Electromagnetic Evaluation and Optimization of a Combined Inductive Power Transfer and Inductive Healing Road

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by

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Abstract

Electrical vehicles (EVs) can be charged wirelessly with an inductive power transfer (IPT) system that uses a magnetic field to deliver power to the EV. Such a system could be embedded in the highway to charge EVs while they are driving. The magnetic field of the IPT system is created using coils that are exited with a high frequency current. Recent developments has created a low maintenance asphalt that can be healed by means of induction heating. Steel wool is added to the asphalt to make it suitable for induction heating, which is also done using coils that are exited with high frequency currents.

This thesis will investigate the feasibility of a combined inductive healing asphalt (IHA) and IPT highway. The main goal will be to reduce the losses in the IHA for an efficient operation of the IPT system, while maintaining the possibility to heat the asphalt by means of induction heating when desired. Also a preliminary economical analysis to estimate the financial profit of a low maintenance road is performed.

A detailed loss model for IPT systems is created that is used to describe the power transfer efficiency and predict the losses in the asphalt. Four concepts are suggested to obtain a feasible combination, which are (1) a sectioned road that separates the IPT and the IHA systems in the geometry, (2) IHA with anisotropic conductivity and permeability, (3) asphalt with heating elements tuned for a certain frequency and (4) asphalt with frequency dependent hysteresis losses. The loss models are verified using an experimental setup, which shows that the models created for concepts (1)-(3) provide an accurate description of the system.

Based on the models and the experimental results it is concluded that the concepts (1) and (3) can provide a feasible combination of an IHA highway in combination with IPT systems. The design of such a highway would however need careful considerations with respect to the dimensioning of the systems and external sources might be needed to apply induction healing for some parts of the highway. The result of the preliminary economical analysis shows that the expected reduction in maintenance will be more than the additional implementation costs and therefore the concepts are also economically feasible.
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1.1. Highway of 2030

In future transportation systems Electrical Vehicles (EVs) are expected to engage a dominant role. Due to the depletion of fossil fuels and their impact on the environment it is likely that there will be a shift from classical fossil fueled cars to vehicles that are powered in a sustainable manner. The Dutch Agreement on Energy for Sustainable Growth drafted in 2013 demands that all vehicles sold from 2035 are capable of driving without emission, and recent debates even plead to reduce the deadline to 2025. Vehicles without emission will most likely be EVs powered with electrical energy from a battery. It is therefore likely that the battery powered EV will dominate the highway in 2030. This change in transportation can benefit from a new infrastructure that combines several technologies in the highway, such that it does not only provide a path for transportation, but can also account for the generation of energy, the transportation of energy to the EVs and perform maintenance on the road in a fast and efficient way. A concept of combined technologies of the highway of 2030 is shown in figure 1.1.

Two of the main concerns about EVs are range anxiety and long charging times [7]. Inductive power transfer (IPT) allows Electric vehicles to be charges without the inconvenience of connecting the car to an electric socket. The transient time of a typical IPT system for EVs is less than 1 ms, which enables the technology to also be used on moving EVs [15]. This makes it possible to develop roads which are equipped with IPT systems that deliver power to the EV while driving, thus extending the driving range. A 30 kW IPT system in the road with a coverage of more than 50% supplies more power to the EV than it consumes, thus charging it while driving which will reduce the charging time when the EV reaches its destination [16]. Implementing IPT systems in the current infrastructure is therefore a very promising way to reduce the concerns of EVs.

Dutch highways are mainly covered with a 5 cm top layer of porous asphalt concrete. Porous asphalt concrete has advantages over dense graded asphalt concrete with respect to noise reduction and water drainage. However the porous structure does not benefit the durability of the asphalt and will cause premature loss of aggregates, which is called raveling [19]. Asphalt concrete is a self-healing material [11], but the practical problem with applying this self-healing property to real roads is that the self-healing process at ambient temperature is to slow to heal the asphalt in between the periods of no stress. The healing rate of the asphalt concrete will increase at higher temperatures [8]. Therefore a heating system in the road will enable the asphalt to use its self-healing properties in a time period which is feasible to apply in a situation where the traffic circulation cannot be interrupted for a long time. Recent studies have shown that induction heating is a very promising way to heat the asphalt [10]. For the asphalt to be able to be heated by means of induction it needs to be conductive, so eddy currents can be induced in the asphalt, or it needs to be hard magnetic so hysteresis losses can heat the asphalt. This is achieved by mixing additives in the asphalt, like graphite or steel wool. Asphalt which is treated with such additives will be referred to further on as inductive healing asphalt. Beside healing the system can also be used to prevent degradation of the asphalt in the winter. When water freezes it will expand, which can cause damage to the asphalt. This can be prevented by using the induction heating system as a de-iceing mechanism.
Induction heating is often implemented with high frequency coils, which is also the primary source of power in most IPT systems. Therefore there is great potential to combine the two technologies in the same road. The main challenge here is to enable the system to switch between inductive power transfer to the EVs and between the induction heating of the asphalt. While designing such a system the highest priority is that the losses in the asphalt are minimized when it is operating in IPT mode. The power rating of IPT systems can reach up to 50 kW, thus even a low factor of losses inside the asphalt can result in a large amount of actual losses.

![Design concept of the green energy highway of 2030. This concept shows the local generation of energy by means of wind energy (wind turbines and vortexes) and solar energy (SolaRoad and PV in noise barriers). There is a lane for IPT to EVs and the road has an inductive healing asphalt top layer.](image)

1.2. Typical system parameters

To get a better understanding of both systems some typical values of an inductive power transfer system for electrical vehicle applications and of an induction heating system for inductive healing asphalt will be investigated.

Inductive power transfer for electrical vehicle applications will operate in the range of 85 kHz-100 kHz, which is currently being standardized. To be able to provide enough energy to the vehicles it is likely that the power rating of IPT systems will be 50 kW. The magnetic flux density of the magnetic field that is produced by such a system will be in the order of several hundred millitesla. Once inductive power transfer has been integrated in the infrastructure it will be used continuously. The average distance between vehicles on the highway is 40 m, thus the typical size of an IPT system will also be of this magnitude such that there will be only one vehicle charging on a single system most of the time. The vertical distance between the primary of the IPT system and the secondary in the car should be as small as possible, therefore the IPT system will be embedded in the road as close to the surface as possible.

The operating frequency of inductive heating asphalt has a wider range than the IPT system. The frequency can not be too low, else there will be insufficient power dissipation in the asphalt. There is also an upper limit due to skin effect, but this still leaves a possible operating range of 1 kHz-500 kHz. Raveling and the development of cracks mostly occur in the porous top layer of the asphalt which is 5 cm thick. The strength of the asphalt degrades in 4-5 years to the point where induction heating is necessary to prevent raveling, thus the system will be used once every 4-5 years. When induction heating is applied the asphalt needs to be heated to 80 °C within several minutes. When the asphalt reaches 80 °C it needs to rest for a period of 3 to 6 hours, dependent on the asphalt mixture used and the damage that was present before the heating. In order to heat the asphalt to 80 °C within 15 min a power dissipation of 233 kW m⁻³ is needed inside the asphalt.

When the two systems are compared to each other by means of their typical values it can be seen that it
will be feasible to combine the two systems by means of the system requirements. The operating frequency can be chosen to be in the same range for both systems, such that the power electronics and all other electrical components can be combined. The power demands of the systems can be converted to power per meter of one driving lane. A driving lane of the Dutch highway where the speed limit is 100 km h$^{-1}$ or higher is 3.5 m wide. The power demand for the induction heating system then becomes 40.8 kW m$^{-1}$. The power demand for the inductive power transfer system is only 1.25 kW m$^{-1}$, which is a large difference. Another large difference is the utilization period of the systems. The inductive power transfer system will be used continuously as long as there are EVs on the road. The inductive heating however will only be used once every 4-5 years for 15 minutes. This might open an opportunity to overcome the difference in power demand. All system parameters that can be compared are listed in table 1.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Inductive power transfer</th>
<th>Inductive healing asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>85 kHz-100 kHz</td>
<td>1 kHz-500 kHz</td>
</tr>
<tr>
<td>Power</td>
<td>1.25 kW m$^{-1}$</td>
<td>40.8 kW m$^{-1}$</td>
</tr>
<tr>
<td>Utilization period</td>
<td>continuously</td>
<td>once every 4-5 year</td>
</tr>
</tbody>
</table>

Table 1.1: Typical system values of inductive power transfer and inductive healing asphalt compared to each other

1.3. Research questions

The research that is performed during this thesis was done in order to investigate the feasibility of combining inductive power transfer for EVs with Inductive healing roads. The main research question is stated below.

Is it possible to combine inductive healing asphalt and inductive power transfer for EVs in the same highway in a feasible way?

In order to answer this question a number of sub questions are answered during the research. These sub questions are sated below.

1. What are the physical processes that are involved in inductive power transfer and inductive healing asphalt and what are the important parameters for those processes?

2. How can the physical processes that are investigated in sub question 1 be modeled and investigated in an time efficient and accurate manner?

3. How can inductive healing asphalt and inductive power transfer be combined in a feasible way based on the answer of sub question 1?

4. What are the economical aspects of a full size implementation of the system?

In chapter 7 the answers to these research questions are summarized.

1.4. Structure of the thesis

This thesis is divided in multiple chapters that each will contribute to answer a sub question.

In chapter 2 the theoretical analysis of the electromagnetic properties of a road with IPT systems and inductive healing asphalt is performed. This is done by first analyzing IPT, induction heating and inductive healing asphalt separately. After that the theories are combined to fully described the electromagnetic behavior of the combined system.

In chapter 3 this electromagnetic description will be used to develop multiple concepts that could enable a feasible combination of the two technologies. The theoretical background of the concepts will be discussed and analyzed such that the performance of the concepts can be predicted.

The analysis of the performance will first be done numerically in chapter 4 by means of FEM models. This will allow a preliminary comparison of the concepts.
After that the concepts will be evaluated experimentally in chapter 5 to verify the theory and the numerical analysis with the actual system.

Finally in chapter 6 a study is performed to check the economical feasibility of a combined IPT and inductive healing asphalt system.
Theoretical Analysis

In this chapter the relevant theoretical analysis will be performed. First high power wireless charging for electrical vehicle applications will be considered. After that the principles of induction heating are evaluated. Then the relatively new subject of inductive healing asphalt is covered. Finally the three separate technologies will be merged to develop an equivalent circuit description of the system where the inductive healing asphalt and inductive power transfer will be used together.

2.1. Inductive Power Transfer

Every form of wireless power transfer of electromagnetic energy relies on time-varying electric, magnetic or electromagnetic fields. Electromagnetic fields can propagate through a vacuum thus there is no need for a medium to transfer the energy. Faraday’s law of induction 2.1 states that a time varying magnetic field can induce an electromotive force. Maxwell-Ampere’s circuital law 2.2 states that besides an electric current also a time-varying electrical field can induce a magnetomotive force. These two laws enable the wireless transfer of electrical energy.

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  
\[ \nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \]

Inductive power transfer entirely relies on the transfer of energy by means of the magnetic field. Two galvanic isolated, but magnetically coupled circuits can exchange energy with the two laws described above. In a primary circuit a time varying current will create a time varying magnetic field according to Maxwell-Ampere’s circuital law. Because of the magnetic coupling a part of that magnetic field can be captured by a secondary circuit making the induction of an electric field in the circuit possible. This electric field can then produce a current in the secondary circuit by means of Ohm’s law 2.3.

\[ \vec{J} = \sigma \vec{E} \]

A setup which has the electromagnetic behavior as described above is sketched in figure 2.1. There are two coils made of copper wire located on top of each other. There is an AC source which creates a sinusoidal current in the primary coil. This current will produce a sinusoidal flux of the same frequency. Depending on the geometry of the system some of the flux will be enclosed by the secondary coil, this is called the mutual flux \( \phi_M \). The flux that is produced by the primary coil, but not enclosed by the secondary coil is the leakage flux of the primary \( \phi_{\sigma 1} \). The mutual flux \( \phi_M \) will induce an electromotive force (emf) in the secondary circuit. Depending on the resistance of the wires that make up the coil and the resistance of the load a current will flow in the secondary circuit. This current will produce a magnetic field which is represented by the red flux lines. Also this flux has a leakage part \( \phi_{\sigma 2} \) and a mutual part. When the system is linear the mutual flux of the primary to the secondary is the same as the mutual flux of the secondary to the primary and thus the mutual flux generated by the secondary is also \( \phi_M \).
2. Theoretical Analysis

2.1. Equivalent circuit

The setup described with figure 2.1 can be represented by an electrical circuit. The circuit of figure 2.2 represents two magnetically coupled coils. The primary source $V_1$ will create a current flow through the primary coil, which is modeled as a resistance in series with an inductance. The resistance $R_1$ represents the copper losses in the primary coil. The inductance $L_1$ represents the total magnetic field that is produced by the current flow through the primary coil. The mutual inductance $M$ is the flux that is produced by the primary coil that is enclosed by the secondary coil. The dots at the coils define the direction of the current that is induced, which is a geometry parameter. In the secondary circuit there are also the copper losses $R_2$ and the inductance $L_2$, which represents the total magnetic field produced by the current flowing in the secondary circuit. However there is no source, but a load resistance $R_L$ which could for example model the equivalent resistance of a battery charger. Using linear circuit analysis a linear system describing the relations between the voltages and currents can be derived. The source is assumed to be sinusoidal, thus the phasor representation will be used.

\[
V_1 = (R_1 + j\omega L_1)I_1 + j\omega MI_2
\]

\[
0 = j\omega MI_1 + (R_2 + R_L + j\omega L_2)I_2
\]

By careful inspection of the equations of 2.4 a more convenient circuit representation of the system can be derived. Two new inductances, the leakage inductances, are defined as $L_{\sigma 1} = L_1 - M$ and $L_{\sigma 2} = L_2 - M$. These leakage inductances represent the magnetic field that is created by the coils which is not enclosed by
the other coil. The equations of 2.4 can then be rewritten as

\[
\begin{align*}
V_1 &= (R_1 + j \omega L_{\sigma 1} + j \omega M)I_1 + j \omega MI_2 \\
&= (R_1 + j \omega L_{\sigma 1})I_1 + j \omega M(I_1 + I_2) \\
0 &= j \omega MI_1 + (R_2 + R_L + j \omega L_{\sigma 2} + j \omega M)I_2 \\
&= j \omega M(I_1 + I_2) + (R_2 + R_L + j \omega L_{\sigma 2})I_2.
\end{align*}
\] (2.5)

These equations both contain the term \(j \omega M(I_1 + I_2)\), thus they share the same branch in a circuit representation. The circuit corresponding to these equations is given in figure 2.3.

![Figure 2.3: Simplified IPT circuit with a sinusoidal primary source and a resistive secondary load.](image)

**2.1.2. Resonant compensation**

The setup of figure 2.1 is capable of wireless power transfer, but without adjustments the power that can be transferred will be very low. The emf \(E\) induced in the secondary circuit is

\[
E = j \omega M I_1,
\] (2.6)

therefore it is convenient to operate the system at high angular frequencies \(\omega\), because the induced emf is linearly proportional to the frequency. But the impedance of the system is also proportional to the frequency, thus the current that will be flowing at high frequencies is very low, reducing the actual power that can be transferred in such a system.

To overcome these limitations resonant compensation can be used. This means that capacitances are added to the primary and secondary side to compensate for the leakage inductances. This can be done in various ways. In the primary side the compensation capacitance can be added in series or in parallel with the source and in the secondary system the compensation capacitance can be added in series or in parallel with the load. Many research has been performed on the optimal compensation strategy for IPT for EV applications. The result is that series-series compensation is the most convenient option [2], thus that is the setup that will be explained here.

![Figure 2.4: IPT circuit with series compensation in the primary and secondary circuit.](image)
Figure 2.4 shows a series-series compensated IPT system. The components $R_1$, $C_1$ and $L_{a1}$ can be combined in an equivalent impedance of

$$Z_1 = R_1 + j\omega L_{a1} + \frac{1}{j\omega C_1}$$

$$Z_1 = R_1 + j(\omega L_{a1} - \frac{1}{\omega C_1}).$$  \hspace{1cm} (2.7)

The frequency at which the highest currents can be achieved is the frequency where this impedance reaches its minimum value. That is when

$$j(\omega L_{a1} - \frac{1}{\omega C_1}) = 0$$

$$\frac{1}{\omega C_1} = \omega L_{a1}$$

$$C_1 = \frac{1}{\omega^2 L_{a1}}.$$  \hspace{1cm} (2.8)

The same principle holds for the series RLC circuit on the secondary side. An important remark is that in this system only the leakage fluxes $L_{a1}$ and $L_{a2}$ are compensated. These leakages are dependent on the mutual inductance, which is determined by the geometrical displacement and orientation of the secondary with respect to the primary. Wireless power transfer is however applied in situations where the object that needs to be powered is not fixed to a specific location. Therefore the mutual inductance will vary in practical applications, which means that also the values for the compensation capacitances would need to be adapted. But for systems with an air gap of more than 5 cm the mutual inductance will be small compared to the self inductances $L_1$ and $L_2$ of the coils. Therefore it is a good approximation to select the compensating capacitances to compensate for the self inductance of the coils. The wires that realize the coils will have a resistance, which leads to a broadening of the resonance peak as will be shown next. This increase in bandwidth will also limit the effect of a changing mutual inductance.

**Bandwidth**

The bandwidth of a single series resonance circuit as shown in figure 2.5 is defined as the range of frequencies in which the power dissipated in the resistance of the RLC circuit is equal to or greater than half of the power at the resonance frequency. This definition is often referred to as the −3 dB bandwidth, because a gain of 0.5 is almost equal to a gain of −3 dB. A sketch of a frequency response of a RLC circuit is shown in figure 2.6. In order to calculate the bandwidth it should first be noted that

$$P_{-3\text{dB}} = \frac{P_r}{2}$$

$$I_{-3\text{dB}} = \frac{I_r}{\sqrt{2}}.$$  \hspace{1cm} (2.9)

where $P_r$ and $I_r$ are respectively the power and the absolute value of the current at the resonance frequency $\omega_r$. The current $I_r$ is determined by the input voltage $V_{in}$ as

$$I_r = \frac{V_{in}}{|Z_r|} = \frac{V_{in}}{R},$$  \hspace{1cm} (2.10)

where $Z_r$ is the impedance of the circuit at the resonance frequency $\omega_r$. Thus the impedance $Z_{-3\text{dB}}$, at which the power transfer is halve, can be calculated as

$$\frac{1}{\sqrt{2}} \frac{V_{in}}{R} = \frac{V_{in}}{|Z_{-3\text{dB}}|}.$$  \hspace{1cm} (2.11)

This equation can be written in terms of $\omega$ as

$$\sqrt{2} R = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

$$\omega^4 L^2 + \left(R^2 - \frac{L^2}{C^2}\right)^2 + \frac{1}{C^2} = 0.$$  \hspace{1cm} (2.12)
There are two roots for this equation, which define the lower cut-off frequency $\omega_L$ and the upper cut-off frequency $\omega_H$.

$$\omega_L = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\omega_H = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}} \quad (2.13)$$

The bandwidth $\text{BW}$, in radians per second, of the resonant circuit can be calculated from the difference between the two cut-off frequencies which is

$$\text{BW} = \omega_H - \omega_L = \frac{R}{L} \quad (2.14)$$

This bandwidth is the ratio between the resistance and the inductance, and thus independent of the capacitance in the circuit. As stated before it can happen that the resonance frequencies of the primary and the secondary circuit are not exactly equal. This can happen in any practical setup where the values of the inductances and capacitances have a slight error, or when the mutual inductance, and therefore the leakage inductance, between the two circuits change. The impact of this difference in the resonance frequencies is dependent on the bandwidth of both resonant circuits. If the resonance frequency of the primary is in the range of the bandwidth of the secondary and vice versa then it is still possible to transfer a reasonable amount of power between the two circuits.

### 2.1.3. Implementation

Practical implementation of an inductive power transfer system can be done in many different ways. A main separation can be made between discrete systems and distributed systems, which are sketched in figure 2.7. A discrete systems as shown in figure 2.7a consists of a primary that is embedded at a certain location and the dimensions of the secondary are comparable to that of the primary. Power transfer from the primary to the secondary is only possible when the secondary is closely aligned. Such a system can be useful for electrical vehicles when it is implemented in a parking space. This would save a driver the inconvenience of plugging the EV into a charger, and it would also make the system invulnerable to vandals that might try to unplug EVs. Distributed systems are able to provide power to the secondary over a larger range in space. This can be achieved by realizing the primary using longitudinal loops as demonstrated in figure 2.7b. In this way a track can be formed over which the coupling between the primary and the secondary is substantiation to enable power transfer. Such an implementation is likely to be used in setups where the secondary is not stationary, as is the case of an EV on a highway.
Pickup design

The secondary coil in a distributed system is called the pickup. It is very important that the system is resistant to misalignment for applications where the displacement between the primary and the secondary during power transfer is not fixed. Misalignment can be expected on a highway, or even in situations where the driver manually needs to park the EV above a charge pad. Many studies are dedicated to reduce the effect of misalignment. This can be done by shaping the magnetic field using ferrites and aluminum shields, or by changing coil shapes such that the coupling between the primary and the secondary is more constant over a wider range.

Different pickup shapes are shown in figure 2.8. The misalignment properties of systems where the primary and the secondary are the same will be discussed now. The most basic shape is the flat circular pickup which is shown in 2.8a. Because of the flat and wide shape the pickup will be able to produce a decent amount of magnetic coupling with the primary. An additional benefit is that the pickup would be easy to mount underneath an electrical vehicle. The magnetic field created by a circular coil will have circular symmetry. The magnetic flux density will have its highest value in the center of the coil. When there is misalignment in the $x$ or $y$ direction the coupling will decrease with a high rate.

Another simple pickup shape is the square pickup as shown in 2.8b. The magnetic coupling without any misalignment of a square pickup will be slightly lower compared to a circular pickup of the same area. This is because the magnetic flux density in the center of the coil will be lower due to the distorted shape. The misalignment properties will however be better. When the coils are misaligned in the $x$ or $y$ direction, because there will be a larger area that is still overlapping and because of the slightly more constant magnetic field. If the square was changed to be a rectangle, then the misalignment properties in the direction of the longer side will be even better.

Figure 2.8c shows the shape of an DD pickup. This are two rectangles that are located next to each other. They are connected in such a way that the current circulation in one rectangle is clockwise and in the other rectangle counterclockwise. This will create a so called polarized pickup. This pickup will have a coupling similar to the square coil when aligned properly. The misalignment in the $y$ direction will also have the same behaviour as the square pickup. The misalignment performance in the $x$ direction behaves different. The magnetic coupling will decrease quickly with the misalignment in the $x$ direction, and it will even reach zero when the pickup is displaced by a quarter of the width. But after the zero point it will rise again because left D of the primary pickup will be aligned with the right D of the secondary pickup. When the misalignment is proceed even further into the $x$ direction the coupling will again drop.

The final pickup shape to be discussed is the DDQ pickup shown in figure 2.8d. An extra square quadrature coil is added to this pickup. The quadrature coil is placed symmetrically in the center of the DD, such that the mutual inductance between the DD and the Q is zero. The purpose of the quadrature coil is to cancel the effect of the zero in the mutual coupling that occurred in the DD pickup. This pickup shape will have the best performance with respect to misalignment. It is however also the topology that requires the largest amount of materials.

One other method to increase the magnetic coupling is to shape the magnetic fields in a more desired way. In every of the previously discussed pickups the magnetic field will be symmetric in the $z$ direction. This means that half of the flux will be in the direction away from the secondary pickup and is therefore not used,
2.1 Inductive Power Transfer

(a) Circular pickup.

(b) Square pickup.

(c) DD pickup.

(d) DDQ pickup.

Figure 2.8: Different common used pickup shapes, (a) Circular pickup, (b) Square pickup, (c) DD pickup and (d) DDQ pickup.

as illustrated in figure 2.9a. With ferrites and aluminium sheets below the primary and above the secondary the flux can be concentrated in the direction of the pickup it needs to couple with. This will create a so called single sided pickup, because the flux is mainly concentrated towards a single side. Figure 2.9b shows a single sided primary. The magnetic flux density will be reflected upward, which results in a higher flux density above the coil. With such an configuration a higher magnetic coupling can be achieved with a secondary located above the coil.

Figure 2.9: Improved pickup design with field shaping. Figure (a) shows the cross-sectional magnetic flux of an unmodified pickup, which is symmetrical in the plane \( z = 0 \). Figure (b) shows the cross-sectional magnetic flux of a single sided pickup, with ferrites and aluminium to reflect the flux upwards.

Highway integration

Distributed wireless power transfer for electrical vehicle applications has not been implemented very often. Several implementations have been reported, like a wireless powered tram track of 2.2 km that was manufactured in 2011 in Seoul Grand Park, a combined zoo and theme park, in Korea. The same technology was used again in 2013 to power electrical buses in Seoul over a 24 km track. In figure 2.10 the primary coils that were used in Seoul Grand Park are shown. The distributed primary coils were implemented in three sections of approximately 120 m, located at different places of the 2.2 km track. Each section has its own inverter which
supplies the power for the coils. The individual sections are again divided into segments of 24 m, which is thus the size of one single coil.

Integration of inductive power transfer for electrical vehicles in highways is most likely to be done in the same topology as used in Korea. Figure 2.11 shows a schematic overview of an implementation. The highway will be divided in sections that are dimensioned to power a single vehicle at a time. Every section is then divided into segments of one coil. The smaller segments will result in lower copper losses, less leakage fields and thus a better efficiency. The segment size used in Korea was 24 m, but a feasibility study for wireless power transfer on the highway in the UK has suggested a segment length of 9 m. In section 2.3.6 the thermal properties of inductive heating asphalt are analyzed. The result of this analysis is that the power needed to properly heat the asphalt is 40.8 kW per meter of highway. With a 50 kW IPT system the maximum segment size is 1.25 m. Such a short segment size is not desired when the electrical vehicles will drive with a normal highway speed of 100 km h$^{-1}$-120 km h$^{-1}$. The vehicle will travel the segment distance of 1.25 m in approximately 40 ms, which means that the system needs to be able to switch very fast to different segments. There are however other solutions one can think of to overcome this problem. The topology could be adjusted in such a way that the inverters of different sections can cooperate in powering a single segment. In this way every coil can be powered with integer multiples of the designed system power. The power rating of the coils will then be overloaded, but for the short period of time that this is necessary it would probably not damage the system significantly.
2.2. Induction Heating

An object can be heated by means of magnetic induction when it consists of an electrically conductive and/or magnetic material. When such an object, called a workpiece, is placed in a time-varying magnetic field eddy currents will be induced inside because of Faraday’s law of induction. These currents will dissipate energy because of the resistance of the workpiece, which will cause Joule heating. Another mechanism that results into heating of the workpiece is magnetic hysteresis.

2.2.1. Simple induction heating system

In order to identify the important parameters for an induction heating system a simple setup will be analyzed. Figure 2.12 shows the setup in a cylindrical coordinate system. It consists of an infinite long solenoid with an infinite long workpiece inside. The solenoid is sourced with a sinusoidal current with an angular velocity of $\omega$. The number of turns per meter is defined as $n = N/l$. The radius of the workpiece is $r$, and it is assumed that the wire making up the solenoid is very thin compared to the radius of the workpiece. The material of the workpiece has a magnetic permeability of $\mu = \mu_r \mu_0$ and a conductivity of $\sigma$. The strategy to derive the power that is dissipated in the workpiece is to first express the magnetic field due to the current in the solenoid. This field will then be used to calculate the induced emf in the workpiece such that the currents in the workpiece can be derived from which the power can be defined.

Maxwell-Amperes law in integral form in the time harmonic domain as defined in equation 2.15 is used to find the magnetic field intensity $\vec{H}$.

$$\oint_{\partial S} \vec{H} \cdot d\vec{l} = \iint_S \vec{J} \cdot dS + j\omega \iint_S \vec{D} \cdot dS$$

(2.15)

It is assumed that there is no displacement current in the setup. Also the magnetic field intensity is assumed to be homogeneous with only a non-zero $z$ component inside the solenoid and zero outside the solenoid. The contour $\partial S$ and corresponding surface $S$ that is taken is shown in figure 2.13. The field is assumed zero outside the solenoid, and only has a $z$ component inside the solenoid thus the contour integral of $\vec{H}$ is just $l \|\vec{H}\|$. The surface integral of the current density will the number of turns that is enclosed by the surface times the current trough one turn. The magnetic field intensity is then

$$l H_z = n I$$
$$H_z = n I.$$ (2.16)

The magnetic flux density $\vec{B}$ is related to the magnetic field intensity $\vec{H}$ through the magnetic permeability $\mu$. The field density inside the workpiece becomes

$$B_z = \mu H_z = \mu n I.$$ (2.17)
To get an expression for the field Faraday’s law of induction in integral form in the time harmonic domain as defined in equation 2.18 will be used.

\[ \oint_{\partial S} \vec{E} \cdot d\vec{l} = -j\omega \iint_{S} \vec{B} \cdot d\vec{S} \] (2.18)

The electric field will only have a non-zero component in the \( \phi \) direction because the magnetic field is only in the \( z \) direction. Also because of the symmetry of the system it can be concludes that the electric field will be the same magnitude on every \( \phi \) coordinate for a constant \( r \). Therefore the contour that is chosen to evaluate the electric field is shown in figure 2.14. The electric field can then be written as

\[ E_{\phi} \oint_{\partial S} 1 \cdot d\vec{l} = -j\omega B_z \iint_{S} 1 \cdot d\vec{S} \]
\[ E_{\phi} 2\pi r = -j\omega \mu \pi r^2 I \]
\[ E_{\phi} = -\frac{j\omega \mu n r}{2} I. \] (2.19)

The current density inside the workpiece due to the electric field is calculated from Ohms law.

\[ J_{\phi} = \sigma E_{\phi} \]
\[ J_{\phi} = -\frac{j\omega \mu n r}{2} I. \] (2.20)

The power per length dissipated in the workpiece can be calculated from the current density \( J_{\phi} \) and the conductivity \( \sigma \). The expression for the power dissipated in a volume of the workpiece is

\[ P = \iiint_{V} \frac{J_{\phi}^2}{2\sigma} dV. \] (2.21)

The factor 2 in the denominator is due to the fact that the current density is sinusoidal and the RMS value is to be used in the calculation of the power. The volume integral will be evaluated over a piece of length \( l \) can
be calculated as

\[ P = \frac{1}{2\sigma} \iiint_V |\mathbf{B}|^2 \, dV \]

\[ = \frac{1}{8\sigma} \iiint_V (\omega\sigma\mu n r |\mathbf{I}|)^2 \, dV \]

\[ = \frac{\sigma\omega^2\mu^2 n^2 |\mathbf{I}|^2}{8} \int_0^t \int_0^{2\pi} \int_0^r (r^2) r \, dr \, d\phi \, dz \]

\[ = \frac{\sigma\omega^2\mu^2 n^2 |\mathbf{I}|^2}{32} \int_0^t \int_0^{2\pi} r^4 \, d\phi \, dz \]

\[ = \frac{\sigma\omega^2\mu^2 n^2 |\mathbf{I}|^2}{32} \int_0^t \frac{2\pi r^4 \, dz}{l} \]

(2.22)

2.2.2. Important parameters

From the analytical derivation of the power dissipated in the workpiece some important conclusions can be drawn with respect to the power that will be dissipated in the workpiece. First of all the frequency \( \omega \) is has a big influence on the power that is dissipated, because the power is proportional to the square of the frequency. This is almost independent on the material properties or geometrical appearance of the system, because it is embedded in the time harmonic Maxwell equations. It should be noted that the analysis did not account for skin effect. As soon as skin effect will play a role, that is when \( r > \sqrt{\frac{2}{\omega\sigma\mu} \mu} \), the magnetic field cannot penetrate the full depth of the workpiece. Thus the magnetic field will not be uniform anymore and will cause the induced current density in the center region to be less. This will result in a lower power that is dissipated.

The power dissipation is linearly proportional to the conductivity \( \sigma \), however it’s relevance to the power that is dissipated in induction heating systems should not be underestimated. The relation between the power and the conductivity is again independent on the geometry of the system, because it originates from Ohm’s law. Therefore the dissipated power will always rise with a larger conductivity as long as when the skin depth is bigger than the dimensions of the system.

The permeability \( \mu \) seems to be as important as the frequency. But this is only because of the chosen geometry of the system. In the infinite cylinder example there is no air gap in the core. Also the material is assumed to experience no saturation. In realistic induction heating systems, like a finite solenoid or a plate above a flat coil, there will be a large path through the air for the magnetic field. The reluctance of the air is independent from the reluctance of the workpiece. Thus when the permeability increases the total reluctance will decrease at first, but when the reluctance of the workpiece becomes very small compared to the reluctance of the air this effect will not be significant anymore. A higher permeability will also decrease the skin depth, which can affect the power dissipation is a negative manner when the skin depth is smaller than the dimensions of the system.

Finally there are some geometry parameters that influence the power that is dissipated. The number of turns \( N \) is directly related to the magnetic field strength. Increasing the number of turns will enhance the power dissipation quadratically. In this example it is assumed that the material does not saturate. The relation between power and number of turns is not quadratically anymore when the field that is generated will saturate the material.

2.2.3. Equivalent circuit

For the induction heating system it is also possible to develop an equivalent circuit that describes electrical properties of the process. To illustrate the process the equivalent circuit of a toroidal workpiece with a small air gap will be derived. This is done using magnetic circuits. The setup is shown in figure 2.15. The system has \( N \) turns trough which a sinusoidal current \( \mathbf{I} \) flows. The major radius of the toroid is \( r_1 \) and the minor radius is \( r_2 \). The toroid has a small air gap with length \( l_g \) and the cross sectional area of is \( A \). Furthermore the material of the toroid has a conductivity of \( \sigma \) and a relative permeability of \( \mu_r \).
The magnetic circuit of the system is shown in figure 2.16. It is assumed that all the flux is contained in the core, thus that there is no leakage flux, and that the size of the air gap is small compared to that of the core such that the magnetic flux density in the air gap is equal to the magnetic flux density in the core. It is also assumed that the magnetic flux is uniformly distributed over the cross sectional area of the core, which is a good approximation for situations where the major radius $r_1$ is a lot larger than the minor radius $r_2$. The two reluctances $R_{gap}$ and $R_{core}$ can be calculated from the area of the core and the permeability. The total reluctance $R_{tot}$ is easily calculated from the series connection.

$$R_{tot} = R_{core} + R_{gap}$$

$$= \frac{2\pi r_1 - l_g}{\mu_0 \mu_r r_2^2} + \frac{l_g}{\mu_0 \pi r_2^2}$$

By definition it holds that

$$R_{tot} = \frac{\Phi}{NBA} = \frac{N}{R_{tot}} I$$

The axis system as shown in figure 2.17 is used. The magnetic flux density inside the core and the air gap will be equal to

$$B_\phi = \frac{N}{R_{tot} A} I$$

From this expression for the magnetic flux density the electric field can be calculated as

$$E_\theta = -j\omega \frac{\rho}{2} \frac{N}{R_{tot} A} I$$
Therefore the current induced in the toroid will be
\[
J_\theta = -j \omega \sigma \frac{N}{2 R_{tot} A} \mathbf{I}
\] (2.27)

With the expression for the current density in the toroid the power dissipated in the core can be calculated as
\[
P = \int \int \int_V \frac{|J|^2}{2 \sigma} dV
= \frac{\sigma}{8} \left( \omega \frac{N}{R_{tot} A} |\mathbf{I}| \right)^2 \int_0^{2\pi} \int_0^{r_2} \int_0^{r_1} \rho^2 r_1 d\rho d\phi d\theta
= \frac{\sigma \omega^2 N^2 \pi^2 r_1 r_2^4}{8 R_{tot}^2 A^2} \mathbf{I}^2.
\] (2.28)

From this result it can be concluded that the power dissipated in the toroid will increase when the reluctance $R_{tot}$ becomes lower. From a material point of view this reluctance can be decreased by increasing the permeability $\mu_r$. But due to the reluctance of the gap, which can only be reduced by reducing the gap length $l_g$, there is a lower limit to which the total reluctance can decrease.

From the result of (2.28) the circuit in 2.18 can be derived. The coil that provides the magnetic field can be modeled in the usual way as an inductance $L$ in series with a resistance $R_{coil}$ that represents the conduction losses in the copper of the coil. The expression for the power that was derived in (2.28) the form $P = R_{wp} \mathbf{I}^2$ can be noticed, with
\[
R_{wp} = \left( \frac{\sigma N^2 \pi^2 r_1 r_2^4}{8 R_{tot}^2 A^2} \right) \omega^2.
\] (2.29)
This resistance is dependent on the square of the frequency. The part before the $\omega^2$ is dependent on the geometry of the system and the materials involved, but is constant over a large range of frequencies. Therefore for a given situation the induction heating constant can be defined as
\[
R_{wp} = K_h \omega^2,
\] (2.30)
which for the toroidal system is equal to
\[
K_h = \left( \frac{\sigma N^2 \pi^2 r_1 r_2^4}{8 R_{tot}^2 A^2} \right).
\] (2.31)
The derived resistance $R_{wp}$ should be added to the circuit in series with the inductance $L$ and the resistance $R_{coil}$, because the power dissipated in the workpiece is $P = R_{wp} \mathbf{I}^2$, thus the same current $\mathbf{I}$ that flows through the coil must flow through the resistance that represents the workpiece.

Another way to model the eddy current losses in an electrical circuit is by means of complex inductances as described in [12, 1]. The circuit then transforms to that shown in figure 2.19. The complex inductance $L$ can be written as $L = L_r - j R_L$. The impedance of the inductance $L$ will then become
\[
Z_L = \omega R_L + j \omega L_r,
\] (2.32)
which is equal to the impedance of a frequency dependent resistance in series with an inductance. The resistance represents the eddy current losses of the system. The advantage of such an approach is that the complex inductance is easy to derive from FEM simulations. The disadvantage is that the resistance that is modeled with the complex inductance is dependent on the frequency instead of the frequency squared. Therefore the the value of the complex inductance will change with frequency. When the frequency is low enough such that skin effect, proximity effect and other disturbances do not occur then it is possible to extract the induction heating constant $K_h$ from measurements by simply dividing $R_L$ by the frequency $\omega$.

$$K_h = \frac{R_L}{\omega}$$ (2.33)

![Figure 2.19: Electrical circuit that describes the induction heating process with a complex inductance.](image)

### 2.2.4. Hysteresis losses

Eddy currents are not the only losses in a material due to the changing magnetic field. Magnetic materials are able to store magnetic energy of an external magnetic field by a process called magnetization. However not all the magnetic energy that is stored the material can be retrieved when the material is demagnetized. The difference in the stored and the retrieved energy is transformed to heat. When the magnetic field has a sinusoidal waveform, like the fields used in IPT, this energy will be lost every period of the oscillation. This means that the energy lost due to hysteresis needs to be considered at the high operating frequencies of IPT. In this section hysteresis losses in magnetic materials will be analyzed.

### Sources of the magnetic field

There are two general sources of the magnetic field. The first source is implemented in Ampere's circuital law (2.34), from which it follows that a moving charge, e.g. a current, induces a magnetic field.

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$ (2.34)

This phenomenon is noticeable from large systems, like a current trough a wire, until microscopic systems, like an orbital electron in an atom.

The second source of the magnetic field is the spin, the quantum mechanical analogue of angular momentum, of elementary particles. It is often stated that the magnetic moment of particles containing spin is analogue to a magnetic moment that will be created when a charged sphere is rotating around its axis, thus relating it to Ampere's circuital law. This is a wrong analogy [18]. The spin of elementary particles is a fixed property like its mass and charge. If it would be like a rotating sphere the rotation could be increased or decreased by interaction with other particles. Also the structure of an electron is not known and is assumed to be a point particle, e.g. a particle with no radius [18][3]. This immediately disagrees with the idea of a rotating sphere. The magnetic moment of an elementary particle is however related to the angular momentum of the particle by [13].

$$\mathbf{\hat{\mu}} = \gamma \mathbf{\hat{L}}$$ (2.35)
where \( \mathbf{\mu} \) is the magnetic angular momentum, \( \mathbf{L} \) is the spin angular momentum and \( \gamma \) is the gyromagnetic ratio. The gyromagnetic ratio depends on the charge, mass and the configuration of the system. For an electron the gyromagnetic ratio is given by \( \gamma = -g \frac{e}{2m} \), where \( e \) is the charge of the electron, \( m \) is the mass of the electron and \( g \) is a factor that characterizes the state of the atom. It is 1 for a pure orbital moment, or 2 for a pure spin moment, and anything in between for a more complicated system like an atom [5].

**Magnetic flux density**

The sources of the magnetic field will produce a field with a certain intensity. This magnetic field intensity is denoted with the letter \( \mathbf{H} \). The H field will generate a magnetic flux density \( \mathbf{B} \). The relation between the H and the B field will depend on the materials involved in the situation. When no matter is involved, thus in a vacuum, the two fields are linearly proportional to each other by a constant which is called the permeability of free space \( \mu_0 \). The relation between H and B is given by

\[
\mathbf{B} = \mu_0 \mathbf{H}.
\]

(2.36)

This relation is different when there is matter involved. The particles in the matter will respond to the external magnetic field. This response is called magnetization and is added to the H field to represent the total magnetic field. The relation between B and H then becomes

\[
\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}).
\]

(2.37)

where \( M \) is the magnetization. Very generally two things can happen to the magnetic flux density when a material is placed in the presence of a magnetic field. The flux density can be higher than that of the flux density in vacuum, or it can become lower. Thus this corresponds respectively to either a positive value for the magnetization \( M \), or a negative value of the magnetization. Materials produce a negative magnetization are called diamagnetic materials. The materials that generate a positive magnetization can be divided in four classes which are paramagnetic, ferromagnetic, ferrimagnetic and anti-ferromagnetic. The classification of these materials is done on the microscopic phenomena that result in the enhancement of the magnetic flux density. All of the five types of responses to the magnetic field will now be discussed.

**Diamagnetism**

When the atoms in a material do not possess a permanent magnetic moment the material will behave diamagnetic. In an atom with no net magnetic moment all the spins cancel each other. Also the orbital magnetic moments will cancel due to electrons which are in the same orbit, but rotate in the opposite direction. These orbital electrons will however respond to the applied magnetic field. According to Lenz’s law they will try to oppose the external field, resulting in a slightly smaller magnetic flux density inside the material [17]. This effect is present in every material, but in paramagnetic and ferromagnetic materials the enhancement of the magnetic flux is stronger than the diamagnetic effect, thus the total magnetic flux density will be larger.

**Paramagnetism**

In paramagnetic materials the individual atoms have a magnetic moment. To reduce the external field due to the magnetic moment, and thus to reduce the energy stored in the material, all the magnetic dipoles will have a random direction. Therefore there is no net magnetic moment produced by the material. When an external magnetic field is applied to the material the atomic dipoles will tend to align slightly with this external field. Now that there is a preferable direction for the atomic magnetic dipoles there will be a net field that is aligned with the external field, thus enhancing the magnetic field inside the material.

**Ferromagnetism**

Ferromagnetic materials also have atoms with a magnetic dipole moment. The difference with paramagnetism is that due to the crystal structure of the material there are domains in which all the atomic dipoles point in the same direction. Depending on the shape of the crystal structure the domains that are formed will point in different directions. This is again in such a way that the external magnetic field is minimized, thus reducing the energy inside the material. When an external field is applied these domains can ‘flip’ in
the direction of the applied field, which will result in a magnetization of the material. This will enhance the magnetic flux inside the material with magnitudes that range from a few hundreds till thousands.

**Ferrimagnetism**

An effect that is very similar to ferromagnetism is ferrimagnetism. This are materials made of multiple elements, most often oxides [17], where the atoms form a crystal structure. In this structure however the magnetic moment of one element opposes the magnetic moment of the other. Because one magnetic moment is larger than the other the domains themselves still have a magnetic moment and thus they behave ferromagnetic. But in general the magnetization of ferrimagnets will be lower than that of ferromagnets.

**Anti-ferromagnetism**

An extreme case of ferrimagnetism is anti-ferromagnetism. Here the opposing magnetic moments have the same magnitude, thus they cancel each other resulting in no net magnetic moment. On macroscopic scale these materials behave just like paramagnetic materials.

**Complex permeability**

The magnetic flux density $\vec{B}$ will always lag the magnetic field $\vec{H}$, because the magnetic domains have a certain delay while they arrange with the external field. This effect will be noticeable at high frequencies. Figure 2.21 gives a time domain representation of the magnetic field and the lagging magnetic flux density, which are created by a sinusoidal source. In phasor representation the magnetic field $\vec{H}$ can be written as

$$\vec{H} = H_0 e^{j\omega t}. \quad (2.38)$$

When the magnetic flux density lags with an angle of $\delta$ then the phasor $\vec{B}$ will be

$$\vec{B} = B_0 e^{j\omega t - j\delta}. \quad (2.39)$$

Then, by definition, the permeability $\mu$ equals

$$\mu = \frac{\vec{B}}{\vec{H}} = \frac{B_0}{H_0} e^{-j\delta}. \quad (2.40)$$

Using Euler's formula the complex permeability can found as

$$\mu = \frac{B_0}{H_0} (\cos \delta - j \sin \delta) = \mu_0 \mu_r \cos \delta - j \mu_r \sin \delta = \mu'_r - j \mu''_r. \quad (2.41)$$

![Diagram of the relations of the complex permeability.](image)

In figure 2.22 the magnetic field is plotted with respect to the magnetic flux density to obtain the B-H curve, which shows the hysteresis loop. The SI units of the magnetic field and the magnetic flux density are
2.2. Induction Heating

inspected to derive an expression for the power dissipated in a piece of material due to hysteresis. The SI units for the magnetic flux density and the magnetic field are

\[ B = \frac{\text{Wb}}{\text{m}^2} = \frac{\text{kg}}{\text{s}^2 \text{A}}, \quad H = \frac{\text{A}}{\text{m}}. \]  \hspace{1cm} (2.42)

The multiplication of \( B \) and \( H \), and thus an area in the B-H curve is equivalent to

\[ B \cdot H = \frac{\text{kg}}{\text{s}^2 \text{A}} \cdot \frac{\text{A}}{\text{m}} = \frac{\text{kg} \cdot \text{s}^2 \text{A}}{\text{m}} = \text{J/m}^3. \]  \hspace{1cm} (2.43)

Thus an area inside the B-H curve corresponds energy per unit volume. In figure 2.22 the area \( A_1 + A_2 \) is the energy per unit volume that is used during half a period to magnetize the material. The area \( A_1 \) is the energy per unit volume that is released from the material when demagnetizing the material. Area \( A_2 \) represents the difference between these energies, and is thus the energy that is lost inside the material due to hysteresis in half a period.

To obtain an expression for the losses the area of \( A_2 \) needs to be calculated. This can be done from the time domain representation of \( H \) and \( B \). The time domain representation of the curves in 2.21 is

\[ H(t) = H_0 \cos(\omega t) \]
\[ B(t) = B_0 \cos(\omega t - \delta). \]  \hspace{1cm} (2.44)

These equations give a parametric description of the hysteresis loop, with the time \( t \) as a parameter. The area of \( A_1 + A_2 \) can be obtained by integrating the parametric equations from \( t = -\frac{\pi}{2\omega} \) to \( t = \frac{\delta}{\omega} \).

\[ A_1 + A_2 = \int_{-\frac{\pi}{2\omega}}^{\frac{\delta}{\omega}} H(t) \frac{dB(t)}{dt} \, dt \]
\[ = -\omega H_0 B_0 \int_{-\frac{\pi}{2\omega}}^{\frac{\delta}{\omega}} \cos(\omega t) \sin(\omega t - \delta) \, dt \]
\[ = \frac{1}{4} H_0 B_0 \left[ 2\omega t \sin(\delta) + \cos(\delta - 2\omega t) \right]_{-\frac{\pi}{2\omega}}^{\frac{\delta}{\omega}} \]
\[ = \frac{1}{4} H_0 B_0 \left( 2\delta \sin(\delta) + \cos(-\delta) + \pi \sin(\delta) - \cos(\delta + \pi) \right). \]  \hspace{1cm} (2.45)
In the same way the area $A_1$ can be calculated by integrating the parametric equations from $t = \frac{\pi}{2\omega}$ to $t = \frac{\delta}{\omega}$.

$$A_1 = \int_{\frac{\pi}{2\omega}}^{\frac{\delta}{\omega}} H(t) \frac{dB(t)}{dt} dt$$

$$= -\omega H_0 B_0 \left[ \frac{\delta}{2\omega} \cos(\omega t) \sin(\omega t - \delta) dt \right]$$

$$= \frac{1}{4} H_0 B_0 \left[ 2\omega t \sin(\delta) + \cos(\delta - 2\omega t) \right] \frac{\delta}{\omega}$$

$$= \frac{1}{4} H_0 B_0 \left( 2\delta \sin(\delta) + \cos(\delta) - \pi \sin(\delta) - \cos(\delta - \pi) \right).$$

The difference between these two areas is the energy per unit volume that is lost inside the material during half a period.

$$A_2 = (A_1 + A_2) - A_1$$

$$= \frac{\pi}{2} H_0 B_0 \sin(\delta)$$

$$= \frac{\pi}{2} |\mu| H_0^2 \sin(\delta).$$

From the diagram in figure 2.20 it is clear that $|\mu| \sin(\delta) = \mu''$. Therefore the energy $E_{hyst}$ that is lost during a total period in a unit volume of the material is

$$E_{hyst} = \pi \mu'' H_0^2.$$

This energy is lost every cycle, thus at a frequency $f$ the power that is dissipated in a piece of material with a volume $V$ in a magnetic field $H$ is

$$P_{hyst} = \iiint_V \pi f \mu'' |H|^2 dV$$

$$= \iiint_V \frac{1}{2} \omega \mu'' |H|^2 dV. (2.49)$$

This power dissipation is linearly proportional to the frequency. Previously it has been found that the eddy current losses are proportional to the square of the frequency. Therefore the eddy current losses will often be dominant at high frequency operations when the material has a conductivity. In materials that have a very low conductivity, like powdered cores for example, the hysteresis losses will be dominant for a large range of frequencies. The magnetic field in the expression for the hysteresis losses is directly related to the current that creates the field, and therefore the hysteresis losses can also be modeled as a resistance that is in series with the coil that creates the magnetic field.

### 2.3. Inductive Healing Asphalt

The Dutch highways are generally covered by porous asphalt concrete, because it has advantages over dense graded asphalt concrete with respect to noise reduction and water drainage. However the porous structure does not benefit the durability of the asphalt and will cause premature raveling of the road [19]. Asphalt concrete is a self-healing material [11]. Micro cracks are formed in the material when it is exposed to a sufficiently large stress or strain. The self-healing process will start after the load that generated the damage has been removed. Due to the diffusion of molecules from one face of the crack to the other face the crack and by rearrangement of the molecules within the bulk of the material the micro crack will be repaired and regain the strength of the original material [9]. The practical problem with applying this self-healing property to real roads is that the self-healing process at ambient temperature is too slow to heal the asphalt in between the periods of no stress. The healing rate of the asphalt concrete will increase at higher temperatures [8]. Heated asphalt can achieve significant amounts of healing after a resting period of 3 to 6 hours, dependent on the asphalt mixture used and the damage that was present before the heating [10]. The heating can be done using different methods, but induction heating is preferred over other methods because it does not contaminate the asphalt, can provide a good distribution of the heating power inside the asphalt and it is possible to properly control the amount of heat generated [10]. For the asphalt to be able to be heated by means of induction
it first needs to be conductive, so eddy currents can be induced in the asphalt, or it needs to be hard magnetic so hysteresis losses can heat the asphalt. This is achieved by mixing additives in the asphalt, like graphite or steel wool. Asphalt which is treated with such additives will be referred to further on as inductive healing asphalt.

2.3.1. Composition and production

Porous asphalt concrete is a composite material that usually consists of stone, sand, filler and bitumen which are illustrated in figure 2.23. The stones are called aggregates and have various sizes. They are classified by the sieve size that is used to separate them. An example of a typical size distribution of aggregates used in porous asphalt concrete is provided in table 2.1 [11]. The sand contains particles of a size between 2.0 mm and 0.063 mm and accounts for 10.5 % of the weight. The asphalt contains 4.5 % limestone filler with a particle size of less than 0.063 mm. The bitumen is the material that binds the composites together. It is a highly viscous liquid which can be found in crude oil. The bitumen is used in porous asphalt concrete with a weight percentage of 4.5 %.

![Figure 2.23: Materials that are used in making porous asphalt concrete.](image)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Sieve size</th>
<th>Density</th>
<th>Weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>22.4 mm - 16.0 mm</td>
<td>2778 kg m⁻³</td>
<td>4 %</td>
</tr>
<tr>
<td></td>
<td>16.0 mm - 11.2 mm</td>
<td>2774 kg m⁻³</td>
<td>21 %</td>
</tr>
<tr>
<td></td>
<td>11.2 mm - 8.0 mm</td>
<td>2762 kg m⁻³</td>
<td>32 %</td>
</tr>
<tr>
<td></td>
<td>8.0 mm - 5.6 mm</td>
<td>2765 kg m⁻³</td>
<td>23 %</td>
</tr>
<tr>
<td></td>
<td>5.6 mm - 2.0 mm</td>
<td>2781 kg m⁻³</td>
<td>5 %</td>
</tr>
<tr>
<td>Sand</td>
<td>2.0 mm - 0.063 mm</td>
<td>2688 kg m⁻³</td>
<td>10.5 %</td>
</tr>
<tr>
<td>Filler</td>
<td>&lt;0.063 mm</td>
<td>2638 kg m⁻³</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>

Table 2.1: Composition of the aggregate size based on the Dutch standard (RAW 2005)

In order to create an asphalt mixture that is compatible with induction heating steel wool is added to the composition. Steel wool are thin fibers of low carbon steel that are available in several grades, as shown in table 2.2. Steel wool is produced by shaving long threads of steel wire past sharp razors as shown in figure 2.24. The razors will shave off a very thin layer from the wire, which creates long and thin steel fibers that are collected on a reel. The average thickness of the steel fibers is dependent on the pressure of the razors to the wire. Therefore steel wool appears in different grades, which is a specification for the average fiber thickness. In table 2.2 a list of the most common available grades is presented.

Inductive healing asphalt is produced in the same way as normal porous asphalt concrete, except for the steel fibers that are introduced into the mixture at some point. When supplied on a reel steel wool will contain...
2. Theoretical Analysis

Figure 2.24: Steel wool is produced by shaving small layers from steel wires.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Name</th>
<th>Average fiber width</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Extra coarse</td>
<td>100 µm</td>
</tr>
<tr>
<td>3</td>
<td>Coarse</td>
<td>90 µm</td>
</tr>
<tr>
<td>2</td>
<td>Medium coarse</td>
<td>75 µm</td>
</tr>
<tr>
<td>1</td>
<td>Medium</td>
<td>60 µm</td>
</tr>
<tr>
<td>0</td>
<td>Medium fine</td>
<td>50 µm</td>
</tr>
<tr>
<td>00</td>
<td>Fine</td>
<td>40 µm</td>
</tr>
<tr>
<td>000</td>
<td>Extra fine</td>
<td>35 µm</td>
</tr>
<tr>
<td>0000</td>
<td>Finest</td>
<td>25 µm</td>
</tr>
</tbody>
</table>

Table 2.2: Steel wool grades and corresponding average fiber width.

longitudinal steel fibers. Because the fibers are obtained by shaving them from larger wires their edges will be very rough and sharp. When long fibers are used in the mixing process they tangle together because of the rough edges. This leads to the clustering of fibers in the asphalt mixture, creating a non uniform distribution of fibers. This is an unwanted effect and therefore the fibers are cut into smaller pieces prior to adding them to the mixture. From the research of Liu [11] it was found that the ideal length for the fibers was an equal distribution of 3.2 mm, 6.4 mm and 9.5 mm of grade 00 fibers. The optimal amount of steel fibers in the mixture was found to be 8 % of the volume of the bitumen. The bitumen content in porous asphalt concrete is 4.5 % by weight. Using these values and the aggregate composition of table 2.1 the total composition of the asphalt can be obtained as listed in table 2.3. The volume percentages are calculated from the densities and the weight percentages. Due to rounding errors the volume percentage does not add up to 100 %.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Density</th>
<th>Weight percentage</th>
<th>Volume percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregates</td>
<td>$2.8 \times 10^3$ kg m$^{-3}$</td>
<td>81.2 %</td>
<td>77.8 %</td>
</tr>
<tr>
<td>Sand</td>
<td>$2.7 \times 10^3$ kg m$^{-3}$</td>
<td>10.0 %</td>
<td>9.9 %</td>
</tr>
<tr>
<td>Filler</td>
<td>$2.6 \times 10^3$ kg m$^{-3}$</td>
<td>4.3 %</td>
<td>4.4 %</td>
</tr>
<tr>
<td>Bitumen</td>
<td>$1.0 \times 10^3$ kg m$^{-3}$</td>
<td>2.7 %</td>
<td>7.2 %</td>
</tr>
<tr>
<td>Steel wool</td>
<td>$7.8 \times 10^3$ kg m$^{-3}$</td>
<td>1.8 %</td>
<td>0.6 %</td>
</tr>
</tbody>
</table>

Table 2.3: Composition of the porous asphalt concrete.

The production process for asphalt samples in a laboratory is different from the bulk production process for real asphalt roads, but the main procedure is the same. For the production of samples in a laboratory environment all the components, aggregates, sand, filler, bitumen, steel fibers and mixing equipment are heated to 160 °C. First the bitumen are poured into the mixing bowl. Then the steel fibers are added to the bitumen. The aggregates, sand and filler are then added to the mixture and it is then blended in the mixer for 1 minute at low speed. After that the mixer will blend 15 minutes at high speed. The then homogeneous asphalt mixture is placed in an compaction mould, which is preheated at 145 °C. The asphalt is then compacted by a gyrator compactor with a pressure of 600 kPa and an angle of 0.820°. The gyrator compactor is an device that compresses the asphalt with a certain pressure under a slight angle. The compaction will create a dense asphalt sample with less air voids. After the compaction the asphalt sample is finished and will have the same mechanical properties as asphalt on the highway.
2.3. Inductive Healing Asphalt

2.3.2. Induction Healing

The porous structure of porous asphalt concrete has certain advantages with respect to dense asphalt concrete. It will reduce noise levels, increase skid resistance and result in less tire wear. It also has a better water drainage which contributes to several other advantages like enhanced visibility during rain, minimize risk of aquaplaning and reduce glare on the asphalt. The disadvantage is that the porous structure of the asphalt does not benefit the mechanical properties which reduces the lifetime. During the winter period it is possible that the ambient temperature reaches the freezing point of water. Any water that may remain in the voids of the porous asphalt structure will expand when it freezes. This expansion will result in significant damage of the porous asphalt concrete. Raveling is the loss of aggregates from the surface of the asphalt due to degradation of the binder. More than 76% of all maintenance required to the asphalt is due to raveling.

The degradation of the binder will result in micro cracks that are formed. The mechanical performance of the asphalt decreases when more of these micro cracks accumulate in the material, which eventually leads to raveling. Degradation of the asphalt can be prevented by repairing the micro cracks in an early stage. The binder of the asphalt has self healing properties because the bitumen in the binder is a highly viscous liquid. During periods when there is no stress applied to the asphalt the two faces of a micro crack will regain contact with each other. After this molecules will start to diffuse from one face of the crack to another. In a further stage the molecules diffuse even more such that there is enough randomization to recover the original strength of the binder.

The healing process as described will start when the stress is removed from the asphalt surface. At common outdoor temperatures the diffusion rate to heal the damage of the micro cracks is to low to recover the original strength of the asphalt within a reasonable amount of time. The healing process can be accelerated by heating the asphalt. The research of Liu has shown that samples of porous asphalt concrete that were heated to 85°C and after that were rested for a period of 3 to 6 hours could recover 70% to 85% of their original strength. It is important that the asphalt is not heated to temperatures above 85°C, because this leads to drainage of the bitumen which will result in a weaker road.

2.3.3. Conductivity

One of the material parameters of interest is the conductivity of the asphalt. It is difficult to measure the conductivity of the asphalt, because the conductive steel wool fibers are embedded inside the asphalt. Therefore an expression for the conductivity of the asphalt will be derived here. For this derivation it is assumed that the steel fibers are distributed uniformly in the asphalt. Figure 2.25 shows a CT-scan that was made of a sample piece of inductive healing asphalt, which done in the research of Q. Liu [10]. From this scan it can be concluded that the assumption that the steel fibers will be distributed uniform trough the asphalt is reasonable. The research of Liu has also shown that depending on the mixture ratio 74% up to 86% of the fibers are con-

![Figure 2.25: A CT-scan of a piece of inductive healing asphalt, which shows a clear random and uniform distribution of the steel wool fibers inside the asphalt.](image-url)
nected in one single cluster. As mentioned before the steel fibers are chopped into small pieces of 3.2 mm, 6.4 mm and 9.5 mm. Current paths that are larger than these dimensions need to be formed using multiple fibers. The fibers will have a contact resistance between them.

**Contact resistance measurement**

A setup as shown in figure 2.26 was made to measure the contact resistance of grade 00 steel wool fibers. Two Fluke 289 true rms multimeters were used in a four terminal measurement method was in order to eliminate the contact resistance between the probes and the multimeters. First the resistance of two individual fibers, \( R_1 \) and \( R_2 \), are measured leaving a space of 20 mm at each end of the fiber. After that first fiber is connected to one side of the measurement setup, and the second fiber to the other side. The fibers are positioned to make contact approximately 20 mm from the free ends. The resistance \( R_{tot} \) of this measurement will be

\[
R_{tot} = R_1 + R_2 + R_c,
\]

where \( R_c \) is the contact resistance. From this resistance and the individually measured resistances \( R_1 \) and \( R_2 \) the contact resistance can be calculated as

\[
R_c = R_{tot} - R_1 - R_2.
\]

In total 50 measurements were performed to characterize the contact resistance. A histogram of the results is shown in figure 2.27. The average contact resistance of the steel wool fibers was found to be 59.5 \( \Omega \) and that value will be used to further determine the conductivity of the asphalt.

![Figure 2.26: Contact resistance measurement using the four terminal method. (a) Schematic of the setup, (b) Picture of the setup.](image)

![Figure 2.27: Histogram of the contact resistance of steel wool grade 00.](image)
2.3. Inductive Healing Asphalt

Small scale geometry

Using the contact resistance the conductivity of the material can be approximated. For this the small scale geometry is analyzed first. The geometry of the steel wool fibers inside the asphalt is approximated by an idealized structure shown in figure 2.28a. This lattice can be build from a unit cell which is shown in figure 2.28b. The dimensions of this unit cell can be calculated from the volume fraction $f_V$ of steel wool inside the asphalt mixture. The width, depth and height of the unit cell are equal, because of the distribution of the fibers is assumed to be uniform. The total volume occupied by a unit cell is $d_f^3$, and a fraction $f_V$ of that volume will be filled with the steel wool fibers. This leads to the equation

$$f_V d_f^3 = 3 w_f^2 d_f - 2 w_f^3$$  \hspace{1cm} (2.52)

The average fiber width is known, because that is a specification of the steel wool grade. The distance $d_f$ between fibers is larger than the width $w_f$ for the low volume fractions that are usually used. Therefore the term $-2 w_f^3$ is neglected to make the equation more straight forward to solve. The average distance between the fibers can then be calculated as

$$f_V d_f^3 = 3 w_f^2 d_f$$

$$f_V d_f^3 - 3 w_f^2 d_f = 0$$

$$d_f (f_V d_f^2 - 3 w_f^2) = 0$$  \hspace{1cm} (2.53)

$$d_f = 0 \text{ or } d_f = \sqrt[3]{\frac{3 w_f^2}{f_V}} \text{ or } d_f = -\sqrt[3]{\frac{3 w_f^2}{f_V}}.$$  \hspace{1cm} (2.54)

The solution $d_f = 0$ appeared because the term $-2 w_f^3$ was neglected. The other two solutions are the same in magnitude, because of the squaring factor. Therefore $d_f = \sqrt[3]{\frac{3 w_f^2}{f_V}}$ is the right expression for the average distance between fibers in an asphalt mixture with a steel wool volume fraction of $f_V$.

![Fiber mesh.](image1)

![Unit cell.](image2)

Figure 2.28: Fibers.

Now that the average distance between the fibers is known another idealized geometry that describes the system is analyzed. In figure 2.29a an idealized structure for the fibers in the $x$ direction is shown, and in figure 2.29a an idealized structure for the fibers in the $y$ direction is shown. The length of the fibers is $l_f$, and the two structures can be combined to create a unit cell as shown in figure 2.29c. In this cell the contact points are noted with a red dot. The total number of horizontal contact points $n$ is equal to the total number of vertical contact points, which is

$$n = \frac{1}{2} \frac{l_f}{d_f}.$$  \hspace{1cm} (2.55)

The resistance from side $A$ to side $B$ in the unit cell can be expressed in terms of the contact resistance $R_c$.
and the number of contact points \( n \) as

\[
R_{AB} = \frac{2R_c}{n^2}.
\] (2.56)

When a three dimensional case is analyzed with faces \( A \) and \( B \) instead of lines \( A \) and \( B \) then the equivalent resistance between face \( A \) and \( B \) becomes

\[
R_{eq} = \frac{2R_c}{n^3}.
\] (2.57)

The conductivity \( \sigma \) of a material with length \( l \), area \( A \) and resistance \( R \) is defined as

\[
\sigma = \frac{l}{AR}.
\] (2.58)

The effective conductivity \( \sigma \) of the three dimensional unit cell as shown in figure 2.30 is then

\[
\sigma = \frac{1}{2l_f} \left( \frac{1}{n^3} \right)^{\frac{2}{3}} \frac{l_f}{R_c}
\]

\[= \frac{n^3}{l_f R_c}.
\] (2.59)

The conductivity of inductive healing asphalt can now be estimated. The mixture described previously con-

\[
\text{tain}s \text{ a volume percentage } f_V = 0.62\% \text{ of steel wool. The grade of the steel wool is } 00, \text{ which has an average fiber width } w_f \text{ of } 40 \mu\text{m and the fiber are chopped in pieces that have an average length } l_f \text{ of } 6 \text{ mm. The using} \]
the experimentally determined contact resistance $R_c = 59.5 \Omega$ the conductivity can then be estimated as

$$d_f = \sqrt{\frac{3w_f^2}{f V}} = 894 \mu m$$

$$n = \frac{1}{2} \frac{l_f}{d_f} = 3.35$$

$$\sigma = \frac{n^3}{l_f R_c} = 105.7 \text{ S m}^{-1} \quad (2.60)$$

2.3.4. Experimental validation

The validity of equation (2.59) is examined experimentally. The same four terminal measurement method as for the contact resistance is used. Steel wool fibers are chopped in the right length and are then placed in a slot inside a mould to ensure the volume that they occupy. A picture of the setup is provided in figure 2.31. The slots in the mould have a depth of 8 mm, are 22 mm wide and the conductivity is measured over a length of 195 mm. A mesh that represents the conductivity of the asphalt, using a volume percentage of 0.62% of grade 00 steel wool with an average length of 6 mm is created two times. An other mesh with a volume percentage of 0.62% of grade 00 steel wool with an average length of 12 mm is also measured to check the validity of the equation for the conductivity. The conductivity is measured over a current range from 10 mA to 1 A.

![Measurement setup used to determine the conductivity of a steel wool fiber mesh.](image)

In figure 2.32 the conductivity that was measured is presented for the different current levels. It can be seen that the measured conductivity is in the same order of magnitude as the predicted conductivity, but that there can be large differences. Therefore the expression given in (2.59) should only be used as an estimation. It is also clear that the conductivity is non-linear with the current. The conductivity for the 6 mm fibers even
doubles to a value of about 200 $\text{S m}^{-1}$. This is probably because the contact resistance is non-linear with the current. One mechanism leading to the non-linear contact resistance is the magnetic attraction between two wires which carry current in the same direction. As illustrated in figure 2.33 two parallel wires which carry current in the same direction will attract each other. Most of the fibers in the mesh will have a current flowing in the same direction, which leads to a magnetic attractive force. This force presses the contacts of the wires together resulting in a lower contact resistance. In all the simulations a conductivity of 500 $\text{S m}^{-1}$ will be used. This is to make sure that the losses in the asphalt are appropriately estimated for an IPT system that is operating at 50 kW.

Figure 2.33: Direction of the force between current carrying parallel wires.

### 2.3.5. Permeability

In the section about induction heating it was shown that the permeability can also influence the power dissipated in the asphalt, therefore the permeability of inductive healing asphalt will be analyzed experimentally. The inductance of a coil is related to the permeability of materials in the vicinity of the coil. In order to measure the permeability a coil is made, which can hold a beam of inductive healing asphalt in its core as shown in figure 2.34. The configuration of the magnetic fields in this geometry is not straightforward to determine analytically. Therefore the inductance will be related to the permeability using FEM simulations of the setup.

The setup in figure 2.34 consists of a square coil made from 1.5 mm diameter litz wire with 16 turns sides of 60 mm and a length of 30 mm. The beam of inductive healing asphalt that is used as a sample has a width and length of 54 mm and a depth of 137 mm. The inductance of the coil is measured over a range of 100 Hz to 1 MHz using an Agilent 4294A Precision Impedance analyzer.

The geometry of the FEM simulation is shown in figure 2.35 and was made to match the geometry of the experimental setup. The inductance of the coil was evaluated for a relative permeability range of $\mu_r = 1$ to $\mu_r = 1.5$ for a constant frequency of 10 kHz.

Figure 2.36 shows the inductance of the coil that was measured over the specified frequency range. The inductance of the air core coil is about 18.6 $\mu H$ and the inductance of the coil with the asphalt beam as a core is about 20.7 $\mu H$. In the range of 100 Hz to 1 kHz the inductance changes a lot. In appendix A the accuracy of the impedance analyzer is shown. It can be seen that for this frequency range with the expected inductance values the accuracy of impedance analyzer is about 10 %. At 10 kHz the accuracy is about 0.3 %, while skin effect is not present. Therefore the values of the inductance at 10 kHz is used to determine the permeability.

In figure 2.37 the inductance of the coil as a function of the permeability is presented. This relation was obtained with the FEM simulations. The inductance values of the measurements are included in the plot as dotted lines. It can be seen that the measured inductance of the air core coil is a bit higher than the simulated inductance with a relative permeability of 1. This is due to the connection wires, and possible differences in the geometry. From the plot it can be determined that the measured inductance of the asphalt sample corresponds to a simulated relative permeability of just above 1.2. To compensate for the difference between the experimental setup and the simulation the relative permeability of the asphalt is estimated to be $\mu_r = 1.2$. This value will be used in the rest of the research.
2.3. Inductive Healing Asphalt

Figure 2.34: Setup used to measure the inductance of the coil with and without asphalt in the core.

Figure 2.35: Geometry of the simulation used to estimate the relation between permeability and inductance.

Figure 2.36: Inductance of the coil with respect to frequency with and without inductive healing asphalt in the core.

Figure 2.37: Simulated inductance of the coil with respect to the permeability of the core at 10 kHz. The dotted lines show the measured values of the inductance at 10 kHz.

2.3.6. Thermal properties

The thermal properties of inductive healing asphalt can be used to calculate the power that is required to heat a slab of asphalt. The expression that will be derived will give the power per unit volume that is needed for a certain temperature change. The relevant material parameters are the density and the specific heat capacity. The expression will be verified with a FEM simulation that also includes the temperature conduction to other parts of the system and the convection losses to the air.

The density $\rho$ of a material relates its mass to the volume it occupies and in SI units the density is expressed in $\text{kg m}^{-3}$. The specific heat capacity $C_p$ of a material represents the amount of energy that is needed to increase the temperature of one kilogram of that material with one kelvin and in SI units the dimension is $\text{J kg}^{-1} \text{K}^{-1}$. The desired heating rate $\frac{dT}{dt}$ is the change in temperature per second and thus has the unit $\text{K s}^{-1}$. 
With these properties the required power per unit volume \( q \) can be obtained by

\[
q = \rho C_p \frac{dT}{dt}
\]

\[
= \frac{\text{kg}}{\text{m}^3} \frac{\text{J}}{\text{K}} \frac{1}{\text{s}}
\]

\[
= \frac{1}{\text{m}^3} \frac{\text{J}}{\text{s}}
\]

\[
= \frac{\text{W}}{\text{m}^3}.
\] (2.61)

With this expression the adiabatic heating of an object can be calculated. In real scenarios there will always be a heat flux from or to the object, because of conductive losses, convective losses or radiation for example. This heat flux will change the actual increase in temperature of the object.

If the asphalt is required to be heated from 10°C to 80°C in 10 min then the desired heating rate is \( \frac{dT}{dt} = 0.133 \, \text{Ks}^{-1} \). The asphalt will be treated as a homogeneous material. The density of the asphalt is approximately \( \rho = 1950 \, \text{kgm}^{-3} \) and the specific heat capacity is \( C_p = 920 \, \text{Jkg}^{-1} \text{K}^{-1} \). Therefore the required power is

\[
q = \rho C_p \frac{dT}{dt} = 1950 \cdot 920 \cdot 0.133 = 233 \, \text{kWm}^{-3}. \] (2.62)

Standard Dutch highways where the speed limit is 120 kmh\(^{-1}\) or higher have a lane width of 3.5 m. For an inductive heating top layer of 5 cm this would mean that the power requirement for the induction heating system is that it can deliver 40.8 kW per meter of highway for every lane. This is a high power demand, but it could be solved with a proper segment length as discussed in section 2.1.3

A FEM analysis is performed to compare the estimated rise in temperature with the case when there are conduction and convection losses. The setup that was used is shown in figures 2.38 and 2.39. The simulation is performed on a solid slab of asphalt that has a size of 1 m \( \times \) 1 m \( \times \) 0.05 m. The slab is surrounded by a concrete hemisphere with a radius of 2 m. The material parameters that were used are listed in table 2.4. The initial temperature of the setup is 10°C for all objects. On the spherical boundary of the hemisphere a constant temperature boundary condition of 10°C is applied. On the entire flat surface a convective heat flux is specified. The convective heat transfer coefficient \( h_c \) is approximated with the formula

\[
h_c = 7.4 + 6.39 \cdot W^{0.75},
\] (2.63)

where \( W \) is the wind velocity at 2 m above the ground. For a wind velocity of 7 m s\(^{-1}\) the thermal convection coefficient is \( h_c = 34.9 \, \text{Wm}^{-2} \text{K}^{-1} \). The heat source was defined to be homogeneously distributed through the asphalt with a value of 233 kW m\(^{-3}\).

<table>
<thead>
<tr>
<th>Material</th>
<th>Density ( \text{kgm}^{-3} )</th>
<th>Specific heat capacity ( \text{Jkg}^{-1} \text{K}^{-1} )</th>
<th>Thermal conductivity ( \text{Wm}^{-1} \text{K}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>1950</td>
<td>920</td>
<td>1.8</td>
</tr>
<tr>
<td>Concrete</td>
<td>2300</td>
<td>880</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 2.4: Material parameters used for the thermal simulation.

The simulation was performed to calculate the temperature transient in the asphalt for the first 30 min of the heating. The temperature was evaluated at three points that are horizontally in the center of the asphalt. The vertical positions are the bottom, where the contact with the concrete is made, in the center and at the top, where the contact with the air is. The temperature transient of the three points is shown in the plot of figure 2.40. It can be seen that the center of the asphalt is heated to 80°C in 620 s, which is very close to the expected 600 s. The top section is heated a bit slower, and takes 940 s to reach the desired temperature. This difference is due to the heat that is lost through the outgoing heat flux of the convection. The bottom part is heated the slowest, because of the conductive losses to the concrete surrounding the asphalt. It takes 1425 s for the bottom part to be heated to a temperature of 80°C. In a real system the heat source will however not be distributed homogeneously through the whole material. The power dissipated in the asphalt will be higher at the locations that are closer to the coils, because the flux densities will be higher in those regions. If the coils are located underneath the asphalt this would mean that the heat source near the bottom is higher, which
will make the temperature distribution through the asphalt more constant. Inductive healing of the asphalt is expected to be necessary once every 4-5 years. This makes it possible to carefully plan the moment at which the induction heating is applied. In the summer, when the initial temperature is higher and the wind velocity is minimal a better temperature distribution can be achieved.

**Steady state temperatures**

The steady state temperatures of the asphalt are important to consider. When the asphalt will be too hot during normal operation due to the losses of the IPT system then trail forming could happen. These are grooves that are formed in the road due to the forces from the tires of vehicles. It could also lead to drainage of the bitumen, which means that the bitumen are too much liquid and will therefore drain to lower regions of the asphalt, which can lead to loss of aggregates in the top section.

A piece of road of 1 m × 1 m is considered. The thickness $x_a$ of the IHA layer is 0.05 m and underneath the top layer there is a layer of concrete with a thickness $x_c$ of 0.5 m. A sketch of the geometry is provided in figure 2.41. A heat source $Q_{in}$ uniformly distributed in the IHA layer is considered. The steady state thermal behavior can be described using a thermal circuit as shown in figure 2.42. The thermal resistances of the asphalt and the concrete can be calculated using the thicknesses, the thermal conductivity $k$ as defined in 2.4.
and the area $A$ as

\[
R_{\text{asphalt}} = \frac{x_a}{A k_a} \\
R_{\text{concrete}} = \frac{x_c}{A k_c}
\]  

(2.64)

The thermal resistance from the asphalt to the concrete is approximated to be one half of the total resistance of the asphalt, because the heat source is distributed uniformly. The bottom of the concrete is assumed to have a constant temperature equal to the ambient temperature. There is also a thermal resistance $R_{\text{ambient}}$ from the top of the asphalt to the ambient. This resistance is the inverse of the convection coefficient $h_c$ multiplied by the area.

\[
R_{\text{ambient}} = \frac{1}{Ah_c}
\]  

(2.65)

The temperature difference between the ambient and the asphalt can be derived from the thermal circuit. The expression for the temperature difference between the asphalt and the ambient is

\[
T_{\text{asphalt}} = \frac{\frac{1}{2} R_{\text{asphalt}} + R_{\text{concrete}}}{R_{\text{asphalt}} + R_{\text{concrete}} + R_{\text{ambient}}} Q_{\text{in}}.
\]  

(2.66)

This temperature difference is independent of the area $A$ that is used. Therefore it is a useful characteristic for a highway where the thicknesses of the asphalt layers are defined. If the maximum temperature difference between the ambient and the asphalt is set to be $5 \, ^\circ \text{C}$ then the maximum power dissipation per unit volume
2.4. Equivalent circuit of the system

An equivalent circuit for the total system with inductive healing asphalt and inductive power transfer can be obtained by combining the results from section 2.1 and section 2.2. The circuit of figure 2.3 is expanded with the series resistances added to the inductances as described before to model the eddy current and hysteresis losses in the asphalt. The equivalent circuit for the system with the inductive healing asphalt is shown in figure 2.43. The linear system describing the model becomes

$$V = \begin{bmatrix} R_1 & R_M \\ R_M & R_2 \end{bmatrix} I + j\omega \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} I. \quad (2.68)$$

In this system the inductances $L_1$ and $L_2$ are the self inductances of respectively the primary and the secondary coil. The resistances $R_1$ and $R_2$ are defined as

$$R_1 = R_{1,coil} + R_{1,field}$$
$$R_2 = R_{2,coil} + R_{2,field}. \quad (2.69)$$

In the circuit of 2.43 the resistance $R_{1,field}$ represents the induced losses in the asphalt that find their origin in the magnetic field that is created by the primary coil. In the same way the resistance $R_{2,field}$ represents the induced losses inside the asphalt due to the field created by the secondary coil. The resistance $R_M$ is less intuitive to understand. This resistance is due to the fact that the magnetic field inside the asphalt is the superposition of the field created by the primary and the field created by the secondary. If the currents $I_1$ and $I_2$ are both positive in the circuit of figure 2.43 then this would mean that a current $I_M = I_1 + I_2$ will be flowing through the mutual path. In the real system this would correspond to the situation where the flux created by the primary coil is mainly in the same direction as the flux created by the secondary coil. Therefore the superposition of the two magnetic flux densities will be mainly constructive leading to a higher flux density inside the asphalt, as shown in figure 2.44a. But when the current $I_1$ is positive and the current $I_2$ is negative, as is usually the case when the current in the primary is only due to induction, then the magnetic flux density created by the primary coil will be mainly opposing the flux density of the secondary coil. Therefore the superposition of the two flux densities will be mainly destructive resulting in a lower flux density inside the asphalt as shown in figure 2.44b. From the analysis in section 2.2 it is known that the lower value of the flux density, and the sideways orientation of the field leads to less eddy currents being induced inside the asphalt, as illustrated in figures 2.44c and 2.44d.
2. Theoretical Analysis

(a) The currents $I_1$ and $I_2$ inside the coils are both positive, which means the magnetic fluxes of the primary and the secondary are constructive, resulting in a larger vertical flux density inside the asphalt.

(b) The currents $I_1$ and $I_2$ inside the coils are in opposite direction, which means the magnetic fluxes of the primary and the secondary are destructive, resulting in a lower vertical flux density inside the asphalt.

(c) Magnitude of the induced eddy current densities inside the asphalt due to the total flux density of the constructive situation at 1 kHz.

(d) Magnitude of the induced eddy current densities inside the asphalt due to the total flux density of the destructive situation at 1 kHz.

Figure 2.44: Constructive and destructive fluxes.

2.4.1. Parameter extraction

The system’s performance will first be evaluated using FEM analysis. In this section it will be demonstrated that the parameters for the matrices in the linear system of equation 2.68 can be extracted from FEM analysis. The system that will be evaluated is shown in figure 2.45, 2.46 and 2.47. The system has a circular primary coil of 26 turns with a wire radius of 1.1 mm, an inner radius of 37 mm and an outer radius of 105 mm. The secondary is circular coil of 16 turns with a wire radius of 1.1 mm, an inner radius of 12 mm and an outer radius of 53 mm. These dimensions were chosen, because these coils were available in the lab such that experimental validation of the result would be easier. The system is modeled in Comsol Multiphysics 5.1. The model is made in the 2D axis-symmetry domain. The vertical distance between the coils and the asphalt layer is 5 mm. The radius of the asphalt layer is 250 mm and the layer is 50 mm thick. The concrete and soil underneath the inductive healing asphalt is assumed to have the same electromagnetic properties as air, and are therefore not included in the geometry.

For each coil the parameters are extracted using the emf $E$, current $I$ and power $P$ from the simulations. The induced emf in an coil is given by

$$E = j\omega \left[ \begin{array}{cc} L_1 & M \\ M & L_2 \end{array} \right] I$$

(2.70)

Using this equation the inductances for the system can be determined. First the self inductance of the primary coil $L_1$ will be calculated by exciting the coil while the secondary is simulated as an open circuit. The
emf will then become

\[
\begin{bmatrix}
  \mathcal{E}_1 \\
  \mathcal{E}_2
\end{bmatrix} = j\omega \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \begin{bmatrix} I_1 \\
  0
\end{bmatrix},
\]

(2.71)

from which \( L_1 \) can be calculated as

\[
L_1 = \frac{\mathcal{E}_1}{j\omega I_1}.
\]

(2.72)

In the same way the inductance of the secondary coil can be calculated by exciting the coil while the primary is simulated as an open circuit. The emf will then become

\[
\begin{bmatrix}
  \mathcal{E}_1 \\
  \mathcal{E}_2
\end{bmatrix} = j\omega \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \begin{bmatrix} 0 \\
  I_2
\end{bmatrix},
\]

(2.73)

from which \( L_2 \) can be calculated as

\[
L_2 = \frac{\mathcal{E}_2}{j\omega I_2}.
\]

(2.74)

To obtain the mutual inductance the secondary coil is simulated as a short circuit while the primary is excited. Using the previously calculated self inductance \( L_1 \) and the current through the secondary \( I_2 \) an expression for the mutual inductance \( M \) can be derived as

\[
\begin{align*}
\mathcal{E}_1 &= j\omega L_1 I_1 + j\omega MI_2 \\
M &= \frac{\mathcal{E}_1 - j\omega L_1 I_1}{j\omega I_2}.
\end{align*}
\]

(2.75)

The mutual inductance from the primary to the secondary will be the same as the mutual inductance from the secondary to the primary, thus only one calculation for \( M \) needs to be done.
The coil conduction losses are calculated from the current through the coils and the power dissipated in them. The dissipated power is calculated using the current density and the conductivity as

\[ P = \iint_A \frac{|J|^2}{2\sigma} \, dA, \]  

(2.76)

where the area \( A \) over which the integral is evaluated is the domain area of the coils, as represented in figure 2.46. The coil resistance can be determined from the power using

\[ R_{\text{coil}} = \frac{2P}{I^2}. \]  

(2.77)

### 2.4.2. Verification

The equivalent circuit of figure 2.43 and the linear system (2.68) that corresponds to it will be verified with the results from the FEM simulations. The parameters were extracted for the system described in the previous section. The material parameters that were used are listed in table 2.5. The material copper was used for both coil domains.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity ( \text{S} , \text{m}^{-1} )</th>
<th>Relative permeability ( \mu )</th>
<th>Relative permittivity ( \varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt</td>
<td>500</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>( 5.998 \times 10^7 )</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.5: Material parameters used in the FEM simulation.

The simulations were done for a frequency range of 1 kHz to 1 MHz. Figure 2.48 shows the currents in the primary and the secondary in the situation where the primary coil is excited with a voltage of 1 V and the secondary is shorted. The power that was dissipated in the asphalt was calculated from the difference between the input power and the power that was dissipated in the copper of the primary and in the copper of the secondary. The plot lines of the currents and the power dissipated the asphalt are exactly on top of each other, thus it can be concluded that the equivalent circuit provides a proper description of the system. From the power dissipation shown in the plot it is also clear that some adjustments need to be made to the system in order to make a feasible combination. At the standard IPT frequencies of 85 kHz - 100 kHz almost all the power is dissipated inside the asphalt, which makes IPT impossible. In the next chapter a few concepts will be proposed which could make the system feasible.

The values of the resistances \( R_{1,\text{field}}, R_{2,\text{field}}, R_M, R_{1,\text{coil}} \) and \( R_{2,\text{coil}} \) of circuit 2.43 are extracted from the simulation and shown in figure 2.49. The field resistances and the mutual resistance define the frequency dependent losses in the system. This resistance is proportional to the square of the frequency for a large range of frequencies, as was expected from the analysis performed in section 2.2. This relation is valid until a frequency of approximately 100 kHz. After this frequency the skin depth of the system will become comparable to the dimensions of the system, which means that the magnetic fields do not penetrate the total volume of the asphalt anymore. As a result of this the resistances \( R_{1,\text{field}} \) and \( R_{2,\text{field}} \) will increase slower, and \( R_M \) will even decrease because the primary will become magnetically shielded from the secondary at those frequencies.

### 2.4.3. System performance

The feasibility of each concept is tested by calculating the maximum possible efficiency \( \eta_{\text{max}} \) for the system parameters in that setup. This is achieved by first calculating the maximum output apparent power, which is defined as

\[ S_{\text{out,max}} = V_{\text{out,oc}} I_{\text{out,sc}}^*, \]  

(2.78)

where \( V_{\text{out,oc}} \) is the open circuit output voltage and \( I_{\text{out,sc}} \) is the short circuit output current. For the maximum output apparent power it is assumed that there is a unity power factor in the input and the output, thus that both of the leakage inductances are compensated by the capacitances. The expression for the maximum
output apparent power then becomes

\[ V_{out,oc} = (R_M + j \omega M) I_1 \]
\[ I_{out,sc} = \frac{(R_M + j \omega M)}{R_2} I_1 \]
\[ S_{out,max} = \frac{R_M^2 + \omega^2 M^2}{R_2} I_1^2. \]  

(2.79)

It should be noted that there is no imaginary part in the expression for the maximum apparent power, and thus it is equal to the maximum output power which gives \( P_{out,max} = S_{out,max} \). The minimum input power for that particular \( I_1 \) is equal to the output power plus the losses in the primary.

\[ P_{in,min} = R_1 I_1^2 + P_{out,max} \]  

(2.80)
The maximum efficiency can now be calculated as $\eta_{\text{max}} = \frac{P_{\text{out,max}}}{P_{\text{in,min}}}$ resulting in

$$\eta_{\text{max}} = \frac{R_M^2 + \omega^2 M^2}{R_1 R_2 + R_M^2 + \omega^2 M^2}.$$  \hspace{1cm} (2.81)

It should be noted that this is a theoretical maximum efficiency which will never be reached in any practical setup, so it should be seen as a upper boundary.

### 2.5. Conclusion

In this chapter the theoretical analysis of the important components of a combined IPT and IHA highway are discussed. The general topic of inductive power transfer is discussed. An equivalent circuit for IPT systems is derived and physical processes of the operation are discussed. Also methods to improve the efficiency of an IPT system are addressed, and the concept of distributed IPT systems for electrical vehicle applications are investigated.

The physical process involved in induction heating are explained and it was found that the conductivity and the permeability of the material that will be heated are important parameters. Also the frequency is very important for the power that will be dissipated in an induction heating setup. It is found that eddy current losses increase with the square of the frequency, while hysteresis losses are proportional to the frequency. The losses of an induction heating system can be modeled in an electrical circuit as a resistance that is in series with the induction heating coil.

The material properties of inductive healing asphalt that are important for the electromagnetic behavior of the system are examined. The conductivity is determined from the structure of the steel wool wires and from measurements. It was found that the conductivity is non-linear with the current, and it is concluded that a conductivity of 500 S m$^{-1}$ should be used for the FEM simulations. The relative permeability of the inductive healing asphalt is determined experimentally, and was found to be 1.2. The thermal properties are investigated and two important values were found. When the system is in IPT operation the power dissipation in the asphalt should remain below 2.38 kW m$^{-3}$ to limit the temperature increase of the asphalt to 5°C. When induction healing is desired the system should be able to deliver 233 kW m$^{-3}$ to the asphalt in order to heat it to 15°C within 15 min.

Finally an equivalent circuit of a system which combines IPT with IHA is created. This is done by adding a series resistance to all the three inductances that are present in the general IPT equivalent circuit. For a system
where the geometry and the material parameters are known the values for the resistances can be extracted using FEM simulations. The inductances that are found in the FEM simulations will have a complex value, and the imaginary part of those inductances correspond to the frequency depended losses in the inductive healing asphalt.
The theoretical analysis done in chapter 2 has explained the physical processes that are involved with induction heating and inductive power transfer. Also the important system, geometry and material parameters were determined. In this chapter that knowledge will be used to describe four different concepts that will enable the combination of an inductive healing road and an inductive power transfer system in an efficient manner. While designing the concepts the main objective will be to lower the losses while the system is in IPT mode. This is done because the system will mainly be used for IPT as discussed in section 1.2. Also a small loss factor inside the asphalt can translate to high actual losses because of the powers involved in an IPT system.

### 3.1. Sectioned road

The first suggestion is to not cover the whole road with inductive healing asphalt. Cracks will occur where the asphalt is stressed the most. On the highway there are properly marked driving lanes as shown in figure 3.1. The vehicle is supposed to drive in between the lines. The result is that the tires of the car will often contact the edges of the driving lanes, and will rarely contact the center of the lanes. This means that the asphalt will wear faster at the edges of the lanes, which is also visible in figure 3.1. The center has asphalt that is darker, but at the edges the asphalt is lighter because it is starting to wear out. Thus when healing is necessary it will most likely be because the edges of the asphalt are worn out. IPT modules will positioned in the center of the lane. This makes it a feasible solution to only cover the edges of the lane with inductive healing asphalt, and cover the center with normal asphalt.

![Figure 3.1: Highway lanes that show wear at the side of the lanes where the car tires make contact with the road most of the time.](image)
The sectioned road will lower the losses of the system, but it can be difficult to heat the sections properly with the coils of the IPT system. A solution to this problem is an induction heating source that is separate from the IPT system. This could be a truck as shown in figure 3.2. This vehicle has a large battery to supply an induction heating coil that is located in a trailer behind the truck. Currently batteries are an expensive way to store and transport energy. The energy could also be provided by the IPT system when the truck has a secondary that can reach to the side to get enough coupling with the primary of the IPT system.

![Figure 3.2: Top view of a vehicle that could be used to heat the asphalt using a separate induction heating coil.](image)

The induction heating of the IHA sections could also be done by separate coils that can use the power electronics of the IPT system when induction heating is necessary. The only additional costs to the system will be the coils, because everything else is already installed for the IPT system. This could make this an economically feasible system.

### 3.2. Dynamic conductivity asphalt

The parameters that influence the power dissipation in an induction heating system were evaluated in section 2.2.2. From this analysis it could be concluded that one of the important material parameters is the electrical conductivity $\sigma$. It is possible to control the induction heating process when this parameter can be modified by the system. Material parameters are often a function of the frequency, and because the operating frequency for induction heating has a large range the frequency can be used to switch between the heating of the road and the charging of EVs.

#### 3.2.1. Conductivity dynamics

Ohm's law for steady state currents and Electrical fields implies that a current in a conductor is accompanied by the dissipation of energy, which leads to the generation of heat. The electric field inside the conductor accelerates the free charges, often electrons, which will collide with impurities, ions or other electrons inside the conductor. These collisions are the source of the energy dissipation inside conductors. Ohm's law can be expanded to the frequency domain which leads to

$$J = \sigma(\omega)E$$

(3.1)

where $\sigma(\omega)$ is called the frequency-dependent or the ac conductivity [6]. To get an expression for the frequency-dependent conductivity the two processes which determine the flow of current, the acceleration by the electric field and the slow down due to collisions, are described. The acceleration of the electrons can be described by Newton's second law of motion. The Force on an electron with charge $e$ in an electric field is $-eE$, thus the acceleration will be $-\frac{eE}{m}$, where $m$ is the mass of the electron. The collisions are a more complicated phenomenon so a few assumptions will be made. The collisions are assumed to be stochastic and the probability that an electron collides per unit time is defined as $\tau^{-1}$. Furthermore the velocity of an electron after a collision is assumed to be completely randomized. The average velocity of the of the electrons is called the drift velocity, which is defined at time $t$ as $\bar{v}_d(t)$. At time $t + \Delta t$ a fraction $\frac{\Delta t}{\tau}$ of the electrons will have collided. The collisions will not contribute to the drift velocity, because the speed after collision is assumed
3.3. Dynamic permeability asphalt

to be completely random. We can therefore write
\[ \vec{v}_d(t + \Delta t) - \vec{v}_d(t) = -\frac{\Delta t}{\tau} \vec{v}_d(t) - \frac{-e\vec{E}}{m} \Delta t \] (3.2)

where the first term gives the change in drift velocity due to the collisions, and the second term is the change in velocity resulting from the acceleration due to the electric field. The free current inside a conductor can be written as \( \vec{J} = -n_f e \vec{v}_d \) where \( n_f \) is the free electron density. If equation (3.2) is multiplied by \( n_f e \), divided by \( \Delta t \) and if the increments are replaced by derivatives, the differential equation describing the current density can be obtained
\[ \frac{d\vec{J}}{dt} = -\frac{\vec{J}}{\tau} + \frac{n_f e^2}{m} \vec{E}(t). \] (3.3)

This equation can be rewritten in the frequency domain
\[ -j\omega \vec{J} = -\frac{\vec{J}}{\tau} + \frac{n_f e^2}{m} \vec{E}(t). \] (3.4)

When this is rewritten in terms of \( \vec{J} \) an expression for the frequency-dependent conductivity follows from the definition of Ohm’s law given in equation (3.1).
\[ \sigma(\omega) = \frac{n_f e^2}{m} \frac{1}{1 - j\omega \tau} \] (3.5)

The expression for the frequency-dependent conductivity in equation (3.5) is known as the Drude model and is verified experimentally to accurately describe the frequency dependent conduction in most materials [4].

**Suitable materials**

The time constant \( \tau \) is known as the collision or relaxation time of the material and is in the order of \( 10^{-14} \) s to \( 10^{-15} \) s for most metals at room temperature. Therefore the frequency-dependent effect on the conductivity will only be noticeable from the terahertz range, which is far above frequencies used in Inductive Power Transfer. It is possible to lower the frequency of the drude response to the GHz range using micro structures as shown in [14]. This frequency range is still to high, and the implementation of micro structures in asphalt would be difficult. It could however be an interesting topic for further research, because the conductivity is an important parameter for the induction heating as shown in section 2.2.

### 3.3. Dynamic permeability asphalt

The permeability of a material is usually dependent on a lot of parameters. Among others it is a function of the field strength, the temperature and the frequency. Also the complex part of the permeability, which represents the losses, is a function of those parameters. In section 2.2 it was shown that hysteresis losses in a material can be represented by the imaginary part of the permeability. In 3.3 a typical response for the complex permeability with respect to frequency is shown. It is clear that there is a resonance in the imaginary part. Ideally small aggregate like parts of this material are mixed in the asphalt. The resonance frequency in the hysteresis losses can then be used to efficiently heat the asphalt at a certain frequency, while efficient power transfer is possible at other frequencies.

Magnetization is not a instantaneous process, there is always a certain delay between the externally applied field \( \vec{H} \) and the magnetic flux density \( \vec{B} \). One of the mechanisms that causes the delay can be derived from the magnetic moment of an atom. The magnetic moment is directly related to the angular momentum as seen in equation (2.35). The torque on a magnetic moment is dependent of the flux density and is given by
\[ \vec{T} = -\vec{\mu} \times \vec{B} \] (3.6)

The torque is also defined as the rate of change of the angular momentum
\[ \vec{T} = \frac{d\vec{L}}{dt} \] (3.7)
From these two equations the dynamics of the angular momentum can be expressed as

\[
\frac{d\vec{L}}{dt} = -\mu_0 \vec{\mu} \times \vec{H}_i.
\]

(3.8)

where \(\vec{H}_i\) is the internal field. From equation (2.35) the angular momentum can be written in terms of the magnetic moment resulting in

\[
\frac{d\vec{\mu}}{dt} = -\gamma \mu_0 \vec{\mu} \times \vec{H}_i.
\]

(3.9)

In ferromagnetic materials the magnetization is related to the magnetic moments of the atoms. In general it holds that \(\vec{M} = n\vec{\mu}\), where \(n\) is the number of atoms per volume. Replacing \(\vec{\mu}\) with \(\vec{M}\) in the equation will lead to

\[
\frac{d\vec{M}}{dt} = -\gamma \mu_0 \vec{M} \times \vec{H}_i.
\]

(3.10)

which is the differential equation that describes the dynamics of the magnetization [13]. It can be seen that the dynamics are dependent on the magnetic field strength. This is an important fact that should be considered when designing an IHA that is based on the principle of the resonance in the complex permeability. The magnetic properties that are provided in datasheet could be different from the magnetic properties in an implemented system because of different field strengths.

### 3.4. Anisotropic Asphalt

The analysis of chapter 2 has shown that the material parameters can influence the induction heating significantly. In this analysis it was assumed that all material properties involved were homogeneous and isotropic. However there are materials that have anisotropic properties, which means for example that the conductivity in one direction is different from the conductivity in another direction. Anisotropy can occur in homogeneous materials like cobalt (Co) and manganese bismuth (MnBi). In these materials the molecules will be arranged in a hexagonal crystalline structure as shown in 3.4. For these materials the \(c\) axis is an easy axis which is magnetized easily. To magnetize the material in other directions more energy is required.

Anisotropy can also be achieved by carefully arranging the distribution of the compounds inside a composite material. Inductive healing asphalt can be treated as a homogeneous isotropic material as discussed in section 2.3. The distribution of the fibers inside the asphalt is randomly as shown in figure 3.5a. The macroscopic properties can be made anisotropic when the fibers in the asphalt are organized to have a preferred direction from top to bottom as shown in figure 3.5b. Such a distribution will result in a permeability and
conductivity that is bigger in the $z$ axis, than in the $x$ and $y$ axis. An inductive power transfer system for electrical vehicles will transfer power from bottom to top. This means that the magnetic field that is involved will also be oriented from bottom to top. If this anisotropic material is introduced in between the primary and the secondary the will be enhanced in two ways. Eddy currents will be induced in a horizontal plane due to the vertically oriented magnetic field. In this plane the conductivity of the material is low, thus the eddy current losses will be reduced. The slab of asphalt will also act as an core for the system. The reluctance of the magnetic path will be reduced, which improves the coupling between the primary and the secondary that will enable more efficient power transfer.

![Hexagonal crystalline structure.](image)

The anisotropic material can be described with rank 2 tensors that contain the direction specific material properties. The relation between the magnetic field and the magnetic flux density then can be written as

$$B = \mu H$$

where

$$\mu = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix}.$$  \hspace{1cm} (3.12)

In the same way Ohm's law can be rewritten as

$$J = \sigma E$$

where

$$\sigma = \begin{bmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{bmatrix}.$$  \hspace{1cm} (3.14)

Figure 3.6 illustrates the magnetic field configurations in different situations. The setup is similar to the one shown in figure 2.47. The primary is excited with a current, while the secondary is an open circuit. In 3.6a there is only air present between the coils, and it is visible that a small amount of flux can couple with the secondary. In 3.6b isotropic asphalt is placed between the primary and the secondary. This will induce eddy currents and the asphalt will shield the field away from the secondary, which reduces the coupling. In figure
3.6c the magnetic field is presented in the case that the asphalt has anisotropic properties. In this situation for the conductivity it holds that
\[ \sigma_x = \sigma_y, \]
\[ \sigma_z > \sigma_x, \] (3.15)
and that
\[ \mu_x = \mu_y, \]
\[ \mu_z > \mu_x. \] (3.16)

When the magnetic field in the anisotropic case is compared to that of the air core case it can be seen that the coupling could be restored to the original level.

The parameters for the anisotropic permeability are measured using the same setup as discussed in section 2.3.5. Steel wool is delivered on reels with longitudinal fibers. Therefore it is already anisotropic when it is manufactured. The same core that was used in the experiment of section 2.3.5 is filled with 0.62 % anisotropic steel wool. The simulations are done again with anisotropic parameters for the permeability. The permeability in the \( x \) and \( y \) direction are set to be 1, and the permeability in the \( z \) direction is varied between 1 and 2. In figure 3.7 the result is shown. From this figure it can be concluded that a proper estimation for the anisotropic permeability is
\[
\mathbf{\mu} = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1.5
\end{bmatrix}.
\] (3.17)
3.5. Resonator Aggregates

Efficient IPT systems are possible because of the resonant compensation that can be applied to both the primary and the secondary, as explained in section 2.1. The limitation of an induction heating system is that the secondary side is a bulk piece of material, to which it is very difficult to apply resonant compensation. This limitation can be eliminated by changing the heating process of the asphalt. Instead of steel wool small heating elements can be used that consists of a series resonant circuit. An example of such an heating element is shown in figure 3.8a and the corresponding electrical circuit is shown in 3.8b.

![Resonating heating element.](image)

**Figure 3.8: Aggregates**

In essence these heating elements are small pickups that will have a magnetic coupling with the primary coil. Therefore the normal IPT theory, as discussed in section 2.1 will apply. It is possible to tune the system accurately to the desired properties because the designer has a lot of control over the $L$, $R$ and $C$ of the circuit.

3.5.1. Electrical design

The inductance is desired to have a proper magnetic coupling with the primary. This can be achieved with a coil that is as wide as possible, and that has a lot of turns. The magnetic coupling between the primary and the heating elements could be improved with a ferrite core inside the heating element, but this gives rise to other difficulties. The permeability of most materials is highly dependent on the applied field, frequency and temperature. Therefore the permeability experienced by resonators close to the primary could be different from heating elements that are further away. This would change the inductance of the circuit, and therefore change the resonance frequency. It would thus be difficult to control the heating in various parts of the asphalt. The permeability of air is very constant in a high range of frequencies, field strengths and temperature, thus an air core inductor will have a very constant value under the changing conditions.

The resistance will be the part where the power is dissipated. It will also, together with the inductance, determine the bandwidth of the series resonant circuit. Practical inductors and capacitors that are available on the market have a tolerance of 10%. Components with a lower tolerance are also available, but will be more expensive. Therefore the resonance frequencies of mass produced heating elements will differ. If the resistance in the circuit is relatively high then the bandwidth will be larger which will reduce the effect of the difference in resonance frequencies. The resistor does not have to be added as a separate component, because the resistance of the wire that resembles the coil can be used. To get the desired resistance the radius of the wire can be adjusted, or the material that is used can be changed. The conductivity of some metals is listed together with their temperature coefficient in table 3.1. While selecting a material it is important to check the magnetic properties. If the material is magnetic then the fields could be altered which will again result in changing inductor values. Magnetic materials also often have hysteresis losses, that will still be present even when the system is operating far from the resonance frequency of the heating elements. Copper and aluminium are suited materials when a low resistance is desired in the design, iron has a good conductivity, but also has magnetic properties which can lead to undesired effects. When a higher resistance is required manganin and constantan, which are both alloys, can be used. These alloys are specially designed to have a low temperature coefficient and are often used to manufacture wire wound resistors.

The resonators need to be able to dissipate a power of $233 \text{ kW m}^{-3}$. If one resonator will is designed to
heat a piece of asphalt of $1.25 \times 10^{-4} \text{ m}^3$, which is a cube with sides of 50 mm, then the power dissipation in the resonator needs to be 30 W. A small coil with a radius of 11 mm, a height of 7 mm and 24 turns is created from copper. This coil has an inductance of 12.8 \mu H and a resistance of 806 m\Omega. The resonance frequency at which the induction heating will be done is chosen to be 241 kHz and therefore the series capacitance used in the circuit will be 34 nF. The power transfer from a primary coil to the resonator is investigated for different resistances of the resonant circuit. In figure 3.9 the power dissipation in the resonant circuits is shown and in figure 3.10 the power transfer efficiency is presented. The current is the input current of the primary coil. It can be concluded that the circuit with the resistance of 4.162 \Omega is the most suitable option. When the resonators are made from constantan wire instead of copper then the resistance of 4.162 \Omega can be included in the coil and no additional resistance will be necessary.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity $\text{S m}^{-1}$</th>
<th>Temperature coefficient $\text{K}^{-1}$</th>
<th>Magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>$5.96 \times 10^7$</td>
<td>0.003862</td>
<td>No</td>
</tr>
<tr>
<td>Aluminium</td>
<td>$3.50 \times 10^7$</td>
<td>0.0039</td>
<td>No</td>
</tr>
<tr>
<td>Iron</td>
<td>$1.00 \times 10^7$</td>
<td>0.005</td>
<td>Yes</td>
</tr>
<tr>
<td>Manganin</td>
<td>$2.07 \times 10^6$</td>
<td>0.000002</td>
<td>No</td>
</tr>
<tr>
<td>Constantan</td>
<td>$2.04 \times 10^6$</td>
<td>0.000008</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3.1: Conductivity and temperature coefficient different metals.

3.5.2. Structural design

The heating elements must be mixed into asphalt without being crushed. It is also important that the orientation of the heating elements is in the right direction. When the coil is oriented orthogonal to the magnetic field than the coupling will be maximum, but when the coil is parallel to the field the coupling will be near to zero. It is possible to assure that the heating elements are always oriented properly without the requirement of an additional process during the assembly of the asphalt. When three individual heating elements are placed mutually orthogonal to each other like demonstrated in figure 3.11. In this way all the spatial components of the magnetic field can be captured by the heating elements, and because of the mutually orthogonal positioning the heating elements will not interfere with each other.

The three heating elements can be encapsulated in a spherical shell. This shell can be made from concrete, epoxy or some other type of material that can be poured into a mould. In this way a type of aggregate can be created that can be used as a heating element. If the aggregates of sieve size 22 mm-16 mm, which makes up 4 % of the weight is replaced by this type of aggregate.
3.6. Conclusion

Five concepts have been proposed to create a feasible combination of an IHA and IPT road. In table 3.2 the important aspects of each concept are summarized. The sectioned road provides a simple solution to the problem based on differences in geometry. It is expected that this solution is easy to implement, but it will not be possible to heal cracks in the center of the road. The dynamic conductivity concept that is proposed could provide an effective solution to combine both technologies. Unfortunately it has not been possible to find or create a material with the desired properties. The dynamic permeability concept can provide a good separation between induction heating and power transfer by changing the frequency. The magnetization processes are not linear with the field strength thus it can be difficult to predict what will happen in a system that operates at high power. The anisotropic asphalt concept uses the direction dependent material parameters to limit the shielding effect of the IHA and to lower the losses. The losses increase with the square of the frequency thus higher frequencies can be used to heal the asphalt. It can however be complicated to produce asphalt with an anisotropic fiber distribution. The last concept, resonator aggregates, implements a dynamic conductivity in small components. The resonators can easily be designed to have the desired properties with respect to resonance frequency and bandwidth. They will have to be packaged in a hard solid casing and the consequences on the mechanical properties of the asphalt will need further investigation.
<table>
<thead>
<tr>
<th>Concept</th>
<th>Principle</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sectioned IHA</td>
<td>Changes in geometry.</td>
<td>Requires very little change to the production process.</td>
<td>Induction heating needs to be done with another source and damage in the center cannot be healed with induction.</td>
</tr>
<tr>
<td>Dynamic Conductivity IHA</td>
<td>Reducing conductivity with frequency.</td>
<td>The resonance will be able to create a proper separation between charging and heating.</td>
<td>No material has been found with the desired properties.</td>
</tr>
<tr>
<td>Dynamic Permeability IHA</td>
<td>Resonance peak in hysteresis losses.</td>
<td>The resonance will be able to create a proper separation between charging and heating</td>
<td>Materials with the desired properties are hard to find and the influence on mechanical properties needs to be investigated, resonance peak can change with different magnetic field strengths</td>
</tr>
<tr>
<td>Anisotropic IHA</td>
<td>Directional dependence of material parameters.</td>
<td>No different material needed and the strength of the asphalt will still be enforced by the steel fibers.</td>
<td>Possibly difficult to implement in the construction process.</td>
</tr>
<tr>
<td>Resonator Aggregates</td>
<td>Difference in resonance.</td>
<td>Very accurate control of resonance frequency.</td>
<td>Influence on mechanical properties needs to be investigated.</td>
</tr>
</tbody>
</table>

Table 3.2: Operating principles and main advantages and disadvantages of the concepts compared to each other.
In this chapter the different concepts will be analyzed by a numerical analysis using FEM simulations. The geometry of the system is the same for every concept, except the sectioned road. The chosen geometry is the same as the system that was analyzes in section 2.4, which has a circular primary coil of 26 turns with a wire radius of 1.1 mm, an inner radius of 37 mm and an outer radius of 105 mm. The secondary is circular coil of 16 turns with a wire radius of 1.1 mm, an inner radius of 12 mm and an outer radius of 53 mm. These dimensions were chosen, because these coils were available in the lab such that experimental validation of the result would be easier. The vertical distance between the coils and the asphalt layer is 5 mm. The radius of the asphalt layer is 250 mm and the layer is 50 mm thick. The system is modeled in Comsol Multiphysics 5.1, and it is evaluated over a range of frequencies from 1 kHz to 1 MHz. It is assumed that the conductivity, permeability and permittivity of the soil and asphalt in a real system are the same as that of air, thus in the simulations the total geometry will be surrounded by air. Every system will be compared on two properties. These are the maximum efficiency as defined in (2.81), and the coupling factor between the primary and the secondary.

4.1. Air core system

An inductive power transfer system that only consists of two coils and air in between is evaluated first. In this system the only losses should be the copper losses of the coil, and thus the results of this analysis can be taken as a reference value for the other systems. The material parameters that were used are shown in table 4.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
<th>Relative permeability</th>
<th>Relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0 S m⁻¹</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>5.998 × 10⁷ S m⁻¹</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.1: Material parameters used in the FEM simulation.

The circuit parameters are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.1. The inductances of the system are constant, which is to be expected from a system with only conduction losses. Also the resistances $R_1$ and $R_2$ which represent the copper losses remain the same. This is to be expected, because skin effect and proximity effect in the coil is not taken into account because the coil domains are exited with a constant current density. The resistance $R_M$ is not smooth and very small. This is due to the finite precision in the numerical analysis, which means that the calculation for the mutual impedance contains a small error in the subtraction and the fraction operation done to calculate the value. The value of $R_M$ is about 10 orders of magnitude lower than the resistances $R_1$ and $R_2$ and thus the contribution of this error is not significant.

The maximum efficiency of the system increases from about 50 % at 1 kHz to almost 100 % from 20 kHz. It is to be expected that the maximum efficiency increases with increasing frequency, because the impedance
of the mutual inductance will increase, while the resistances $R_1$ and $R_2$ remain equal. This means that the open circuit voltage becomes larger with frequency, while the short circuit current remains about equal and that results in a larger maximum efficiency.

Figure 4.1: Results of the numerical evaluation of the air core system. Plot (a) shows the inductance values with respect to frequency and plot (b) shows the resistance values. The maximum efficiency of the system over a range of frequencies is provided in plot (c).

### 4.2. Regular inductive healing asphalt

An other reference that is made is the regular inductive healing asphalt without adjustments. In this system more losses are to be expected, because of the eddy currents that will be induced inside the asphalt. It is assumed that the eddy current losses will be dominant, and thus the hysteresis losses are not implemented in the system. In table 4.2 the material parameters that were used during this simulation are shown. The frequency $f_s$ where the skin depth $δ$ of the asphalt is equal to the thickness of the material can be calculated as

$$f_s = \frac{2}{\sigma \mu δ^2} = \frac{2}{2\pi \cdot 500 \cdot 1.2 \cdot 4 \cdot 10^{-7} \pi (0.05)^2} = 169 \text{ kHz}. \quad (4.1)$$

The circuit parameters are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.2. It can be seen that the inductor values are approximately constant for the frequencies below $f_s$. When the frequency exceeds 169 kHz the skin depth of the asphalt will become important. The inductance values of $L_1$ and $L_2$ drop because of the eddy currents induced in the surface of the asphalt that
reduce the flux that is created by the coils. The mutual inductance drops rapidly after $f_s$. This is because the field is not able to penetrate the total thickness of the asphalt anymore. It is also due to the fact that the inductances $L_1$ and $L_2$ become lower in value. The resistances of the circuit change a lot with respect to frequency. Up to 10 kHz the conduction losses of the coils will dominate the losses in the system. After that the induced currents in the asphalt will become significant, and the losses will rise quadratically with the frequency until the frequency $f_s$ is reached. At that point the resistance $R_M$ will drop rapidly. This is again because of the fact that the fields cannot penetrate the asphalt anymore. Therefore there is almost no difference in magnitude between the constructive and the destructive flux inside the asphalt, which means that $R_M$ will decrease.

The maximum efficiency of the system will start again around 50%. From that point it will rise, because of the same reasons as in the air core system. It reaches its peak value at about 10 kHz, which is the point where the AC losses will become significant. From that point the maximum efficiency drops until it almost becomes zero, because the induced currents inside the asphalt will only increase with an increasing frequency.

### 4.3. Sectioned road

The sectioned road is simulated using an adjusted geometry. The asphalt domain is a cylinder with a hole in the center, as shown in figure 4.3. The losses will be analyzed for multiple radii of the hole in the center. The outer radius of the asphalt slab is chosen such that the total volume of asphalt in the simulation is equal to the simulations of the other concepts. Beside the change in geometry everything is equal to the simulation of the regular inductive healing asphalt, also the material parameters that are shown in table 4.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
<th>Relative permeability</th>
<th>Relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$0 \text{ S m}^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt</td>
<td>$500 \text{ S m}^{-1}$</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>$5.998 \times 10^7 \text{ S m}^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.3: Material parameters used in the FEM simulation.

First the maximum efficiency is investigated for different sizes of the hole in the center. Images of the field configurations for every situation can be found in appendix B. For a small radius of 50 mm the performance decreases in the lower frequencies. This is because the magnetic field is pulled into the sides of the asphalt due to the difference in permeability of the asphalt and the air as seen in B.2. This reduces the coupling factor between the primary and the secondary, resulting in a lower performance. For higher frequencies the performance still becomes better than in the solid IHA case, because the losses in the asphalt will be lower. When the radius of the hole becomes larger the magnetic coupling at low frequencies will restore to the value of the coupling in air, increasing the performance at lower frequencies. At high frequencies the losses that can be induced in the asphalt are lower when the radius of the hole becomes bigger. With a hole radius of 100 mm, which is almost equal to the radius of the coil, there is already a significant amount of improvement in the efficiency. Increasing this radius to 150 mm, which is one half times the radius of the primary coil, results in a maximum efficiency curve that is almost equal to that of air. When the radius of the hole is increased further the performance does not increase significantly.

The circuit parameters for the situation where the hole has a radius of 100 mm are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.5. It can be seen that the impact of the skin effect on the system is less. Because of the hole in the center there is always a clear path for the flux, which means that the coupling between the primary and the secondary is still substantial, even for higher frequencies. The mutual impedance is however lower in value for a large range of frequencies. The losses increase slower with frequency than in the solid inductive healing asphalt case.
Figure 4.2: Results of the numerical evaluation of a regular inductive healing asphalt system. Plot (a) shows the inductance values with respect to frequency and plot (b) shows the resistance values. The maximum efficiency of the system over a range of frequencies is provided in plot (c).

The maximum power transfer starts at approximately the same value of 50%. It then rises with frequency in the same way as in the air core system. Eventually at higher frequencies the losses that are induced in the asphalt will become significant and the efficiency will drop. This reduction in efficiency can be controlled with the horizontal displacement between the asphalt and the coils, as shown in figure 4.4.

The mutual inductance between the primary and the secondary starts equal to that of the air core system. This mutual inductance remains the same for a large range of frequencies. However in the range of the fre-
frequency where skin effect will start to become important the mutual inductance of the sectioned system will remain very constant. Therefore the maximum efficiency will remain high.

### 4.4. Dynamic permeability asphalt

The dynamic permeability concept is investigated using a complex permeability that is dependent on the frequency. The complex permeability curve that is used is based on the curve of the 3E25 ferrite material of Ferroxcube. The curve of this material is shown in figure 4.6. It can be seen that the real part of the permeability has its $-3$ dB point at 500 kHz, and that the peak in the complex part is reached at 700 kHz. This curve is approximated with a first order Butterworth filter, and is scaled down to simulate the effective permeability of an piece of asphalt with small pieces of ferrite inside. The values for the complex permeability that were used during the simulation are shown in figure 4.7.

$$
\mu'(f) - j\mu''(f)
$$

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
<th>Relative permeability</th>
<th>Relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0 $\text{Sm}^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0 $\text{Sm}^{-1}$</td>
<td>$\mu'(f) - j\mu''(f)$</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>$5.998 \times 10^7$ $\text{Sm}^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.4: Material parameters used in the FEM simulation.

The circuit parameters are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.8. Because the conductivity of the asphalt is zero all of the frequency dependent losses are hysteresis losses. These losses are proportional to the imaginary part of the permeability. Therefore they will be low up to 100 kHz, where the value of $\mu''(f)$ remains low. After this point the losses will follow the resonance peak of the imaginary permeability.

The maximum efficiency starts with the same trajectory as the air core system up to approximately 100 kHz. Above that frequency the hysteresis losses will become significant and the maximum efficiency will reduce to a local minimum at the frequency of the resonance peak of the imaginary permeability. This is a nice feature that can be used to efficiently heat the asphalt at that frequency. After the resonance frequency the maximum efficiency will increase again because the imaginary permeability reduces again.

### 4.5. Anisotropic Asphalt

The anisotropic asphalt can easily be investigated numerically. The tensors to be used for the permeability and the conductivity are provided in table 4.5, together with the other parameters. The conductivity and the permeability in the $z$ direction are approximated to be greater than the isotropic case. This is because the fibers will be the same length as the thickness of the asphalt. Therefore the contact resistance and reluctance
4. Numerical Analysis

Figure 4.5: Results of the numerical evaluation of a sectioned road system. Plot (a) shows the inductance values with respect to frequency and plot (b) shows the resistance values. The maximum efficiency of the system over a range of frequencies is provided in plot (c).

Figure 4.6: Complex permeability with respect to frequency of Ferroxcube 3E25 ferrite.

Figure 4.7: Complex permeability used in the simulation.

will not dominate the effective values.
The circuit parameters are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.9. The inductances and resistances follow the same familiar curve again. The frequency at which the skin depth becomes important is higher, because of the lower conductivity in the $r$ and $\phi$ direction. This can also be seen in the graphs.

The maximum efficiency shows an interesting result. The asphalt will act as a magnetic core for the system because the permeability is higher in the $z$ direction. The vertical path has a lower reluctance and this benefits the mutual inductance in this setup. Up to the frequencies where the induced currents inside the asphalt will become important the efficiency is higher than in the air core system. Above 100 kHz the losses will become important, which makes frequencies higher than that suited for the heating of the system.
4.6. Resonator Aggregates

The resonators are difficult to implement in the simulation. The cylindrical symmetry and the resonance of the resonators make it hard to implement them in a proper way. This difficulty is overcome by simulating the asphalt as a bulk piece with a resonance in the conductivity. The phase shift that will occur in the series resonant circuit of the resonator aggregates is included by giving the conductivity a real and an imaginary part. This is an approximation of the equivalent impedance of the real resonators. The conductivity function that is used is shown in figure 4.10.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
<th>Relative permeability</th>
<th>Relative permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0 Sm$^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt</td>
<td>$\sigma_r(f) + j\sigma_i(f)$ Sm$^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Copper</td>
<td>$5.998 \times 10^7$ Sm$^{-1}$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.6: Material parameters used in the FEM simulation.

The circuit parameters are evaluated over a range of frequencies from 1 kHz to 1 MHz, and the result is plotted in figure 4.11. The inductance values are approximately constant when the frequency is not in the range of the resonance frequency. When the resonance frequency is reached the losses rise rapidly. After the
4.7. Conclusion

Each individual concept is analyzed numerically with identical circumstances. This allows the comparison of each concept in an easy way. The maximum efficiencies of each concept are plotted together in figure 4.12. In order to perform a proper comparison the factor $f_\eta$ between efficiencies of the concepts $\eta_{\text{max},c}$ and the air core case $\eta_{\text{max,air}}$ are calculated according to

$$f_\eta = \frac{\eta_{\text{max},c}}{\eta_{\text{max,air}}}.$$ (4.2)

In figure 4.13 the maximum efficiency relative to that of air is shown. Some very interesting conclusions can be drawn from this figure. Every concept that was suggested results in a better efficiency than the regular IHA. The sectioned asphalt has an efficiency that has is slightly lower than that of the air core system, which further decreases as the frequency becomes higher. The resonators and dynamic asphalt perform the same as the air core system over a long range of frequencies. They both have a resonance peak at which the efficiency of power transfer is low. But that means that the power transfer to the IHA is high at those frequencies, which enables the asphalt to be heated efficiently. The anisotropic asphalt shows the most interesting result. In the lower frequency range this concept has a higher efficiency than the air core system. This is because it will act as a magnetic core. Dependent on the precise values of the conductivity and the permeability the influence of the eddy current losses will become higher than the increases mutual inductance which will make the efficiency lower than that of the air core system.

The concepts are also compared by means of the magnetic coupling factor in figure 4.14. Here it can be seen that again the regular IHA has the lowest coupling factor of all systems, and that the coupling factor decreases rapidly when skin effect becomes important. At the low frequencies the coupling factor of the dynamic permeability asphalt is approximately the same as that of the regular IHA. This is because the permeability is the same, which has a shielding effect. The coupling factor for the dynamic permeability asphalt remains constant, until the resonance point is reaches, where it will rise to the same coupling factor as the air core case because the relative permeability reduces to 1. The resonators and the sectioned asphalt start at the same coupling factor as the air core setup. The coupling of the sectioned asphalt will reduce when the losses that are induced in the nearby IHA will increase. The coupling of the resonators will increase right before, and decrease after the resonance frequency because of the phase shift of the currents in the resonators. The anisotropic asphalt has the highest coupling factor, because of the enhanced path for the magnetic field from the primary to the secondary. This coupling eventually decreases when the skin effect in the anisotropic asphalt will become significant.

The conclusions about the performance of the concepts are summarized in table 4.7.
Figure 4.11: Results of the numerical evaluation of a regular inductive healing asphalt system. Plot (a) shows the inductance values with respect to frequency and plot (b) shows the resistance values. The maximum efficiency of the system over a range of frequencies is provided in plot (c).

Figure 4.12: Maximum efficiency of the different concepts with respect to frequency.

Figure 4.13: Maximum efficiency of the different concepts relative to the maximum efficiency of the air core system.
Concept Performance

Regular IHA Has the worst efficiency and coupling, which both drop rapidly when the skin depth is comparable to the thickness of the asphalt.

Sectioned IHA The efficiency is good for a large range of frequencies, and the efficiency increases when the horizontal displacement between the coils and the asphalt is larger.

Dynamic Permeability IHA The efficiency is equal to the air core transformer for all frequencies outside the resonance. At the resonance frequency the performance of the power transfer is lower, which means that the induction heating can be performed efficiently.

Anisotropic IHA The efficiency is better for a range of low frequencies, until the losses will exceed the benefit of the better magnetic coupling. For higher frequencies the efficiency drops, which enables induction heating.

Resonator Aggregates The efficiency is equal to the air core transformer for all frequencies outside the resonance. At the resonance frequency of the aggregates the performance of the power transfer is low, which means that the induction heating can be performed efficiently.

Table 4.7: Performance of the different concepts.
Experimental Analysis

The systems that were analyzed numerically in the previous chapter will be realized for experimental analysis. Measurements will be done in order to extract the equivalent circuit parameters, which will be compared to those extracted from the numerical analysis. This will first be done on small samples to verify the correctness of the numerical models. The same experiment will be done using large samples to investigate the losses in the asphalt. Finally, efficiency measurements at higher power levels will be performed to identify non-linear behavior in the circuit parameters.

5.1. Parameter measurement method

The parameters of the circuit will be extracted in four measurements. The first two measurements will identify the self inductances $L_1$ and $L_2$ of the coils and the loss resistances $R_1$ and $R_2$. The remaining two measurements will determine the mutual inductance $M$ and the mutual loss resistance $R_M$. The measurements will be performed using the Agilent 4294A Precision Impedance Analyzer.

The equivalent circuit derived in section 2.4 for an inductive power transfer system with losses is shown in a different form in figure 5.1. The linear system describing this circuit is

$$\mathbf{V} = \begin{bmatrix} R_1 & R_M \\ R_M & R_2 \end{bmatrix} \mathbf{I} + j \omega \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \mathbf{I},$$

(5.1)

where the resistance $R_M$ is the resistance from the imaginary part of the mutual inductance which is equal to

$$R_M = \omega M_R.$$  

(5.2)

Figure 5.1: Magnetically coupled circuit.
The mutual impedance can then be obtained by subtracting the destructive impedance from the constructive impedance. The impedance between the terminals can be written as

\[ V_Z = R_1 I_1 + R_M I_2 + j \omega L_1 I_1 + j \omega M I_2 \]
\[ = R_1 I_1 + j \omega L_1 I_1 \]
\[ Z_p = \frac{V_1}{I_1} = R_1 + j \omega L_1 \]  

The self inductance \( L_2 \) of the secondary and the corresponding resistance \( R_2 \) are measured with the circuit shown in figure 5.2b. The impedance analyzer is connected between the positive and the negative terminal of the secondary, while the primary side remains an open circuit. The impedance between the terminals can be written as

\[ V_Z = R_M I_1 + R_2 I_2 + j \omega M I_1 + j \omega L_2 I_2 \]
\[ = R_2 I_2 + j \omega L_2 I_2 \]
\[ Z_s = \frac{V_Z}{I_2} = R_2 + j \omega L_2 \]  

The self mutual inductance \( M \) and the corresponding resistance \( R_M \) are measured in two separate steps. First the constructive mutual impedance is measured with the circuit shown in figure 5.2c. The impedance analyzer is connected between the positive terminal of the primary and the negative terminal of the secondary, while the negative terminal of the primary is shorted with the positive terminal of the secondary side. In this way the current \( I_1 \) and \( I_2 \) are equal, and will both enter the inductances at the dotted terminal such that the mutual inductance is to be added in the primary and the secondary inductance. The impedance between the terminals can be written as

\[ V_Z = R_1 I_1 + R_2 I_2 + j \omega L_1 I_1 + j \omega L_2 I_2 + j \omega M I_1 + j \omega M I_2 \]
\[ = (R_1 + R_2 + 2R_M) I_1 + j \omega (L_1 + L_2 + 2M) I_1 \]
\[ Z_c = \frac{V_Z}{I_1} = (R_1 + R_2 + 2R_M) + j \omega (L_1 + L_2 + 2M). \]  

Subsequently the setup is changed to measure the destructive mutual impedance with the circuit shown in figure 5.2d. The impedance analyzer is connected between the positive terminal of the primary and the positive terminal of the secondary, while the negative terminal of the primary is shorted with the negative terminal of the secondary. In this way the current \( I_1 \) and \( I_2 \) are the same in magnitude, both opposing in polarity. Therefore the current enters the primary inductances at the dotted terminal, but exits the secondary inductance at the dotted terminal. This means that the mutual inductance is to be subtracted in the primary and the secondary inductance. The impedance between the terminals can be written as

\[ V_Z = R_1 I_1 + R_2 I_2 + j \omega L_1 I_1 + j \omega L_2 I_2 + j \omega M I_1 + j \omega M I_2 \]
\[ = (R_1 + R_2 - 2R_M) I_1 + j \omega (L_1 + L_2 - 2M) I_1 \]
\[ Z_d = \frac{V_Z}{I_1} = (R_1 + R_2 - 2R_M) + j \omega (L_1 + L_2 - 2M). \]  

The mutual impedance can then be obtained by subtracting the destructive impedance \( Z_d \) from the constructive impedance \( Z_c \). This results in

\[ Z_c - Z_d = [(R_1 + R_2 - 2R_M) + j \omega (L_1 + L_2 - 2M)] - [(R_1 + R_2 + 2R_M) + j \omega (L_1 + L_2 + 2M)] \]
\[ = 4R_M + j \omega 4M \]
\[ Z_m = \frac{Z_c - Z_d}{4} = R_M + j \omega M. \]  

In this way all the circuit parameters of the equivalent circuit for the combined system can be obtained in an experimental setup.
5.2. Small scale samples

In a first analysis multiple small samples for every concept except the sectioned road are prepared. A picture of such an sample is shown in figure 5.3. Only the electromagnetic properties of the asphalt is of importance during these measurements. Therefore the samples were created using a Portland cement mix. Cement will have a relative permittivity that is different from that of asphalt due to the high amount of water that is locked into the cement. But as seen in section 2.2 the performance of the system only depends on the conductivity and the permeability of the materials. For each concept four samples are prepared in the following way.

- **Control**  Control samples that consists only of Portland cement are created to verify that the cement does not influence the power transfer efficiency of an IPT system. The cement is created by mixing 400 mL water with 770 g of Portland cement. In this way a very liquid cement is created in which the steel wool can be processed easily. For every sample 90 mL is poured in a cup and covered with plastic. Then they are left to harden for two days.

- **Regular IHA**  A comparative sample with regular IHA, which has a random and uniform fiber distribution, is also created. To achieve a volume percentage of 0.62% every sample is prepared with 4.4 g of steel wool grade 00 that is chopped in fibers with an average length of 45 mm. The same mixture of 400 mL water with 770 g Portland cement is used. Again 90 mL of cement is poured in a cup and the steel wool is then distributed uniformly in the cement. The samples are covered with plastic and left to dry for two days.

- **Anisotropic IHA**  Steel wool is supplied on reels that contain longitudinal fibers. Therefore it is relatively easy to manufacture anisotropic samples. Sections of 45 mm are chopped from the reel and are carefully collected to keep the anisotropic structure intact. In total 4.4 g of steel wool grade 00 is collected in this way for each sample, such that the volume percentage of steel wool in the sample will again be 0.62%. The same mixture of 400 mL water with 770 g Portland cement is used. Again 90 mL of cement is poured in a cup and the steel wool is then carefully added to the mixture in order to keep the anisotropic structure intact. The samples are covered with plastic and left to dry for two days.

- **Dynamic IHA**  For the dynamic inductive healing asphalt samples the material 3E25 of Ferroxcube is used. Regular E cores are crushed to smaller pieces of about 7 mm. For every sample 25 g of these small pieces are added to the cement mixture. The same mixture of 400 mL water with 770 g Portland cement is used. Again 90 mL of cement with the ferrites is poured in a cup, covered with plastic and left to dry for two days.
5. Experimental Analysis

- **Resonator aggregates** Small coils with a radius of 11 mm, a height of 7 mm and 24 turns as shown in figure 5.4 are made from constantan wire with a radius of 0.25 mm. These coils have an average inductance of 12.8 \( \mu \)H and an average resistance of 4.7 \( \Omega \). The resonance frequency is chosen to be 241 kHz and therefore the series capacitance used in the circuit will be 34 nF.

![Figure 5.3: Small concrete sample that was used to measure the material properties of the different concepts.](image)

![Figure 5.4: Resonant RLC circuit that is placed in the resonator aggregate samples.](image)

**Setup**

The concrete samples are made in cups and therefore they are shaped like cone, which can be seen in figure 5.3. The samples have a bottom radius of 25 mm, a top radius of 29 mm and a height of 40 mm. The primary coil used in the measurement setup has 15 turns with a wire radius of 1.1 mm, an inner radius of 23.5 mm and an outer radius of 61.5 mm. The secondary coil is identical to the primary. These coil dimension are chosen because the total length of the wire will be 4 m and thus they can be described by the lumped circuit theory for frequencies up to 750 MHz. The vertical distance between the primary and the asphalt sample is 5 mm, and the vertical distance between the secondary and the sample is 35 mm. New numerical simulations are performed to match the geometry of the experimental setup that is used with the small samples.

First an air core system is measured to determine the coil losses without the asphalt. Also the control samples, made from pure concrete, are measured to verify that the concrete does not influence the measurement. The results are shown in figure 5.5. It can be seen that the concrete does not influence the measurement. There is a notch visible at 110 kHz, which is not expected to be there. This notch is present in every measurement and therefore it will be possible to compare the measurements relative to each other. The average value for the coil resistance will be used as a reference to calculate the field losses that are induced in the asphalt. This is done by subtracting the resistances of the air core system from the resistances measured in the other systems.

**Results**

In figure 5.6 the circuit parameter values are presented for the regular inductive healing asphalt samples. The conductivity of the simulations is set to be 500 S m\(^{-1}\) and the relative permeability is 1.2. The dotted line in the figure represents the simulated results and the solid line are measured parameters. It can be seen that the measurements match very accurately with the simulations for the frequencies above 10 kHz. In the range of 1 kHz-10 kHz the added resistance from the field losses is below the resolution of the impedance analyzer. From 10 kHz the field resistances are within the resolution of the impedance analyzer, and from that point the simulation results match the measurements closely.

The circuit parameters that are measured for the anisotropic samples are shown in figure 5.7. The numerical analysis is performed with the conductivity in the \( x \) and \( y \) direction set to 100 S m\(^{-1}\) and the conductivity in the \( z \) direction set to 1000 S m\(^{-1}\). The relative permeability in the \( x \) and \( y \) direction is 1 and the relative permeability in the \( z \) direction is 1.5. The values for the field resistance are below the resolution of the impedance...
Figure 5.5: Measured circuit parameters of the air core system and the control samples.

analyzer for a larger range of frequencies due to the lower conductivity in the x and y direction. It can be seen that in the higher frequency range, where the resolution and the accuracy of the impedance analyzer is better the numerical results are comparable to the measured data. It can also be seen very clearly that the hysteresis losses are dominant for the lower frequencies and that the eddy current losses are dominant in the higher frequencies because of the steepness of the curves. The hysteresis losses can be approximated with a imaginary part of the permeability of $\mu'' = 0.003$.

In figure 5.8 the measured circuit parameters for the dynamic permeability asphalt are presented. It can be seen that the simulated losses do not match the measured losses in any way. The resonance peak in the hysteresis losses that was expected from the complex permeability is not visible in the measured data. The model that was used is thus not representative for the losses in the circuit. The reason that there is no resonance peak in the hysteresis losses is most likely because this resonance is dependent on the field strength as discussed in 3.3. This will make it difficult to predict the losses in a system that relies on the complex permeability of the asphalt.

The circuit parameters for the resonators are plotted in figure 5.9. It is clear that the peak in the field losses that were predicted by the simulations is also present in the measurements. The peak has shifted to a higher frequency than the 241 kHz it was designed for. This is because there is a mutual inductance between the primary and the resonators, and the resonance frequency is determined by the leakage inductance. The simulation was adjusted such that the resonance peak is at the same frequency as the measurements. The shape of the resonance peaks in the simulations is the same as the ones in the measured data. The peak for the secondary is higher in the simulation than in the experiments. This is because the simulation models the entire sample as a conductive material, while the real conductive RLC circuit in the measurements is closer to the primary.

The small scale experiments have shown that the methods used to simulate the losses in the asphalt are consistent with the reality for the regular asphalt, the anisotropic asphalt and the resonator aggregates. The dynamic permeability asphalt did not have the properties that were expected, and therefore this concept will be discarded from further experiments. Conclusion about the performance of the concepts cannot be drawn yet. This is because the induced currents in the asphalt that create the losses will have the highest value in the asphalt that is located above the middle turn of the coil, as seen in figure 2.44d for example. This is because the enclosed flux by the asphalt is the highest at that location. The samples used in this experiment are smaller than the diameter of the coils, thus most of the losses are not present. Therefore larger samples will be made in order to verify the large scale behavior and the power transfer efficiency.

5.3. Large samples

The small samples were useful to verify the numerical models that were used. It was found that the regular IHA, the anisotropic IHA and the resonator aggregates performed as was to be expected from the numerical analysis. The dynamic permeability asphalt did not have the desired properties, and therefore this will not be included in the large scale experiments. The sectioned asphalt sample could not be tested with the small scale samples, and will therefore be tested in the large samples for validity of the models. The large samples
Figure 5.6: (a) Inductance and (b) resistance values of the regular inductive healing asphalt samples.

Figure 5.7: (a) Inductance and (b) resistance values of the anisotropic inductive healing asphalt samples.

Figure 5.8: (a) Inductance and (b) resistance values of the dynamic inductive healing asphalt samples.

Figure 5.9: (a) Inductance and (b) resistance values of the resonator aggregates asphalt samples.
are blocks of concrete with a width and depth of 200 mm, and a height of 45 mm.

- **Regular IHA**  First a sample of regular IHA, which has a random and uniform fiber distribution is created. For the sample 87.0 g of steel wool grade 00 is chopped in fibers with an average length of 6 mm. The concrete mixture is made from 1.5 L water and 2.8 kg Portland cement. The mould is filled with 2 L of cement and steel wool is then distributed uniformly in the cement. The sample is covered with plastic and left to dry for two days.

- **Sectioned IHA**  The sectioned sample is made to have the same volume percentage of steel wool. In the center a cylindrical hole with a radius of 30 mm is created. To get the same volume percentage of 0.62 % steel wool 81.9 g fibers with an average length of 6 mm is used. The same cement mixture of 1.5 L water and 2.8 kg Portland cement is made and 1.86 L is poured in the mould with a cylindrical spacer in the center to keep the center clear from the cement. The steel wool is then uniformly distributed in the cement, the mould is covered with plastic and left to dry for two days.

- **Anisotropic IHA**  Steel wool is supplied on reels that contain longitudinal fibers. Therefore it is relatively easy to manufacture anisotropic samples. Sections of 45 mm are chopped from the reel and are carefully collected to keep the anisotropic structure intact. In total 87.0 g of steel wool grade 00 is collected in this way for the sample. The same cement mixture of 1.5 L water and 2.8 kg Portland cement is used. The mould is filled with 2 L of cement and steel wool is then carefully located in the cement to keep the anisotropic distribution intact. The mould is covered with plastic and left to dry for two days.

- **Resonator aggregates**  Four small coils with a radius of 11 mm, a height of 7 mm and 24 turns as shown in figure 5.4 are made from constantan wire with a radius of 0.25 mm. These coils have an average inductance of 12.8 µH and an average resistance of 4.7 Ω. The resonance frequency is chosen to be 241 kHz and therefore the series capacitance used in the circuit will be 34 nF. The four resonators are placed at 50 mm from the corners of the sample, such that the distance between the resonators is 100 mm. The resonators are located at a height of 20 mm from the bottom. 2 L of the same cement mixture is used to fix the resonators in place.

**Setup**

In figure 5.10 a picture of the setup used to measure the circuit parameters is shown. The same primary and secondary of 15 turns with a wire radius of 1.1 mm, an inner radius of 23.5 mm and an outer radius of 61.5 mm are used. Because of the small size of the coils compared to the size of the samples all the important eddy current losses will be included. The vertical distance between the primary and the bottom of the sample is 10 mm. The height of the samples is 45 mm and the vertical distance between the top of the sample and the secondary is 37 mm. The method as described in section 5.1 at the start of this chapter is used to extract the circuit parameters.

![Figure 5.10: Picture of the setup used to measure the large sample circuit parameters.](image)
Results

Resistances

The resistance values are extracted from the measurements and presented in figures 5.11 to 5.14. The measured values are plotted with solid lines and the simulated values are plotted with dotted lines. The hysteresis losses are modeled with an imaginary part of the permeability of $\mu'' = 0.003$, which was found in the anisotropic small scale samples.

In figure 5.11 the resistance values of the regular IHA sample are shown. Up to a frequency of 10 kHz the expected value of the resistances is below the accuracy of the impedance analyzer and therefore the values do not match. Above that frequency the measured and the simulated values match very well.

In figure 5.12 the resistances that were measured for the sectioned asphalt sample are shown. The resistance values are lower for this sample, and this is also expected based on the theory. Because of the lower resistances the losses are below the accuracy of the impedance analyzer for the frequencies below 20 kHz. For the frequencies above 20 kHz the measured resistances are very close to the expected values. The measured values are a bit lower and this is probably because the steel wool inside the sample is not located directly against the edge of the hole in the center. Therefore the effective hole in the center is larger than the simulated radius of 30 mm.

The measured resistance values for the anisotropic sample are shown in figure 5.13. The resistance $R_{1,\text{field}}$ is described successfully by the numerical model, and the resistances $R_{2,\text{field}}$ is also accurately approached with the simulations, but the resistance $R_M$ is off. From the simulations it is expected that the resistance $R_M$ is higher than the resistance $R_{2,\text{field}}$, but in the measurements it is the other way around. The reason for this difference is not known. The measured resistances are lower than the resistances of the regular IHA, thus the efficiency of this ample is expected to be better.

The resistances that were extracted from the resonator sample are shown in figure 5.14. The resistances are lower than the accuracy of the impedance analyzer for all frequencies below 100 kHz. This is a good result, because this means that the losses in the asphalt are minimum for the frequencies where inductive power transfer is used. At a frequency of approximately 270 kHz the resonance peak of the resonators is reached, and the losses are maximum, which is useful for the heating of the asphalt at that frequency.

Power dissipation in the asphalt

The power dissipation per unit volume in the asphalt is investigated for measured circuit parameters. For a given input current $I_1$ the current $I_2$ through the secondary and the current $I_M$ trough the mutual path can be calculated as

$$I_2 = \frac{R_M + j\omega M}{R_2 + R_M + j\omega M} I_1$$

$$I_M = \frac{R_2}{R_2 + R_M + j\omega M} I_1.$$

In the calculations for these currents it is assumed that the secondary leakage inductance is completely compensated with the secondary compensation capacitor. The power that is dissipated in the asphalt then becomes

$$P_{\text{asphalt}} = R_{1,\text{field}} \frac{|I_1|^2}{\sqrt{2}} + R_{2,\text{field}} \frac{|I_2|^2}{\sqrt{2}} + R_M \frac{|I_M|^2}{\sqrt{2}}.$$ (5.9)

In figure 5.15 the power that is dissipated in the asphalt during IPT operation with a RMS input current of $I_1 = 10$ A is presented. The lower dotted line is placed at 2.38 kW m$^{-3}$, which is maximum allowable value for the power dissipation in the asphalt during IPT operation, as calculated in section 2.3.6. The upper dotted line is the minimum power dissipation value of 233 kW m$^{-3}$ for fast heating of the asphalt when it is desired, which is also calculated in section 2.3.6. It can be seen the regular IHA is above the maximum allowable value for the normal IPT frequencies of 85 kHz-100 kHz. The sectioned asphalt and the anisotropic asphalt are just below the maximum power dissipation. The resonators are far below the maximum allowable losses for the IPT frequencies.

When the system is used for induction heating of the road only the primary coil will be used. Due to the absence of the secondary there will be no power dissipation in the resistances $R_M$ and $R_2$. Instead the system will only have the losses described by $R_{1,\text{field}}$ in the asphalt that are due tot the primary coil. In figure 5.16 the power dissipation in the asphalt during induction heating is presented. The upper dotted line
is again the minimum power that is necessary to be able to heat the asphalt in 15 min. This value is only reached by the regular inductive healing asphalt at a frequency of 850 kHz. This is 10 times higher than the frequency the system will be designed for, and therefore it is likely that the power electronics and the coils will not be able to operate at this frequency with high powers. The sectioned IHA that was used in the sample is just below the minimum power at a frequency of 1 MHz. This is however very specific for the distance between the IHA and the coils, which was very short in the sample. As discussed in section 3.1 the most likely scenario is that the IHA in a sectioned road configuration will be heated with an other source than the primary of the IPT system. The anisotropic asphalt also has power dissipation just below the required minimum at 1 MHz. It will be difficult to properly heat the anisotropic asphalt with the same system that is used for IPT. The resonators show the most promising result. The maximum power per volume that is dissipated in the asphalt at the resonance peak is far below the required power dissipation. The derivative of the power dissipation with respect to the frequency is however the highest of all concepts. From that rate of change it is clear that the power dissipation can be below the maximum in IPT operation at a frequency of 85 kHz, while the power dissipation can be above the minimum required for induction heating at a frequency of approximately 200 kHz. It is likely that the power electronics and the coils can be created to be able to operate at both frequencies with little additional costs. To achieve this more resonators will be needed in the asphalt. Another option is to use higher currents when the system is used for induction heating. As seen from (5.9) the power dissipated in the asphalt is related to the square of the current. If the system is operated at double the current level the power dissipation will increase with a factor of 4. The power dissipation in all other components of the system will also double, and therefore it is dependent on the design of the system if it is able to deliver this current for 15 min without being damaged.

The power dissipation in the asphalt that was calculated in this analysis depends highly on the coils that are used and the current levels of the IPT operation. The derivatives of the power dissipation with respect
5. Experimental Analysis

to the frequency is however a given variable of the system. In section 2.2 it was shown that the eddy current losses are proportional with the square of the frequency. Therefore the dissipated power will increase with a factor 100 when the frequency increases with a factor of 10. The minimum power dissipation for induction heating, $233 \text{kWm}^{-3}$, is approximately a factor 100 higher than the maximum power dissipation of $2.38 \text{kWm}^{-3}$ during IPT. Therefore if the switch between IPT and induction heating needs to be made in a system that only relies on eddy currents the operating frequency will have to become 10 times higher, or the currents that are used need to increase with a factor 10. In the resonator aggregates case it is seen that the derivatives of the power dissipation with respect to the frequency is very high for frequencies just below the resonance frequency of the resonators. This is because the frequency increases in that region when it gets closer to the resonance frequency, but also the conductivity of the resonators increases with the increasing frequency. This results in a high derivative, which will enable to operation frequencies of IPT and induction heating to be closer together.

**Maximum efficiency**
The measured circuit values are used to calculate the maximum efficiency of the circuit in the same way that was done during the numerical analysis of chapter 4. In order to perform a proper comparison the factor $f_\eta$ between efficiencies of the concepts $\eta_{\text{max,c}}$ and the air core case $\eta_{\text{max,air}}$ are calculated according to

$$f_\eta = \frac{\eta_{\text{max,c}}}{\eta_{\text{max,air}}}.$$  \hspace{1cm} (5.10)

In figure 5.17 the efficiencies relative to that of the air core case for the different concepts are plotted together. The plot is very similar to the maximum efficiencies that are expected from the numerical analysis, as seen in figure 5.18. The efficiency of the anisotropic asphalt is higher than that of the air core system for lower frequencies which is a very interesting result. The efficiency of the resonators is equal to that of the air core setup, with a small difference at the resonance frequency of the resonators. The regular IHA has a lower efficiency than expected for the lower frequencies, and this is probably due to higher coil losses in the measured setup. The efficiency is higher than that of the sectioned asphalt as expected from the simulations. Eventually the efficiency of the regular asphalt will drop below that of the sectioned asphalt as expected from the numerical analysis. The sectioned IHA starts at the lowest efficiency as is expected, but the value is lower than that of the numerical analysis, which is also due to the higher coil losses. At higher frequencies the efficiency of the sectioned road will be higher than that of the regular asphalt.

5.4. Power transfer efficiency

The circuit parameters that are obtained from the analysis of the large samples can be used to calculate the power transfer efficiency for a known load resistance. In section 2.3.3 it was discussed that the conductivity of
the steel wool is not linear. Magnetization curves are also not linear and therefore it is interesting to inspect
the power transfer efficiency for different input current levels. The efficiency will be evaluated at a frequency
of 90 kHz, which is in the 85 kHz-100 kHz range at which most IPT systems will operate.

Setup

In figure 5.19 the schematic and a picture of the setup are shown. The efficiency is measured from the output
of the inverter to the load resistance at the secondary side at a frequency of 90 kHz. The same geometry
as with the parameter identification of the large samples will be used. The coils are identical and have an
inductance of 20.9 \( \mu \)H, thus the compensation capacitors for both sides can be calculated using (2.8) to be
150 nF. At the primary the voltage over the resonant circuit is measured using a Yokogawa 700924 differential
probe, and the current trough the primary circuit is measured using a Keysight N2783B current probe. The
voltage and current are processed in a Yokogawa DLM2034 oscilloscope to calculate the input power using

\[
P_{\text{in}} = \frac{1}{T} \int_{0}^{T} v(t) i(t) \, dt. \tag{5.11}
\]

At the secondary side a load resistance of \( R_L = 9.98 \Omega \) is connected. The current trough the load resistor
is measured using a current probe. The RMS value of the secondary current \( I_{2,\text{rms}} \) is used to calculate the
output power as

\[
P_{\text{out}} = R_L I_{2,\text{rms}}^2. \tag{5.12}
\]

The efficiency is measured over a range of currents from 200 mA to 10 A. For every measurement it is assured
that the system operates at resonance. The minimum frequency that was used is 88.96 kHz and the maximum
frequency is 92.00 kHz. The circuit parameters will change with frequency, but the frequencies are considered
sufficiently close together that this difference can be neglected. Fans are used to ensure a constant temper-
ature for the components, and the system is exposed to the currents for a limited amount of time to prevent
measurement deviations because of temperature differences.

Results

In figure 5.20 the results of the measurement are presented. The dotted lines show the expected efficiency
based on the circuit parameters that were measured using the impedance analyzer. The solid lines show the
real efficiency that was measured. For the air core setup the efficiency is very constant over the total current
range. Very little non-linearity are expected in this system, thus this is a reasonable result. The real efficiency
is a bit lower than the 33.7 % that was expected. This could be due to the resistance that the capacitors add to
the system.

The regular IHA has the lowest efficiency, which is expected from the data of figure 5.17 at 90 kHz. When
the system is excited with a low current the efficiency starts at the expected efficiency of 22.4 %. With in-
Increasing current the efficiency drops, until it reaches a minimum of 10% at a current of 10 A. The expected non-linear behavior of the field losses are clearly visible in this measurement.

The sectioned IHA shows the same responds in a similar way. The expected efficiency for this sample is 25.5%, and at low currents this efficiency is almost achieved. But with higher currents the conductivity of the asphalt becomes larger leading to higher losses which lower the efficiency to 13.7% at an input of 10 A. For the sectioned asphalt there is a solution to the problem of the decreasing efficiency, and that is to increase the distance between the inductive healing asphalt and the coils.

The anisotropic IHA is expected to have an efficiency of 33.5% based on the circuit parameters. At low currents it has the same efficiency as the air core setup. However when the currents increase the same effects as with the regular IHA and the sectioned IHA will start happening and the efficiency will drop. Over the whole input current range the efficiency is better than that of the regular IHA and the sectioned IHA, but at a current of 10 A the efficiency has decreased to 15.7%, which is less than half of the efficiency at the lower current levels.

The efficiency of the resonator aggregates is approximately the same as that of the air core system. Because the frequency of 90 kHz is far from the resonance frequency of the resonators this is to be expected. The efficiency is constant over the total current range, because the resonators are made from components that have almost no non-linear behavior, especially outside the resonance frequency. The expected efficiency based on the measured circuit parameters was 33.9%. The measured efficiency was again a bit lower, which is also assumed to be the result of the extra resistance due to the compensation capacitors.

The decrease in efficiency with increasing currents could be used to benefit the concepts that use steel wool to heat the asphalt. The losses in the are not linear with the current. Therefore the increase in operating current of a factor 10 that was discussed before could be decreased. This makes it more feasible to apply induction healing with the power electronics that were designed for the IPT system.
5.5. Conclusion

The results of numerical analysis that was performed in chapter 4 were verified experimentally in this chapter. It was shown that the numerical results of the regular IHA, the sectioned road, anisotropic asphalt and resonator aggregates correspond properly to the experimental results. The relations of the resistances with respect to frequency show the same behavior in the numerical analysis and the experimental results. Also the values of the resistances are properly estimated by the numerical models. The dynamic permeability asphalt did not perform as expected and was therefore discarded for the large scale experiments.

In the large scale experiments the relations between the concepts of the maximum efficiency and the magnetic coupling factor were found to be the same as in the numerical analysis. The anisotropic asphalt can provide an improved efficiency up to a certain frequency, which is a very interesting result. The resonator aggregates have an efficiency that is similar to the air core case for all frequencies except those around the resonance frequencies of the resonators. The sectioned IHA was found to have the same properties that were expected from the simulations. The efficiency in the experiments that were performed is lower than that of the air core case, but as seen in the numerical analysis of chapter 4 this efficiency can be increased when the displacement between the coils and the IHA is larger.

The power dissipated in the asphalt during IPT and the during induction heating were examined and it was found that the resonators have the best potential to create a feasible combination of IHA and IPT in one system due to the large derivative in the power dissipation with respect to the frequency. This large derivative makes it possible to have the operating frequencies of IPT and induction heating close together, which will make it easier to combine the systems using the same power electronics and coils.

The power transfer efficiency from the source to a load resistance at the secondary side was measured for a range of currents. It was seen that the efficiency is close to the efficiency that is expected from the measurements at low current values up to 0.5 A. For the resonator aggregates system the efficiency remained constant at the expected value for the total range of currents. The samples for the regular IHA, the sectioned IHA and the anisotropic IHA showed a large decrease in the efficiency when the currents become larger. At a primary current of 10 A the efficiencies even decrease to less than half the value of the efficiency at low currents. This is due to the non-linear conductivity of the steel wool fiber mesh inside the asphalt. This decrease in efficiency is due to an increase in the field losses, which could be used as an advantage to make the switch between IPT and induction heating with the same system easier.
A combination of inductive power transfer for electrical vehicle applications and an inductive healing road can both provide a convenient infrastructure for electrical vehicles and lower maintenance costs for the road. However for the implementation of inductive power transfer and inductive healing asphalt additional materials and systems are needed in the road. The process of constructing a road will also become more complicated, and thus a highway with IPT and inductive healing asphalt will be more expensive. The additional costs in the road production process will need a more detailed study to achieve a reliable estimation, and therefore they will not be included in this research. In this chapter a preliminary economic feasibility is investigated using the additional material costs, which will be compared to the assumed reduction in maintenance costs of the road. All the numbers about the road maintenance are retrieved from annual reports of the Ministry of Infrastructure and the Environment, from Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS), and reports from the Court of Audit (Algemene Rekenkamer). Market prices for specific materials and components are retrieved from the online trading platform Alibaba and from the catalog of Farnell.

6.1. Road maintenance

Every year the Dutch government invests in the road infrastructure of the Netherlands. The Dutch road network is supervised by different governmental organizations. The small roads, and city roads are under supervision of the municipalities of the Netherlands. These roads are often short in length, but due to the dense infrastructure in cities they add up to be 118,851 km, which is about 93% of the total road length in the Netherlands. A large section of these roads are made from an other material than asphalt, and the information about maintenance costs are to be determined independently for the 393 municipalities. Therefore these roads will not be considered in this research. The larger roads that connect different cities and provinces are the provincial roads. Their maintenance is under the responsibility of the Dutch provinces. The provincial roads have a combined length of 6,342 km and are all covered in asphalt, but not all of this asphalt is porous asphalt concrete. Finally there are the national highways which run trough multiple provinces and add up to a total length of 3,057 km. Most of these highways are covered with a top layer of porous asphalt concrete and the maintenance of these highways is done by the ministry of Infrastructure and the Environment.

In figure 6.1 the expenses on the highway by the ministry of Infrastructure and the Environment from the year 2013 to 2015 and the budgets for the years 2016 to 2020 are presented. The expenses are divided in maintenance and replacement, new construction projects and other expenses like management of the road. The average costs of maintenance for the roads from 2013 to 2015 was €623,961,000. This amount is not exclusively destined for the actual roads, but also for the maintenance of bridges, tunnels and other structures that are directly related to the roads.

The costs that are spend on the maintenance and replacement of the road top layer are of importance for this research. Inductive healing asphalt will reduce the raveling of the roads. An estimate of the annual costs for road damage due to raveling is made by analyzing a report of the Court of Audit, that investigated the expenses of the province of Drenthe in the period of 2007-2013. The causes of road damage are investigated,
and are presented in figure 6.2. There are four damage categories, which are

- **Raveling**  the loss of aggregates,
- **Trail forming**  formation of grooves by the wheels of vehicles,
- **Crack forming**  formation of cracks and tears in the asphalt,
- **Unevening**  bumps and dents in the asphalt layer.

In the right bar plot of figure 6.2 the percentage of damage due to raveling is presented. It can be seen that usually a significant amount of the damage to the road is due to raveling. On average 57% of the damage to the road is because of raveling. On the highways in the Netherlands this percentages is expected to be even more, because there is more porous asphalt concrete on the highways.
6.2. Inductive healing asphalt costs

The costs to implement each concept will be analyzed here. The estimation is limited to the material costs. Additional costs due to more complicated production processes can not be estimated in a reliable way and will thus only be evaluated qualitatively. In the calculations a road with three driving lanes of 3.5 m wide with an porous asphalt concrete top layer of 50 mm will be considered. The costs will be estimated of the regular inductive healing asphalt, the sectioned road, the anisotropic asphalt and the resonator aggregates. The dynamic permeability road is not considered because it was not possible to select a material that had desired properties.
6. Economical Aspects

6.2.1. Regular inductive healing asphalt
Regular inductive healing asphalt is created by adding 8% of steel wool to the asphalt by volume of the bitumen. The bitumen is 4.5% of the asphalt by weight. From table 2.3 it can be seen that the steel wool content in by volume of the asphalt is 0.6%. The price for steel wool grade 00 is €2 per kg. The total asphalt volume $V$ for one km of asphalt is

$$V = 10.5 \cdot 0.05 \cdot 1000 = 525 \text{ m}^3 \quad (6.1)$$

Therefore the total volume of steel wool in the asphalt will be 3.15 m$^3$. The density of iron is 7800 kg m$^{-3}$, thus a total of 24.570 $\times 10^3$ kg of steel wool is needed. With a price of €2 per kg the total price for this solution is €49 140 per km highway. This is below the savings of €490 100 per km, thus this solution could be economically feasible.

The additional production costs are estimated to be minimal. If the fibers are chopped in the correct size by the supplier then it only needs to be added to the asphalt mixture at the right moment. Only the mixing process will need more time, thus the additional production costs are estimated to be minimal.

6.2.2. Sectioned inductive healing asphalt
The sectioned road will contain the same volume percentage of steel wool in the inductive healing regions. There are however also regions where normal asphalt is used. If the section with normal asphalt in the center of the road is 1 m wide then the total volume $V$ of inductive healing asphalt for one km of highway is

$$V = 7.5 \cdot 0.05 \cdot 1000 = 375 \text{ m}^3 \quad (6.2)$$

The amount of steel wool that needs to be used for that volume of asphalt is 2.25 m$^3$. With a density of 7800 kg m$^{-3}$ the total mass of steel wool will be 17.550 $\times 10^3$ kg. With the same price of €2 per kg the total price for the asphalt is €35 100 per km highway. As discussed in section 3.1 it can be difficult to properly heat the sectioned asphalt lanes with the IPT coils. Therefore it is necessary to heat the asphalt lanes with an external source from a truck for example. This truck can however be used for more than one km of road, thus to make an reasonable estimate about the costs a total highway needs to be reviewed.

Also for the sectioned road the additional production costs are estimated to be moderate. For the inductive healing sections again only the mixing process will need more time, while the normal asphalt sections can be prepared as usual. The road will have to be produced in lanes. This is already the usual procedure, but the lanes will have to be smaller, thus more machines and employees will be needed. Therefore the additional production costs are estimated to be moderate.

One note that needs to be added to the cost estimation of the sectioned road is that there will be sections in the center of the road where inductive healing is not possible. Most of the wear will happen at the sides of the lanes where the tires are, but occasionally raveling can occur in the center of the road. The decrease in maintenance costs for the sectioned road will this be less than that of the other concepts.

6.2.3. Anisotropic inductive healing asphalt
In the way the anisotropic asphalt was designed in the experiments of this research it will contain the same amount of steel wool as the regular inductive healing asphalt. The additional material costs are thus €49 140. The main challenge is the production process of asphalt with an anisotropic steel wool distribution inside. No suitable production process for the large scale production of anisotropic asphalt has been developed yet. Therefore the additional costs of the production process are unknown.

6.2.4. Resonator aggregates
The resonators used in the experiments were designed to heat $1.25 \times 10^{-4}$ m$^3$ of asphalt. Using the previously calculated volume for one km highway of 525 m$^3$ the total amount of resonators that is needed becomes $4.2 \times 10^6$. A single resonator is made from 3.5 g of constantan wire and one capacitor. Constantan wire has a price of €10 per kg. The capacitors that were used are film capacitors of the Epcos B32560 Series. The price of a single capacitor, when ordered in large quantities, is €0.05. The material costs for a single resonator will be

$$\text{Costs resonator} = \frac{3.5 \times 10^{-3}}{10} + 0.05 = €0.085$$
With a total of $4.2 \times 10^6$ resonators per km the price per km highway for the resonators is €357 000. This is below the estimated reduction in maintenance, but a lot more expensive than normal inductive healing asphalt.

In the ideal scenario the resonators can be added to the aggregate mixture without any changes in the process. To be able to achieve that the resonators need to have the same mechanical properties as the other aggregates. It is assumed that it will be possible to manufacture resonators that are cased in a material such that they contain the desired mechanical properties. The additional production costs are estimated to be moderate.

### 6.3. Conclusion

In this chapter an estimation of the economical feasibility of an inductive healing asphalt road was made. First the costs that could be saved on maintenance were estimated from governmental expenses on infrastructure and reports on maintenance causes. This is then compared to the additional material costs that an inductive healing road would need. A summary of the results is presented in table 6.3. The conclusion is that every concept is feasible from this point of view. In this study the additional costs due to more complicated production processes are only evaluated qualitatively. Therefore it is recommended that a more detailed study is performed to properly quantify the additional costs in the production process. Also a more detailed study on the financial profit of low maintenance roads is advised. Beside the maintenance costs the financial profit might be increased because the availability of the road increases, which leads to less traffic jams.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Material costs</th>
<th>Production costs</th>
<th>Possible savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular IHA</td>
<td>€49 140</td>
<td>Minimal</td>
<td>€440 960</td>
</tr>
<tr>
<td>Sectioned IHA</td>
<td>€35 100</td>
<td>Moderate</td>
<td>€455 000</td>
</tr>
<tr>
<td>Anisotropic IHA</td>
<td>€49 140</td>
<td>Unknown</td>
<td>€440 960</td>
</tr>
<tr>
<td>Resonator aggregates</td>
<td>€357 000</td>
<td>Moderate</td>
<td>€133 100</td>
</tr>
</tbody>
</table>

Table 6.3: Comparison of economic feasibility of the different concepts. The additional costs are presented in the table. In this study the additional production costs are only estimated qualitatively.
Conclusions and recommendations

7.1. Conclusions

The main goal of the research in this thesis was to create a feasible combination of a highway that incorporates both inductive healing asphalt and inductive power transfer. In order to achieve this losses in the asphalt need to be reduced during IPT operation, while maintaining the ability to easily switch to induction healing of the road with the same system.

The physical processes for both the IPT system and the induction heating of asphalt are investigated. It is calculated that in order to keep the temperature difference between the ambient and the asphalt less than 5 °C the maximum allowable power dissipation in the asphalt during IPT operation is 2.38 kWm$^{-3}$. When induction healing is necessary a power dissipation of 233 kWm$^{-3}$ is needed to heat the asphalt to 80 °C within 15 min.

From the physical analysis an equivalent circuit for a combined IPT and IHA system is created, which can be used to calculate power transfer efficiency from the primary source to the secondary load and to investigate the power dissipation in the asphalt. The parameters for the equivalent circuit can be extracted from a numerical analysis. The numerical analysis is experimentally validated and it is concluded that it provides an accurate description of the real losses in the system.

Four concepts are proposed in order to create a feasible combination between the inductive healing asphalt and the inductive power transfer system. The concepts are (1) a sectioned road that separates the IPT and the IHA systems in the geometry, (2) inductive healing asphalt with anisotropic conductivity and permeability, (3) asphalt with resonator aggregates as heating elements tuned for a certain frequency and (4) asphalt with frequency dependent hysteresis losses.

The sectioned road is the easiest solution to implement and it can be designed to reduce the losses in the asphalt to any desired amount. The disadvantage is that the center of the road will not be covered with inductive healing asphalt, and can therefore not be healed using induction heating. The sections will be located away from the center of the coil which makes it infeasible to heat them with the same coils that are used for the IPT system. Therefore either separate coils need to be installed, or an external induction heating coil mounted on a vehicle should be used in order to apply induction healing.

The anisotropic IHA has interesting properties with respect to the power transfer efficiency. Due to the increased permeability in the vertical direction a easier path for the magnetic flux is created which increases the coupling between the primary and the secondary coil of the IPT system, enabling a more efficient power transfer. However to achieve enough power during induction healing operation the frequency or the current will have to increase with a factor of 10 from that of normal IPT operation, which means that more expensive power electronics are needed. This factor of 10 could be decreased if the non linear behavior of the losses in the asphalt is used.

The resonator aggregates concepts has the most desired electromagnetic behavior. The resonance frequency of the heating elements can be tuned very accurately, and the difference in operating frequencies for
IPT and induction healing can be decreased to 3 times the IPT frequency. The aggregates will be very easy to mix into the asphalt. The mechanical design of the aggregates and its impact on the mechanical properties of the asphalt should be investigated.

Asphalt with a resonance peak in the hysteresis losses is investigated and has promising results in the numerical models. The resonance behavior was however not verified experimentally, which is possibly because the losses are dependent on a lot of external parameters such as the applied magnetic field.

A preliminary economical analysis was performed that estimated that €49010 per km highway can be saved for each year that maintenance can be delayed. The expected increase in the lifetime of the road is 10 years. The possible reduction in maintenance costs is compared to the additional material costs for the implementation of the concepts. The result is that every concept is feasible in an economical sense. The additional production costs for creating an inductive healing highway are not considered.

The final conclusion is that it is always possible to combine the inductive healing asphalt with an inductive power transfer system. The losses in the asphalt during IPT operation can be decreased to any amount by choosing the right volume percentage of steel wool that is mixed in the asphalt. The asphalt can then be heated by increasing the frequency and current until the losses in the asphalt are high enough to heat it properly. This combination is however not feasible because the power electronic of the IPT system will need to be over designed in order to be able to provide the power for the induction healing. The resonator aggregates can reduce the gap in operating conditions of the IPT and the induction healing system, which will make a combined system more feasible.

7.2. Recommendations and future work

The research that was performed in this thesis has only considered the electromagnetic behavior and performance of the system. A detailed mechanical analysis of asphalt with steel wool had already been performed, and the conclusion was that the fibers enhance the mechanical properties of the asphalt. For the resonator aggregates a new research is needed. A suitable way to package the resonators needs to be found and the mechanical properties of the asphalt with these aggregates must be examined.

The resonance behavior of the resonator aggregates reduces the gap in operating conditions of the IPT and the induction healing system. It was discussed that the hysteresis losses in certain materials also contain a resonance peak. It was however not possible to select a material that had the desired properties in the experimental setup. It is recommended that more research is performed to find or create a material that has the desired behavior.

A preliminary economical analysis is performed to check the financial feasibility of an inductive healing asphalt highway. The first estimation is that a low maintenance inductive healing highway will result in a financial profit. In this analysis the additional costs of the production process of the asphalt are not included. Also the financial profit is only estimated from the maintenance costs and not from other effects like increased availability of the highway. A more detailed study into this subject is suggested in order to properly quantify the economical aspects.
Appendix A: Agilent 4294A accuracy
Appendix B: Magnetic field sectioned road

Figure B.1: Solid
Figure B.2: Hole radius 50 mm
Figure B.3: Hole radius 100 mm
Figure B.4: Hole radius 150 mm
Figure B.5: Hole radius 200 mm
Figure B.6: No asphalt
Bibliography


Cause of premature raveling failure of porous asphalt. 