination of additives in the asphalt mortar is 4% of steel fibers and 15% of iron powder. This combination leads to a shorter conductive pathway in the mortar and hence the electrical resistivity of the asphalt mortar decreases significantly. This volume combination of steel fiber and iron powder will be used for the further steps of this research.

Figure 5.2: Effect of (a) the volume content of steel fibers and of (b) iron powder after substituting mineral filler with iron on the electrical resistivity of asphalt mortars

5.3.2 THERMAL PROPERTIES OF ASPHALT MORTARS

The protocol of thermal properties measurements was the same with those in Chapter 4. For composite materials such as asphalt mixtures, the thermal properties can be determined by the properties, dispersion and proportion of individual components in the final mix. By increasing the proportion of a component in the mix, the thermal properties of the final mix can be increased or decreased depending on the type and the nature of the component. An asphalt mixture can be considered as a combination of the components mortar and stone fraction. In this study, TCI Therm Analyzed was used to examine the thermal conductivity of the conductive asphalt mortars.

It is observed that adding steel fibers to the asphalt mortar leads to increase of thermal properties, see Figure 5.3. Because of the thermal properties of steel fiber is quite high, when the volumetric part of steel fibers into the asphalt mortar is increased or decreased, the thermal properties of the whole mix will increase or decrease respectively.
5.3.3 **DIRECT TENSILE STRENGTH AND FATIGUE PERFORMANCE OF ASPHALT MORTARS**

The asphalt mortar is the first decentralized system of an asphalt mixture and represents the matrix of the asphalt mixture between the aggregates. This implies that the mechanical behaviour of the mortar has a direct effect on the behaviour of the asphalt mixture on pavements. In order to investigate the impact of conductive additives on the mechanical properties of the asphalt mortar, direct monotonic and cyclic tensile tests are carried out. The theoretical background of these types of tests is given in Appendix G.

Now the alignment of the set-up and localization of material failure is important to measuring and understanding the mechanical response and for this reason special design was needed, see Appendix H. The tension tests with freely rotating hinges are performed on specimens from conductive asphalt mortar, see Figure 5.4.b. In order to reduce undesired eccentricities, the specimens were carefully positioned in the special designed steel hinges, see Figure 5.4.b.1. Furthermore, the conductive asphalt mortar specimens have a parabolic geometry, with height of 34 mm for the parabolic part and a thickness of 10 mm in the middle. The monotonic tension tests were performed at different displacement rates. The fatigue performance is tested in load control mode. All tests are carried out at a constant temperature of -10 °C. A 25 kN electro-hydraulic servo testing machine is used, see Figure 5.4.a. The total results of these tests are given in Appendix I.

![Figure 5.3: Effect of the volume content of steel fibers on (a) the thermal conductivity and (b) heat capacity of asphalt mortar with and without substituting mineral filler with additives](image-url)
The typical stress-strain curves at low temperatures (-10°C) and at different displacement rates are presented in Figures 5.5. It is obvious that the amount of steel fibres influences the maximum tensile stress. The tensile strength of the asphalt mortar increases with increasing fibre content. Therefore, the reinforcing effect of fibres on the asphalt mortar is apparent in Figure 5.6, where the average values of the maximum tensile stresses are presented.

The effect on brittleness and ductility of the conductive asphalt mortar can be observed in Figure 5.5. At high displacement rates, all samples show brittle response. More ductility can be observed for lower fiber contents and lower displacement rate. Particularly, the replacement of the part of mineral filler with iron powder, it did not influence significantly on the tensile strength of the asphalt mortar and the reinforcing effect of the steel fibers.
In order to study the fatigue response of asphalt mortar with different combinations of conductive additives, the cyclic sinusoidal load is utilized. The magnitude of the loading is defined as the 40%...
of the ultimate tensile strength (0.3 kN). The loading frequency was 5 Hz. and all the tests were carried out at -10 °C.

It can be observed that all the asphalt mortar samples show the tertiary phase of deformation after certain loading time, see Figures 5.7.a and 5.7.b. Particularly, by increasing the amount of steel fibers within the asphalt mortar from 0% to 4%, the tertiary phase is significantly delayed and the fatigue life increases. Moreover, the fatigue life is extended when steel fibers were added from 4% to 6% within the asphalt mortar. It can be seen that the asphalt mortar with 15 % of iron powder appear slightly higher fatigue life than the one without iron powder, see Figure 5.7.c.

![Figure 5.7: Influence of steel fibres on fatigue performance of asphalt mortars (a) with and (b) without iron powder, and (c) the total graph with the fatigue life of different mortars](image)

### 5.3.4 INDUCTION HEATING EFFICIENCY OF ASPHALT MORTARS

The asphalt mixes are characterized as non-conductive materials, but when conductive particles are added, such as steel fibers and/or iron powder, their electromagnetic properties are enhanced. Consequently, these new conductive asphalt mixes can be heated up with a RF generator (Figure 5.8) under 550 V and at a maximum frequency of 63.5 kHz. The distance from the mortar sample...
 Experimental Evaluation of Asphalt Mortar for Induction Healing Purposes

(125 × 20 × 25 mm) to the coil was 10 mm and the data were obtained from the surface of the specimen by using an infrared (IR) thermometer.

Figure 5.8: Induction heating machine used at laboratory

In order to investigate the induction heating efficiency of the conductive asphalt mortar, at ambient temperature (20 °C), the test samples were heated for 120 seconds by inductor. The test samples were mixed with different volumetric combinations of steel fibers and iron powder. Figure 5.9 shows that the average temperature at the top surface of samples at 120 seconds induction heating. It can be observed that the maximum surface temperature is related to the volume of steel fibers added in the asphalt mortar. The higher amount of fibers in the mortar sample led to the higher surface temperature and hence the higher induction heating efficiency of the asphalt mortar. However, the tendency of increasing heating efficiency of the mortar is not linear increase. For example, after 6% of fibers added in the mortar, the tendency of increasing temperature is not significant and it is stabilized. It means that the mortars achieve the induction heating saturation limit where all the conductive paths are linked.

Similar observation can be found for the samples mixed with both iron powder and steel fibers. It can be seen that the induction heating efficiency can be enhanced by combination of iron powder and steel fibers into the asphalt mortar. The average surface temperature of the samples with 15% iron powder is higher than the samples without powder.
5.3.5 **INDUCTION HEALING OF ASPHALT MORTARS**

In order to determine the healing efficiency of an asphalt mortar after induction heating, asphalt mortar beams are used with specific dimensions and a notch at the middle. A similar experimental procedure as proposed by Liu et al (9) was selected to test the healing capacity of the asphalt mortar. The sample is placed in a chamber at -10 °C and is broken into two pieces. The two pieces are then placed back into the mould. At the final stage, the two pieces are heated via induction energy until the surface temperature reaches 120 °C. This process is continued after resting the sample for 2 hours at 20 °C, see Figure 5.10. Moreover, this process is repeated until the accumulated damage is too high to continue the healing process (9). Concerning the temperature, -10 °C was chosen in order to avoid permanent deformation of the material and to obtain a brittle fractured surface. For the induction healing analysis, 5 samples were used for each type of conductive mortar.

The induction healing performance is evaluated by using the relation given in equation 5.1:

\[ S(t) = \frac{F_i}{F_0} \]  

(5.1)

where \( F_0 \) is the fracture force of the sample during a three point bending test, and \( F_i \) is the fracture force after the induction heating.
The induction healing efficiency of asphalt mortar with steel fibers is presented in Figure 5.11.a. Apparently, after the first intrinsic healing with induction energy, the strength reduces approximately 40% of its original strength. The fracture-healing process was continued in successive cycles, in total six, and for the third and fourth cycles the strength recovery was maintained approximately to 60% of the initial strength. In the fifth cycle, the material lost completely its strength.

Additionally, the combination of steel fibers and iron powder in asphalt mortar provides sufficient induction healing capacity, similar with mortar with only fibers, see Figure 5.11.b. For the induction healing analysis 5 samples were used for each mortar system.
5.4 CONCLUSIONS

In this Chapter, the micro-structural and micro-morphological study was developed for different induction additives of asphalt mortars. Electrical and thermal properties of mortars as influential factors of induction heating efficiency were observed, simultaneously with induction heating and induction healing of different combinations of steel fibers and iron powder. The conclusions at this level of novel asphalt mixes are the followings:

1. The increase of conductive additives (e.g. iron powder and/or steel fibers) contributes to the enhancement of the electrical and thermal conductivity of asphalt mortar. The utilization of steel fibers has significant improvement on the electrical conductivity of asphalt mortar than the one with iron powder. Moreover, combining steel fibers and iron powder within the asphalt mortar, the thermal conductivity is slightly higher than using only steel fibers as conductive additives.

Figure 5. 11: Representative stress-strain curves for asphalt mortar system containing 4\% of steel fibers (MA_F100_P0+4\%of fibers) and (b) strength evolution after 6 fracture-healing cycles for two asphalt mortar systems containing steel fibers and steel fibers with iron powder.
2. When steel fibers are added in the asphalt mortar, the tensile strength is improved and the fatigue life is extended. Similar mechanical response is obvious also by combining iron powder and steel fibers.

3. The induction heating efficiency is increased when iron powder and steel fibers are added to a certain limit, where the temperature does not increase anymore, independently. Apart from the highest induction heating efficiency, asphalt mortars have similar induction healing capacity with mortars with steel fibers when iron powder is mixed.
REFERENCES


Numerical Evaluation of Electro-Thermal Properties and Induction Heating of Asphalt Mixes

The research of this Chapter focuses on utilization of advanced finite-element analyses (COMSOL) for the design and assessment of the induction heating capacity of asphalt mixture by adding electrically conductive additives (e.g. steel fibers), and to understand the factors that influence the mechanisms of induction heating in asphalt mixtures. In order to determine numerically the effective electrical and thermal properties of the conductive asphalt mortar with different volumes of steel fibers, 3D finite element meshes were generated by using X-ray images and utilized for calibration of the model parameters to perform a more realistic simulation of the asphalt mixture induction healing process. The findings of this research show that it is possible to optimize the development of the necessary tools and equipment needed for the implementation of the induction technology for healing asphalt mixes.
6.1. **INTRODUCTION**

Recently, several efforts were made to develop innovative techniques to accelerate the healing capability of asphalt mixtures (1-5). It has been shown that the induction heating of asphalt mixtures can significantly improve the mechanical performance of material by healing of the micro-cracks and preventing the formation of macro-cracks. However, more data is still required to clarify the role and the significance of the various parameters on the asphalt heating phenomenon.

Induction heating is a complex phenomenon that combines the electromagnetic and heat transfer theory, and has a strong relationship with the electro-magneto-thermal properties of materials (6-8). The necessity of experimental and numerical analysis of electro-magneto-thermo-mechanical properties of asphalt mixtures is becoming very important in terms to determine the most crucial material parameters for obtaining enhanced durability, simultaneously with high induction heating rate.

In order to evaluate the effective electrical and thermal properties of asphalt mortars on induction heating, the 3D finite element meshes of asphalt mortars with different volumes of steel fibers are generated by using X-ray scans. After the numerical determination of important induction parameters of the conductive asphalt mortar, a finite element 3D model of electromagnetic phenomena coupled with heat transfer physics is developed. This model can be used to perform a more realistic simulation of asphalt mixture induction healing process. Moreover, in the numerical simulations, both static and moving induction heating source have been utilized for modeling of the induction heating in the conductive asphalt mortar. The findings of this chapter will provide a guideline for the development of the necessary tools and equipment that will enable the implementation of induction technology for healing asphalt concrete mixtures.

6.2. **NUMERICAL EVALUATION OF ELECTRO-THERMAL PROPERTIES**

**GENERATION OF THE MICROSTRUCTURAL MESHES IN 3D**

Previous research (2, 5) indicated that, by adding electrically conductive additives (e.g. steel fibers), an asphalt mixture can be heated up in a very short time by using the induction heating technology. In order to simulate the effective electrical and thermal properties of conductive asphalt mixtures, the 3D finite element meshes of conductive asphalt mortars - as a representative of the asphalt mixtures without stone aggregates - with different volumes of steel fibers are generated by using High-resolution X-ray CT (Computed Tomography) images.

The High-resolution X-ray CT is a completely nondestructive technique for visualizing features in the interior of opaque solid objects, and for obtaining digital information on their 3-D geometries and properties. By the X-ray CT technology, the different densities of individual components (e.g. sand, filler, air voids and bitumen) in the asphalt mortar can be distinguished by the gray levels in a CT slice.

SIMPLEWARE software was utilized to comprehensively process 3D image data and to generate volume and surface meshes from the image data (9). Meshes can be directly imported into the COMSOL Multiphysics finite-element software for the electrical and thermal conductivity analyses. The process of reconstruction of 3D images of conductive asphalt mortars is illustrated in Figure
6.1. The 3D images of the asphalt mortar with different steel fibers contents are presented in Figure 6.2.

![Diagram](image)

Figure 6.1: Overview of 3D image data post processing

![Images](image)

Figure 6.2: Reconstructed images after segmenting the NanoCT-scans for the conductive asphalt mortars with different steel fibers content; (a) 3.4 %, (b) 4.7 %, (c) 5.2 %, (d) 6.8 % and (e) 13.3 % of steel fibers

**INPUT PARAMETERS**

For the determination of electro-thermal properties of the conductive asphalt mortar, it is necessary to predefine the properties of individual components in the asphalt mortar. Therefore, in this investigation, the magnitudes of the electrical and thermal conductivity of the bitumen, mineral filler and sand were assumed to be 9e-5 S/m and 0.487 W/(m·K) respectively and for steel fiber
20e+3 S/m and 16 W/(m·k) (16). The effective electrical and thermal conductivities of the conductive asphalt mortar with different volume fractions of fiber are determined numerically.

**RESULTS**

The numerical results in Figure 6.3 indicate that the electrical conductivity of the asphalt mortar increased with increasing the content of steel fiber. As it can be noticed, the electrical conductivity of the asphalt mortar increases rapidly when the volume fraction of the steel fiber is close to 6%. The reason of this dramatic increase of the electrical conductivity can be explained by the percolation threshold theory. The percolation threshold is reached when the shorter conductive pathways are formed by the higher amount of steel fibers in the asphalt mortar. This can be seen in Figure 6.4 where the electrical potential distribution is different between asphalt mortars with different amounts of steel fibers (3.4% and 6.8% of steel fibers). Similarly, it can be observed that, with the stepwise increase of steel fibers in the asphalt mortar, the effective thermal conductivity of the conductive asphalt mortar is increased from 0.71 W/(m·K) to 1.58 W/(m·K). This happened because the thermal conductivity of steel fibers is higher than the other components in the asphalt mortar.

![Figure 6.3](image1)

**Figure 6.3:** Numerically determined effective (a) electrical and (b) thermal conductivity of different asphalt mortars
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Numerical Evaluation of Electro-Thermal Properties and Induction Heating of Asphalt Mortar

Figure 6.4: Representative images of resulted electrical potential in conductive mortar: 3.4\% of steel fibers (left), 6.8 \% of steel fibers (right)

6.3. **NUMERICAL EVALUATION OF 3D HEATING WITH STATIC SOURCE**

A finite element COMSOL Multiphysics software (13, 14), which can simulate electro-magnetic and thermo-mechanical phenomena in a real time domain, has been utilized for modelling of the induction heating in the conductive asphalt mortar.

The electromagnetic field is modeled by means of the magnetic field intensity vector $\mathbf{A}$ [A/m$^2$] and the magnetic flux density vector $\mathbf{B}$ [A/m] as shown in equation 6.1

$$
(j \omega - \omega^2 \varepsilon_0 \varepsilon_r) \mathbf{A} + \nabla \times \left( \frac{1}{\mu_0 \mu_r} \mathbf{B} \right) - \sigma \mathbf{v} \times \mathbf{B} = j \varphi^e
$$

(6.1)

where $j$ denotes the imaginary unit and $\omega$ the angular frequency of the harmonic current.

The 3D finite element model was created by using a Single-Turn Coil feature and the governing equation of the induction coil under frequency-transient study analysis is given by:

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

(6.2)

where $I_{\text{coil}}$ denotes the flowing current of the coil.

Finally, the heating equation governed by the Fourier heat transfer equation is defined by:

$$
\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q
$$

(6.3)

where $\rho$ is the density, $c_p$ is the specific heat capacity, $k$ is the thermal conductivity and $Q$ is the energy generated in the asphalt mixture per unit volume and time.
FINITE ELEMENT MODELS AND INPUT PARAMETERS

In order to study the influence of frequency, power and distance of coils on the induction heating capacity of the conductive asphalt mortar, two finite element (FE) models were utilized. One model makes use of one induction coil at a distance of 50 mm above the surface of the mortar sample, Figure 6.5.a.1. In the second model, an additional coil is used at a distance of 200 mm above the surface of the mortar, Figure 6.5.a.2. The induction coils with a square cross-section of side 0.1 m were assumed. By imposing the alternative current to the coils, eddy current can be generated in the vicinity of the conductive asphalt mortar. It should be noted that the geometry of the induction coil has significant impact on the induction heating efficiency (10, 11). For this reason, the higher order tetrahedral elements were utilized to model the coils and the entire induction heating system, see Figure 6.5.b.1 & 6.5.b.2. In addition to the coils, each model consists of one layer of the conductive asphalt mortar with a thickness of 30 cm, one layer of ground sand soil underneath the mortar layer and air is assumed above the mortar layer.

Normally the electrical-thermal properties of conductive asphalt mixtures are temperature dependent. However, for simplicity, the electro-thermal properties of the conductive asphalt mortar are assumed constant in the simulations.

In order to make the asphalt mortar conductive in this simulation, it was assumed that 6% of steel fibers was added into the asphalt mixture. The electrical and thermal conductivity of the conductive asphalt mortar were taken from the numerical analysis from the previous section. Furthermore, in the following numerical simulations, the parameters of the relative permeability and heat capacity of the conductive mortar were assumed to be 1 and 920 J/(kg·K) respectively. Moreover, an ambient temperature of 20 °C was assumed to simulate the induction heating operation at normal environmental conditions. The duration of the induction heating in the simulation was 120 second. The applied power voltage and the frequency of the alternating magnetic field were set to 550 V and 64 kHz for the simulations based on previous experimental experience (5).
RESULTS AND DISCUSSION

Effect of Electrical and Thermal Properties on Heating Efficiency
The numerical simulations for the one coil system were carried out first. The distribution of magnetic flux density and temperature on the conductive asphalt mortar are shown in Figure 6.6.

Figure 6.5: (a.1&a.2) Schematic of coil induction systems at 3D and (b.1&b.2) mesh refinements
The influence of the electrical conductivity on the temperature distribution within the cross-section of the asphalt mortars is shown in Figure 6.8. It should be noted that the asphalt mortar with 100 S/m of electrical conductivity corresponds to the response of the asphalt mortar mixed with 6% of steel fibers. Hence, the asphalt mortar with 1 S/m of electrical conductivity represents the mortar mixed with a very low amount of steel fibers.

![Magnetic field and temperature distribution](image)

**Figure 6.6** Magnetic field (a.1) and temperature (a.2) at the end of heating, 120 s

![Temperature distribution graph](image)

**Figure 6.7** Influence of the electrical conductivity of the conductive asphalt mortars on temperature distribution (induction time 120s, one induction coil system)

It can be observed in Figure 6.7 that, after 120 seconds of induction heating, for the case of the asphalt mortar with 100 S/m of electrical conductivity, the surface temperature is higher than with 1 S/m (lower amount of steel fibers). This finding supports the observations made by previous
Numerical Evaluation of Electro-Thermal Properties and Induction Heating of Asphalt Mortar

researches (8), where the induction heating efficiency appears to be proportional to the volume of the conductive additives added in the asphalt mixes.

The amount of steel fibers can also influence the thermal gradient inside the asphalt mortar, see Figure 6.7. For example, for the case of asphalt mortar with 100 S/m of electrical conductivity, the temperature decreases faster inside the mortar, than the case 1 S/m. This thermal gradient difference is caused by the skin effect. When a conductive asphalt mortar has a high electrical conductivity, the alternating magnetic field induces electric currents which are concentrated on the surface of the conductive asphalt mortar. The high concentration of the electric currents leads to a higher heat generation at the surface of the conductive asphalt mortar. Therefore the asphalt mortar with higher electrical conductivity (e.g. 100 S/m) has a higher temperature at the surface but a lower temperature inside the material.

In Figure 6.8, the effect of thermal conductivity and heat capacity of conductive asphalt mortars is also presented. The parametric analyses are done for conductive asphalt mortar with two different heat capacities (i.e. 875 and 925 J/(kg·K)), four different thermal conductivities (i.e. 0.5, 0.7, 0.9, 1.1 W/(m·K)), while the electrical conductivity of the compared mortars is constant (100 S/m). By comparing to Figure 6.8, it can be concluded that the impact of the thermal properties of the asphalt mortar on the temperature distribution is not of the same importance with the effect of electrical conductivity.

**Effect of Operational Parameters on Heating Efficiency**

The numerical results in Figure 6.9 show that the distance between the induction coil and the conductive mortar can influence significantly the heat generation in the conductive asphalt mortar. By increasing the coil distance from 50 mm to 100 mm to the mortar surface, it leads to 50% reduction of the temperature at the surface of the asphalt mortar. This means that for surface induction heating coil closer to the surface is more efficient than one at larger distance from the surface of the asphalt mortar. Moreover, the tendency is similar for the materials with different electrical conductivity values.
Numerical Evaluation of Electro-Thermal Properties and Induction Heating of Asphalt Mortar

Figure 6.9: Maximum temperature generated by the single coil system at the different electrical conductivities at the different coil distances to the conductive asphalt mortar (one induction coil system)

The power and the frequency of the alternating magnetic field of the induction machine are two important operational parameters that can influence significantly the induction heating efficiency of the conductive asphalt mortar. Figure 6.10 shows the comparison of the effect of the power and the frequency of the induction coil on the temperature distribution inside the conductive asphalt mortar. It can be observed that, at the same frequency (e.g. 30 kHz), higher machine power results in higher temperatures generated in the material over the whole height.

Figure 6.10: Influence of the supplied power of induction coil (electrical conductivity 1 S/m, induction time 120s, one induction coil system)

**Effect of Double Coil Induction System on Heating Efficiency**

In order to show the possibilities for guidance for the induction machine design, the influence of at two coils system on the heating efficiency of the asphalt mortar was also studied. The influence of
the supplied powers of the two induction coils system and the distance of the upper induction coil to the sample surface is presented.

Figure 6.11 shows the plots of the temperature distribution in the asphalt mortar with 6% of steel fibers for the different combinations of the power of the bottom and the top induction coil. It can be observed that the power of the coil closer to the surface of the induction material has a significant effect on the heat generation. When the power of both coils is doubled from 250 V to 500 V, the induction heating efficiency of the system increases by 8%. The distributions of the temperature within the cross-section of the conductive asphalt mortar show the same tendency for both cases.

![Temperature Distribution](image.png)

**Figure 6.11**: Influence of the supplied powers of the two induction coils system (frequency 64.5 kHz, electrical conductivity 100 S/m, induction time 120s)

With the bottom coil at constant distance (50 mm) to the sample surface, the induction heating efficiency decreases with increasing the distance of the top coil, see Figure 6.12. Increase of the distance of the top coil to the sample surface from 180 mm to 280 mm, leads to reduction of the heat efficiency. Despite the fact that the maximum temperature drops because of the increase of the distance of the top coil to the sample surface, the distribution of the temperature within the cross-section of the conductive asphalt mortar show the same tendency for all the cases.
Finally, a comparison of the two coils system with the one coil system is presented in Figure 6.13. It can be observed that, at the same induction time (120 s), the two coils induction system generates two times higher surface temperature the one coil induction system. Also, the two coil induction system is more powerful and efficient for asphalt concrete healing application, because it can generate higher temperatures in the top part of the first layer which enables the contractor to heal the micro cracks quickly at this place. Thus, the induction heating technique can be approved very highly efficient for preserving pavement surface defects, such as the raveling, when two coils systems are utilized.

Figure 6. 12: Influence of the distance of the upper induction coil to the sample surface (frequency 64 kHz, electrical conductivity 100 S/m, induction time 120s)

Figure 6. 13: Comparison of the different types of induction coil systems on heating distribution in the conductive asphalt mortar (electrical conductivity 100 S/m, induction time 120s)
6.4. **Numerical Evaluation of 3D Heating with Moving Source**

The numerical analysis of a continuously moving induction coil under an alternating electromagnetic field is presented in this subchapter. The numerical simulations of heating conductive asphalt mixes require the solution of a coupled alternating magnetic and thermal field with a moving electromagnetic source.

**Finite Element Model and Parameters**

As it has been described in the previous section, the magnetic field, which is created by imposing alternative current to the coil, generates eddy currents to the asphalt mix. In this simulation, the heating source with cylindrical shape of radius 0.05 m is at a distance 100 mm above the surface of asphalt layer with thickness 50 cm, see Figure 6.14.a. The higher order tetrahedral elements were utilized to create the finite element mesh, see Figure 6.14.b.

In this simulation, the dependence of the electro-thermal properties of asphalt mix on the temperature is neglected at the range of 20 °C to 120 °C. The material's effective electrical and thermal conductivity were assumed to be $1 \text{ S/m}$ and $1.2 \text{ W/(m·K)}$ respectively. The ambient temperature 20 °C and the applied frequency of the alternating magnetic field 64 kHz were assumed for the simulations. Moreover, the applied current density from the coil to the surrounding area was set to $4 \times 10^{11} \text{ A/m}^2$ and the induction coil moves with a speed $v \text{ (m/s)}$ along the x coordinate direction.

![Figure 6.14: (a) Schematic of moving induction coil at 3D and (b) mesh refinements](image)

**Results and Discussion**

For field pavement maintenance by using induction heating technique, the speed of the induction heating coil is crucial operational parameter. The adequate speed results to good healing quality of asphalt pavement. In Figure 6.15, the distribution of temperature on the conductive asphalt layer after 20 min of induction heating with coil speed 0.01 m/s is shown.
It can be observed that the surface temperature increase differs at different points on the asphalt surface when the induction heating source is moving with specific speed. For example, a point (Point A) that is below of induction coil at the beginning of heating appears faster increase of temperature than a point 0.5 m away (Point C), see Figure 6.16. However, in the same Figure 6.16, point A (point below of the coil at time 0 s) reaches lower maximum temperature after 120 s of induction heating than point B, 1 m away. Therefore, controlling the speed and the initial position of moving induction coil it is possible to heat up the pavement structure at the desired levels and time.

Figure 6.16: Surface temperature increase at different points on asphalt mix (speed v=0.01 m/s)
Additionally, the influence of moving speed of induction coil is presented in Figure 6.17. By increasing the speed from 0.01 m/s to 0.02 m/s, it leads to 40% reduction of the surface temperature of asphalt mix. Similarly, when the speed increases to 0.04 m/s reduction of maximum temperature on the surface is obvious as well. This means that in order to reach higher temperature on the surface the moving speed of coil should be lower.

![Figure 6.17: Influence of the moving speed of induction coil on heating efficiency](image)

**6.5. CONCLUSIONS**

The electrical and thermal characteristics of the conductive asphalt mortar play an important role for the design or assessment of the induction heating capacity of an asphalt concrete mixture. The 3D finite element models enable us to calibrate the model parameters to perform more realistic induction heating simulations for asphalt concrete mixtures. The findings of this research show that it is possible to optimize the development of the necessary tools and equipment needed for the implementation of the induction technology for healing asphalt concrete mixtures.
REFERENCES

Summary and Conclusions

The objective of this thesis as mentioned in the beginning was to evaluate the induction heating technique in asphalt mixes. Thus, (a) experimental methods were developed following past techniques or introducing new ones to study asphalt mixes at different scales with main purpose to enhance the induction heating and healing efficiency without reducing the durability and (b) finite element numerical models were developed to simulate the induction heating technique on asphalt mixes under different properties and operational conditions.

In the first part of this thesis conductive asphalt mastics and mortars were developed for induction heating and healing purposes. Specifically, asphalt mastics were developed with different proportions of mineral fillers and additives (iron powder) and the impact of them on the workability and performance on asphalt mastics was examined. At the mastic scale of asphalt mixes it was understood that the physical properties of fine particles and the interaction of them affect the rheological performance of mastics, contributing to manufacturing more durable asphalt mixes with enhanced induction heating capabilities.

Additionally, the experimental part of this thesis was focused also on mortar scale. Control the electrical, thermal and mechanical properties in parallel with increasing the induction heating and induction healing efficiency of asphalt mortars provide us clear imagine of additives’ impact. Among the conclusions of adding conductive additives within the asphalt mortar is the enhancement of the electrical and thermal conductivity of asphalt mortars, in parallel with the improvement of mechanical properties – strength and fatigue life. Moreover, apart from the highest induction heating efficiency when iron powder and steel fibers are added to a certain limit, asphalt mortars with only steel fibers have similar induction healing capacity with mortars with both the additives.

In the second and final part, finite element numerical models were developed in order to evaluate the electro-thermal properties of asphalt mortars and to understand the influential factors of induction heating. The main purpose of adopting the finite element based tools to facilitate the generation of induction heating was the reduction of time and cost of the analysis by conducting full-scale experiments. The numerical analysis of three-dimensional models - one with static source and one with moving heat source - provide us with the opportunity to understand the influential factors of induction heating in order to enhance the efficiency of this process for the asphalt mixes. Calibration of model parameters to perform more realistic induction heating simulations for asphalt concrete mixtures was the other achieved goal.

By accounting both the experimental and numerical studies of this thesis it can be possible to optimize the production of asphalt concrete mixtures and the necessary equipments needed for the adoption of the induction technology as maintenance technique in asphalt pavement industry.
Appendix A

Poynting’s Theorem

The Poynting’s theorem represents the relation between the rate of energy stored in the fields and the energy flow. This theorem expresses that the summation of the ohmic loss and the power absorbed by the magnetic field is equal to the power input in a small volume element of area $A$.

Figure A.1: Electromagnetic wave passing through a volume element

Scalar multiplication by $H, E$ and subtracting gives

\[
H \cdot (\nabla \times E) - E \cdot (\nabla \times H) = \nabla \cdot (E \times H) = -H \cdot \frac{\partial B}{\partial t} - E \cdot j - E \cdot \frac{\partial D}{\partial t}
\]

\[
= -\frac{1}{2} \frac{\partial}{\partial t} (H \cdot B + E \cdot D) - j \cdot E
\]  \hspace{2cm} (A.1)

Integrating over the entire volume $V$ and using Gauss’s theorem

\[
- \frac{\partial}{\partial t} \int_{V'} d^3x' \frac{1}{2} (H \cdot B + E \cdot D) = \int_{V'} d^3x' j \cdot E + \oint_{S'} d^2x' (E \times H) \cdot \hat{n}
\]  \hspace{2cm} (A.2)

Assuming the presence of an electromotive force field and using Ohm’s law

\[
j = \sigma (E + E^{EMF})
\]  \hspace{2cm} (A.3)

Consequently
Therefore, inserting the above equation into equation A.2, the energy theorem in Maxwell’s theory is derived

\[ \int_{V'} d^3x' \mathbf{E} \cdot \mathbf{j} = \int_{V'} d^3x' \frac{j^2}{\sigma} - \int_{V'} d^3x' \mathbf{j} \cdot \mathbf{E}^{EMF} \]  \hspace{1cm} (A.4)

where the different energies are

\[ \int_{V'} d^3x' \mathbf{j} \cdot \mathbf{E}^{EMF} \]  \hspace{1cm} (A.6)

which is the applied electric power,

\[ \int_{V'} d^3x' \frac{j^2}{\sigma} \]  \hspace{1cm} (A.7)

which is the Joule heat,

\[ \int_{V'} d^3x' \frac{1}{2} (\mathbf{E} \cdot \mathbf{D} + \mathbf{H} \cdot \mathbf{B}) \]  \hspace{1cm} (A.8)

which is the field energy,

\[ \oint_{s'} d^2x' (\mathbf{E} \times \mathbf{H}) \cdot \hat{n} \]  \hspace{1cm} (A.9)

which is the radiated power.

It is common to introduce the quantities

\[ U_e = \frac{1}{2} \int_{V'} d^3x' \mathbf{E} \cdot \mathbf{D} \]  \hspace{1cm} (A.10)

\[ U_m = \frac{1}{2} \int_{V'} d^3x' \mathbf{H} \cdot \mathbf{B} \]  \hspace{1cm} (A.11)
The Poynting vector, which appears in Poynting's theorem, is usually denoted by $\mathbf{S}$ [W/m$^2$], represents the case of an energy flux vector, is called Abraham form and is defined as

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} \quad (A.12)$$

where $\mathbf{E}$ is the electric field and $\mathbf{H}$ the magnetic field, and $\mathbf{S}$ is measured in W/m$^2$. Otherwise, it is written

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \quad (A.13)$$

The Poynting vector $\mathbf{S}$ can be given for the electromagnetic wave travelling in vacuum as

$$\mathbf{S} = \frac{\mathbf{E}\mathbf{B}}{\mu_0} = \frac{\mathbf{E}^2}{c\mu_0} \quad (A.14)$$

For example, assuming the electric field associated with a plane sinusoidal electromagnetic wave, then its form is

$$\mathbf{E} = E_0 \cos(kx - \omega t)\hat{j} \quad (A.15)$$

Also, the corresponding magnetic field is

$$\mathbf{B} = B_0 \cos(kx - \omega t)\hat{k} \quad (A.16)$$

and the direction of propagation is the positive $x$-direction, then the Poynting vector is

$$\mathbf{S} = \frac{1}{\mu_0} (E_0 \cos(kx - \omega t)\hat{j}) \times (B_0 \cos(kx - \omega t)\hat{k}) = \frac{E_0B_0}{\mu_0} \cos^2(kx - \omega t)\hat{i} \quad (A.17)$$

The intensity of this wave $I$ is denoted as the time-average of $\mathbf{S}$ and is the following

$$I = \langle \mathbf{S} \rangle = \frac{E_0B_0}{\mu_0} |\cos^2(kx - \omega t)| = \frac{E_0}{2\mu_0} = \frac{E_0^2}{2c\mu_0} = \frac{cB_0^2}{2\mu_0} \quad (A.18)$$

The complex Poynting vector is written as

$$\mathbf{S} = \frac{1}{2} (\mathbf{E} \times \mathbf{H}^*) \quad (A.19)$$

where $\mathbf{H}^*$ is the complex conjugate of the magnetic field.
Exploring the momentum balance in a non-relativistic field, it is necessary to consider the force density by the Lorentz force \( \rho E + j \times B \). Via this way and implying the Maxwell’s equation

\[
\rho E + j \times B = (\nabla \cdot D)E + (\nabla \times H) \times B = E(\nabla \cdot D) + (\nabla \times H) \times B - \frac{\partial D}{\partial t} \times B
\]

\[
= E(\nabla \cdot D) - B \times (\nabla \times H) - \frac{\partial}{\partial t} (D \times B) + D \times \frac{\partial B}{\partial t}
\]

\[
= E(\nabla \cdot D) - B \times (\nabla \times H) - \frac{\partial}{\partial t} (D \times B) - D \times (\nabla \times E) + H(\nabla \cdot B)
\]

\[
= [E(\nabla \cdot D) - D \times (\nabla \times E)] + [H(\nabla \cdot B) - B \times (\nabla \times H)] - \frac{\partial}{\partial t} (D \times B)
\]

with

\[
[E(\nabla \cdot D) - D \times (\nabla \times E)]_i = \frac{1}{2} \left( E \cdot \frac{\partial D}{\partial x_i} - D \cdot \frac{\partial E}{\partial x_i} \right) + \frac{\partial}{\partial x_i} \left( E_i D_j - \frac{1}{2} E \cdot D \delta_{ij} \right)
\]

(B.2)

and

\[
[H(\nabla \cdot B) - B \times (\nabla \times H)]_i = \frac{1}{2} \left( H \cdot \frac{\partial B}{\partial x_i} - B \cdot \frac{\partial H}{\partial x_i} \right) + \frac{\partial}{\partial x_i} \left( H_i B_j - \frac{1}{2} B \cdot H \delta_{ij} \right)
\]

(B.3)

Consequently, applying the above expression in the \( i \)-th component of equation B.1, it is given

\[
(\rho E + j \times B)_i = \frac{1}{2} \left[ (E \cdot \frac{\partial D}{\partial x_i} - D \cdot \frac{\partial E}{\partial x_i}) + (H \cdot \frac{\partial B}{\partial x_i} - B \cdot \frac{\partial H}{\partial x_i}) \right] + \frac{\partial}{\partial t} (D \times B)_i
\]

\[
= \frac{\partial}{\partial x_j} \left( E_i D_j - \frac{1}{2} E \cdot D \delta_{ij} + H_i B_j - \frac{1}{2} B \cdot H \delta_{ij} \right)
\]

(B.4)

Implying the electric volume force \( F_{ev} \)

\[
(F_{ev})_i = (\rho E + j \times B)_i = \frac{1}{2} \left[ (E \cdot \frac{\partial D}{\partial x_i} - D \cdot \frac{\partial E}{\partial x_i}) + (H \cdot \frac{\partial B}{\partial x_i} - B \cdot \frac{\partial H}{\partial x_i}) \right]
\]

(B.5)

and the Maxwell stress tensor \( T \) with components
\[ T_{ij} = E_i D_j - \frac{1}{2} E \cdot D_{\delta ij} + H_i B_j - \frac{1}{2} H \cdot B_{\delta ij} \]  \hspace{1cm} (B.6)

In other words, the above expression of Maxwell stress tensor can be written as

\[ n_1 T_{2i} = -\frac{1}{2} n_1 (E \cdot D) + (n_1 \cdot E)D^T \]  \hspace{1cm} (B.7)

the electric field force on the surface of the object and

\[ n_1 T_{2i} = -\frac{1}{2} n_1 (H \cdot B) + (n_1 \cdot H)H^T \]  \hspace{1cm} (B.8)

the magnetic field force on the surface of the object. Therefore, the force equation is

\[ [F_{ev} + \frac{\partial}{\partial t} (D \times B)]_i = \frac{\partial T_{ij}}{\partial x_j} = (\nabla \cdot T)_i \]  \hspace{1cm} (B.9)

In case of introducing the relative electrical permittivity \( \varepsilon_r \) and the relative magnetic permeability \( \mu_r \) as

\[ D = \varepsilon_r \varepsilon_0 E = \varepsilon E \]  \hspace{1cm} (B.10)

\[ B = \mu_r \mu_0 H = \mu H \]  \hspace{1cm} (B.11)

Then,

\[ \frac{\partial T_{ij}}{\partial x_j} = (F_{ev} + \frac{\varepsilon_r \mu_r}{c^2} \frac{\partial S}{\partial t}) \]  \hspace{1cm} (B.12)

wherein S is the Poynting vector. Integration over the entire volume \( V \) obtains the momentum theorem in Maxwell’s theory

\[ \int_V d^3x' F_{ev} + \frac{d}{dt} \int_V d^3x' \frac{\varepsilon_r \mu_r}{c^2} S = \oint_{S'} d^2x' T_\mathbf{n} \]  \hspace{1cm} (B.13)

where
\[ \int_{\nu'} d^3 x' F_{\text{ev}} \]  
which is the force on the matter

\[ \int_{\nu'} d^3 x' \frac{e_r \mu_r}{c^2} S \]  
which is the field momentum

\[ \oint_{s'} d^2 x' T_{\text{in}} \]  
which is the Maxwell stress.
# Appendix C

## Basics of Electromagnetic Field

<table>
<thead>
<tr>
<th>Derived quantity</th>
<th>Symbol</th>
<th>SI unit</th>
<th>Base unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric field intensity</td>
<td>E</td>
<td>V/m</td>
<td>kg·m·A⁻¹·s⁻³</td>
</tr>
<tr>
<td>Electric flux density</td>
<td>D</td>
<td>C/m²</td>
<td>A·s·m⁻²</td>
</tr>
<tr>
<td>Magnetic field intensity</td>
<td>H</td>
<td>A/m</td>
<td>A·m⁻¹</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>B</td>
<td>T</td>
<td>kg·s⁻²·A⁻¹</td>
</tr>
<tr>
<td>Current density</td>
<td>J</td>
<td>A/m²</td>
<td></td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>φ</td>
<td>Wb</td>
<td>kg·m²·s⁻²·A⁻¹</td>
</tr>
<tr>
<td>Permeability</td>
<td>μ</td>
<td>H/m</td>
<td>kg·m·s⁻²·A⁻²</td>
</tr>
<tr>
<td>Permittivity</td>
<td>ε</td>
<td>F/m</td>
<td>Kg⁻¹·m³·s⁻⁴·A²</td>
</tr>
<tr>
<td>Volume charge density</td>
<td>ρ</td>
<td>C/m³</td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>σ</td>
<td>S/m</td>
<td>Kg⁻¹·m³·s⁻³·A²</td>
</tr>
<tr>
<td>Resistivity</td>
<td>ρₖ</td>
<td>Ωm</td>
<td>Kg·m³·s⁻³·A⁻²</td>
</tr>
<tr>
<td>Electric resistance</td>
<td>R</td>
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<td></td>
</tr>
<tr>
<td>Impedance</td>
<td>Z</td>
<td>Ω</td>
<td>Kg·m²·s⁻³·A⁻²</td>
</tr>
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<td>Reactance</td>
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<td></td>
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<td>C</td>
<td>F</td>
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<tr>
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<tr>
<td>Conductance</td>
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<td>Y</td>
<td>S</td>
<td>Kg⁻¹·m²·s⁻³·A²</td>
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<tr>
<td>Susceptance</td>
<td>B</td>
<td></td>
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</tbody>
</table>
Appendix D
Viscoelasticity of Asphalt Mixes

The basic laboratory testing methods in which we are trying to explore the linear and non-linear behavior of the asphalt mixes, binders and mastics, are presented here. It is well-known that an asphalt mix behaves as linear viscoelastic material for low stress levels and as non-linear viscoelastic material for high stresses. The threshold for the linear region depends on the composition of the mix, the loading time and the temperature.

FREQUENCY DOMAIN EXPERIMENTAL METHODS
Dynamic tests are required to obtain the material response at very short loading times. The common approach is to apply a periodically varying strain or stress signal with a fixed frequency.

Since asphalt mixes are viscoelastics, there is a phase lag between the applied and the response signal in a dynamic test. For sinusoidal varying strain input with an amplitude $\gamma_0$ and frequency $\omega$, the resulting response signal is also sinusoidal in shape with a phase lag, $\delta$. In mathematical form it is expressed as:

$$\gamma(t) = \gamma_0 \sin(\omega t)$$

$$\tau(t) = \tau_0 \sin(\omega t)$$  \hspace{1cm} (D.1)  \hspace{1cm} (D.2)

Using the basic theory of viscoelasticity the stress in a viscoelastic material for a sinusoidal strain signal can be obtained. For a sinusoidal strain input the resulting formulation for the stress is

$$\tau(t) = \gamma_0 [\omega \int_0^\infty J(\xi) \sin(\omega \xi) \, d\xi] \sin(\omega t) + \gamma_0 [\omega \int_0^\infty J(\xi) \cos(\omega \xi) \, d\xi] \cos(\omega t)$$

$$\hspace{3cm} \text{where } \xi \text{ is history variable and } J(\xi) \text{ is the relaxation function.}$$

In the above equation the expression placed in bracket are functions of frequency only. The first term is in phase with the applied sinusoidal strain while the second term with the cosine expression is 90 degree out of phase. The expressions in two brackets are the components of the dynamic modulus of the material. Therefore, this equation can be transformed in terms of loss and storage modulus components as:

$$\tau(t) = \gamma_0 [J'] \sin(\omega t) + \gamma_0 [J''] \cos(\omega t)$$

$$\hspace{3cm} \text{where } J' \text{ is the storage modulus and } J'' \text{ is the loss modulus.}$$
By comparing the above equation, the fundamental relations for analyzing dynamic analysis data that relate available experimental data, $\tau_0$, $y_0$ and $\delta$, to the material property, $J'$ and $J''$ are obtained. After some mathematical manipulations, the relations given in the following equation summarize these fundamental relations for analyzing dynamic test data.

\[
J'(\omega) = \frac{\tau_0}{y_0} \cos\delta \\
J''(\omega) = \frac{\tau_0}{y_0} \sin\delta \\
tan\delta = \frac{J''(\omega)}{J'(\omega)} \\
|J^*(\omega)| = \sqrt{(J''(\omega))^2 + (J'(\omega))^2}
\]

where $J'$ is the storage modulus, $J''$ is the loss modulus, $\delta$ is the phase angle and $J^*$ is the complex modulus.

**TIME DOMAIN EXPERIMENTAL METHODS**

**CREEP COMPLIANCE TESTING**

Relaxation and creep tests are the most commonly used experimental methods to examine the time dependent behavior of viscoelastic materials. A creep test is characterized by an increasing deformation with time under a constant stress. For long loading times, these tests are suitable particularly for investigating the viscoelastic properties of asphalt mixes.

For short loading times, which correspond to high frequency loadings, these tests cannot provide complete material information. Therefore, for lower time intervals of 1 second or in the order of 0.1 to 1 second, in the fraction of second cannot properly be extracted material information. For this reason, the frequency domain tests are the most sufficient way of obtaining information for the viscoelastic behavior of material.

To determine creep properties, material is subjected to prolonged loading and creep compliance is obtained by applying a constant stress and measuring the resulting time-dependent strain. Compliance which a function of time and temperature is defined as:

\[
J(t) = \frac{\gamma(t)}{\tau_0}
\]

where $J(t)$: creep compliance, $\gamma(t)$: time dependent strain and $\tau_0$: constant stress.

The purpose of studying the time domain tests is for understanding deeper the linear and nonlinear behavior of selected materials. Knowing that the asphalt mixes may have similar characteristics in the linear region do not necessarily behave in a similar way in nonlinear region. For this reason, the characterization of nonlinear region of viscoelastic behavior is crucial for
proper selection of pavement’s constituents. Multiple Stress Creep and Recovery test is selected for understanding the non-linear behavior.

**Dynamic Shear Rheometer (DSR)**
The Dynamic Shear Rheometer (DSR) which is a form of dynamic mechanical analysis (DMA) is used to measure the rheological properties of time dependent materials, such as asphalt mixes. It does this by measuring the complex shear modulus \(G^*\) and phase angle \(\delta\) of these materials, such as asphalt binder and mastic. \(G^*\) is a measure of the total resistance of a material to deforming when repeatedly sheared. It consists of two parts, a part that is elastic (recoverable) and a part that is viscous (non-recoverable) and is the ratio of the amplitude of shear stress and shear strain. Delta, \(\delta\), is an indicator of the relative amounts of recoverable and non-recoverable deformation.

**Standard Test Method**
The standard testing procedure to acquire the response of viscoelastic materials involves a small sample of material sandwiched between two parallel plates, also called test geometries. The specimen size and plate diameter to be used depend upon the temperature. For intermediate to high temperature, the DSR plate geometry is 25 mm in diameter and the specimen size is 1 mm. For low to intermediate temperatures the DSR plate geometry is 8 mm in diameter and the specimen size is 2 mm. In case of studying mastic materials, mastics are likely to be significantly stiffer than pure bitumen, an 8 mm plate is used during the experiments described in this work.

During the experiment, a predefined oscillating torque is applied on the upper plate while the lower plate remains fixed and the angular rotation is measured. Interpretation of the applied torque and the measured deformation provide the material response information. By torque and angular frequency, easily can be derived the fundamental material properties complex shear modulus, complex shear compliance and the phase angle.

\[
\gamma_{max} = \frac{\theta \cdot r}{h} \quad (D.10)
\]

\[
\tau_{max} = \frac{2T}{\pi r^3} \quad (D.11)
\]

\[
G^* = \frac{\tau_{max} - \tau_{min}}{\gamma_{max} - \gamma_{min}} \quad (D.12)
\]

\[
\delta = 2\pi f \cdot \Delta t = \omega \cdot \Delta t \quad (D.13)
\]

where \(\tau\) is shear stress, \(T\) is torque, \(\gamma\) represents shear strain, \(r\) is the radius of specimen, \(h\) is the specimen thickness, \(\theta\) is the deflection angle, \(\delta\) is the phase angle, \(f\) is the frequency, \(\omega\) is the radial frequency, \(\Delta t\) is the time lag and \(G^*\) is the complex modulus.

The corresponding equations for the applied shear strains and the stress response are given below.
According to complex modulus and creep compliance are obtained by:

\[ \gamma^* = \gamma_d e^{i\omega t} = \gamma_d (\cos \omega t + i \sin \omega t) \quad (D.14) \]

\[ \tau^* = \tau_d e^{(i\omega t + \delta)} = \tau_d (\cos [\omega t + \delta] + i \sin [\omega t + \delta]) \quad (D.15) \]

According to complex modulus and creep compliance are obtained by:

\[ G^*(\omega) = \frac{\tau^*}{\gamma^*} = \frac{\tau_d}{\gamma_d} e^{i\delta} = \frac{\tau_d}{\gamma_d} (\cos \delta + i \sin \delta) = G' + iG'' \quad (D.16) \]

\[ \tan \delta = \frac{G''}{G'} \quad (D.17) \]

\[ J^*(\omega) = \frac{\gamma^*}{\tau^*} = \frac{1}{G^*} = J' - ij'' \quad (D.18) \]

where \( \gamma^* \) is complex shear strain, \( \gamma_d \) is the shear strain amplitude, \( \tau^* \) is the complex stress, \( \sigma_d \) is the stress amplitude, \( G^* \) is the complex modulus, \( G' \) represents the storage modulus, \( G'' \) represents the loss modulus, \( J^* \) is the creep compliance with \( J' \) and \( J'' \) the storage and loss compliance respectively.

The relationship between the complex shear modulus, the in-phase component and the out-of-phase component, and the phase angle is illustrated as the plane Cartesian system in Figure D.1.a.

![Figure D.1](image-url)

Figure D.1: (a) The Cartesian representation of the principal viscoelastic parameters, (b) input and output signal of standard strain control method and (c) viscous and elastic behavior of asphalt mixes
The test setup is basically meant for response measurements at very low stress levels where the material is assumed to have linear viscoelastic behavior. However, for measurement at higher stress levels, where the bitumen response is likely to become nonlinear, the non uniform nature of the stress distribution across the sample geometry makes interpretation very difficult.

The values of $G^*$ and $\delta$ for asphalt mixes are highly dependent on the temperature and frequency of loading. At high temperatures, that represents the high pavement temperatures, asphalt mixes behave like viscous fluids as indicated by the vertical arrow in Figure D.1.c. On the other side, at very low temperatures, that represents the low pavement temperatures, asphalt mixes behave like elastic solids as demonstrated by the horizontal arrow in Figure D.1.c.

**MASTER CURVE USING TIME TEMPERATURE SUPERPOSITION PRINCIPLE**

The use of master curves is an effective tool to understand and analyze the rheological response – stiffness and phase angle - of viscoelastic materials. Master curves allow the estimation of properties at a wider range of temperature and frequencies and were created using the Time-Temperature superposition principle. This principle allows shifting the response data obtained at various temperatures with respect to time or frequency to a selected reference temperature. The amount of shifting required at each temperature can be obtained using the Williams-Landel-Ferry (WLF) and expressed as

$$\log(a_T) = \frac{-C_1(T - T_0)}{C_2 + (T - T_0)}$$

(D.19)

where $C_1$, $C_2$ are constants, $T$ and $T_0$ are the temperature and the reference temperature respectively, and $a_T$ is the shift factor.

Figures D.2&D.3 demonstrate the master curve plots for 70/100 bitumen and SBS bitumen Cariphalte XS respectively. The master curves were constructed at a reference temperature of 30°C and the frequency sweep test was conducted from -10°C to 60°C.
Figure D.2: The master curve for two different bitumen from frequency sweep test

Figure D.3: The diagram between phase angle and frequency from frequency sweep test
Appendix E

MSCR Test

The MSCR test covers the determination of percent recovery and non-recoverable creep compliance of bitumen and asphalt mastic at two stress levels, 0.1 kPa and 3.2 kPa, at a specified temperature. The temperature range conducting the test is between 40 °C to 70 °C. According to the specification AASHTO TP 70-10, the asphalt binder is loaded at constant stress for 1 s, then allowed to recover for 9 s. Ten creep and recovery cycles are run at 0.1 kPa creep stress followed by ten more cycles at 3.2 kPa creep stress. Record the stress and strain at least every 0.1 seconds for the creep cycle and at least every 0.45 seconds for the recovery cycle on a running time.

For each of the twenty creep and recovery record, the strain values are taken at certain time position. From this measured values, the adjusted strain values at the end of creep portion and recovery portion are derived. Especially, the adjusted strain value at the end of creep portion, after 1 s, of each cycle is obtained by:

\[ \varepsilon_1 = \varepsilon_c - \varepsilon_0 \]  

(E.1)

where \( \varepsilon_c \) is the strain absolute value at the end of the creep portion, after 1 s, and \( \varepsilon_0 \) is the initial absolute value at the beginning of the creep portion. Additionally, the adjusted strain value at the end of recovery portion, after 10 s, of each cycle is given by:

\[ \varepsilon_{10} = \varepsilon_r - \varepsilon_0 \]  

(E.2)

where \( \varepsilon_r \) is the strain value at the end of the recovery portion after 10 s, of each cycle.

The resulted values for the test are used for the determination of the average percent of recovery and non recoverable creep compliance for bitumen and asphalt mastic at creep stress levels of 0.1 kPa and 3.2 kPa. The percent recovery \( R_N \) of 0.1 kPa and 3.2 kPa for each cycle is obtained respectively by:

\[ R_N(0.1 \text{ kPa}, N) = \left( \frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1} \right) \times 100 \]  

(E.3)

and

\[ R_N(3.2 \text{ kPa}, N) = \left( \frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1} \right) \times 100 \]  

(E.4)

Consequently, the average percentages of recovery at 0.1 kPa and 3.2 kPa are:
\[ R_{0.1\, kPa} = \sum (R_N(0.1\, kPa, N))/10 \]  \hspace{1cm} (E.5)

for \(N=1\) to 10, and

\[ R_{3.2\, kPa} = \sum (R_N(3.2\, kPa, N))/10 \]  \hspace{1cm} (E.6)

for \(N=1\) to 10.

Similarly, the non-recoverable creep compliance at 0.1 kPa and 3.2 kPa is given respectively by:

\[ J_{nr}(0.1\, kPa, N) = \frac{\varepsilon_{10}}{0.1} \]  \hspace{1cm} (E.7)

and

\[ J_{nr}(3.2\, kPa, N) = \frac{\varepsilon_{10}}{3.2} \]  \hspace{1cm} (E.8)

with the average values:

\[ J_{nr}(0.1\, kPa) = \sum (J_{nr}(0.1\, kPa, n))/10 \]  \hspace{1cm} (E.9)

for \(N=1\) to 10, and

\[ J_{nr}(3.2\, kPa) = \sum (J_{nr}(3.2\, kPa, n))/10 \]  \hspace{1cm} (E.10)

for \(N=1\) to 10.
Appendix F

Stress Sweep Results
Figure F.1: Stress sweep results for all the mastic systems at temperatures between -10 °C and 60 °C
Appendix G
Theoretical Background of Direct Tension Test

MONOTONIC TENSION TEST
The simplified expressions of stress and strain in a material are described with the following relationships. Particularly, strain describes the degree of deformation of a material. For uniaxial test, engineering deformation can be expressed as:

\[ \varepsilon = \frac{L_i - L_0}{L_0} \]  \hspace{1cm} (G.1)

where \( L_0 \) is the original length of specimen and \( L_i \) is the length after certain deformation.

A material deforms under applied load. For uniform deformation, the applied stress may be defined as:

\[ \sigma = \frac{F}{A_0} \]  \hspace{1cm} (G.2)

where \( F \) is the vertical force to the cross section and \( A_0 \) is the original cross sectional area. In this case, the stress is defined to the original cross sectional and is named engineering stress. Experimentally, the force-elongation data is converted to engineering stress and strain and the stress-strain curve is plotted. The advantage of dealing with stress versus strain rather load versus elongation is that the stress-strain curve is virtually independent of specimen dimensions. It is useful for small deformation.

For a more realistic analysis of stress, the true stress is derived from the instantaneous cross section \( A \):

\[ \sigma = \frac{F}{A} \]  \hspace{1cm} (G.3)

The above relationship gives the true stress and is based on the instantaneous material configuration. Similarly, the corresponding strain increment becomes:

\[ d\varepsilon = \frac{dL}{L} \]  \hspace{1cm} (G.4)

and the true strain for a change of the length from the original \( L_0 \) to \( L_i \) is
The true and the engineering stress and strain are related by:

\[ \sigma = \ln(1 + s) \]  \hspace{1cm} (G.6)

\[ \epsilon = \ln(1 + e) \]  \hspace{1cm} (G.7)

It should be noted that the difference between true and engineering stress and strain are very small for low strains.

On the other hand, the state of stress is expressed in six stresses \((\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx})\) and six strain components \((\epsilon_x, \epsilon_y, \gamma_{xy}, \gamma_{yz}, \gamma_{zx})\) based on the general plasticity theory. In the uniaxial state of stress, there is only one non-zero stress:

\[ \sigma_x = \sigma \]  \hspace{1cm} (G.8)

\[ \sigma_y = \sigma_z = \tau_{xy} = \tau_{yz} = \tau_{zx} = 0 \]  \hspace{1cm} (G.9)

Knowing that for any given stress state there exists an equivalent uniaxial stress state, the equivalent uniaxial stress is:

\[ \sigma_e = \frac{1}{\sqrt{2}} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right]^{1/2} + \left( \tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2 \right]^{1/2} \]  \hspace{1cm} (G.10)

The corresponding equivalent strain is given by:

\[ \epsilon_e = \int d\epsilon_e \]  \hspace{1cm} (G.11)

where \(d\epsilon_e\) is the strain increment:

\[ d\epsilon_e = \frac{\sqrt{2}}{3} \left[ (d\epsilon_x - d\epsilon_y)^2 + (d\epsilon_y - d\epsilon_z)^2 + (d\epsilon_z - d\epsilon_x)^2 + 6 \cdot (d\gamma_{xy}^2 + d\gamma_{yz}^2 + d\gamma_{zx}^2) \right]^{1/2} \]  \hspace{1cm} (G.12)
CYCLIC TENSION TEST

In the cyclic loading test, the fatigue performance of a material can be observed. The deterioration of material under cyclic loading with force and displacement as sinusoidal functions of time and frequency is translated to strength and stiffness reduction. The force and displacement in each cycle is described as:

\[ F = F_0 \sin(2\pi f \cdot t + \phi_1) + \alpha \]  \hspace{1cm} (G.13)

\[ L = L_0 \sin(2\pi f \cdot t + \phi_2) + b \]  \hspace{1cm} (G.14)

where \( F \) is the applied force [N], \( F_0 \) is the amplitude of the applied force in a cycle [N], \( f \) is loading frequency [Hz], \( t \) is the testing time [s], \( L_0 \) is the amplitude of the displacement in a cycle [mm] and \( \alpha, b, \phi_1, \phi_2 \) are regression coefficients. The last coefficients can be derived by the data obtained from any cyclic loading material analysis.

For the asphalt mixes as linear visco-elastic under relatively low strain applications, their fatigue performance can be described by the stiffness change during the cyclic. Stiffness can be obtained from the stress and strain under uniaxial fatigue test as:

\[ E = \frac{\sigma_i}{\varepsilon_i} \]  \hspace{1cm} (G.15)

where \( \sigma_i \) tensile stress and \( \varepsilon_i \) tensile strain.

In the current case and based on the classical fatigue approach, the point of failure exists at the point of complete fracture, \( N_f \), where the fatigue mode is stress-controlled.

Figure G. 1: Strain versus load cycles evolution curve
Appendix H
Alignment and Localization of Failure

The alignment of the set-up should be flexible in order to accommodate imperfect specimen in parallel to eliminate the horizontal movement of hinges. Specifically, Erkens et al (20) suggested a uniaxial set-up of three hinges, capable to compensate the misalignment of horizontal movement ensuring in parallel that the specimen was subjected to normal forces along its axis only. Moreover, the way of load transfer during the uniaxial test is another crucial part of alignment of set-up. The most common approach of connecting the load transfer system with the testing specimen is glue end cap onto the specimen, but this way leads easily to cracking close to the end caps due to suppression of radial deformation (20). This phenomenon is characterized localization of failure near the end caps and should be avoided. The goal of this study was to break the asphalt mortar specimen in the middle of specimen. For achieving this, the specimen geometry was important.

Previous Specimen Geometry
The existed geometric system was a specimen with a linearly reducing diameter from the end of the ring to the specimen’s centre and near the centre the shape was changed to parabola. The pulling ring of specimen was embedded in the mass of it and together with the testing material forms the specimen, see Figure H.1. This geometry had as consequence the creation of susceptible areas of failure at the transition positions between the ring end and the straight area of specimen. Thus and after various tests of glued specimens onto the pulling cap, it became clear that the controllability of failure at the centre was difficult. Therefore and in order to prevent these phenomena of failure close to the pulling ring, it was decided to redesign the geometry of the specimen simultaneously with the arrangement of hinges design.
CURRENT SPECIMEN GEOMETRY

For the development of a new specimen, the height of the specimen and the diameter at the top and the bottom were kept constant. Concerning the diameter, it remained the same through the contacting area with the pulling ring and started to reduce gradually when the contact ends. The parabola approach was followed for the design of specimens’ shape. The radius in the middle of specimen was considered under investigation and five different cases were produced on Excel sheets. The produced case had radius from 7.5 mm to 5 mm in the specimen centre, see Figure H.2.b.

From the above cases, 10 mm thickness in middle or 5 mm radius was chosen for the new specimen design. The parabolic part of the specimen had 34 mm height. Moreover, new pulling rings were designed avoiding the creation of susceptible areas and having sufficient adhesion with asphalt mortar as well. For manufacturing rings with sufficient adhesion with the ring, it was selected PVC with high temperature resistance because of the need to acquire the same temperature with the asphalt mortar during the specimen production. The internal and external diameter of the ring was 21.5 mm and 26.5 mm respectively, with height 15 mm.
Figure H.2: The new asphalt mortar specimen with the critical location (a), the resulted graphs of parametric study of parabolas (b), the dimensions of new specimens (c) and the tested samples all broken in the middle (d)
## Appendix I

### Results of Direct Tensile Test

Table I.1: Uniaxial monotonic tension test result at -10°C (displacement rate: 0.05 mm/s)

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<th>Type of Material</th>
<th>Force Peak [N]</th>
<th>Stress [MPa]</th>
<th>Displacement [mm]</th>
<th>Strain</th>
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Table I.2: Uniaxial monotonic tension test result at -10°C (displacement rate: 0.0275 mm/s)

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Table I.3: Uniaxial cyclic tension test result at -10 °C (load controlled: 0.3 kN)

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Figure I.1: Direct monotonic tensile test results in time, including LVDTs’ displacement (displacement rate 0.0275 mm/s)
Figure I.2: Direct monotonic tensile test results in time, including LVDTs’ displacement (displacement rate 0.05 mm/s)
Appendix J
Induction Heating with Moving Coil
Figure J.1: Temperature distribution at different time intervals