Review of the Applications of Microwave Heating for Asphalt Pavement Maintenance

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Thomas Andrew Calhoon

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ABSTRACT

The propagation of microcracks into more serious pavement distresses is a major concern for asphalt pavements. Much work has been done to accelerate and control the asphalt self-healing of microcracks through the application of external heating methods including microwave heating. This thesis provides a state of the art of application of microwave heating of asphalt pavements, including self-healing. The principles of microwave heating, components of a microwave system, and different types of microwave systems are discussed. Then, an extensive literature review on the use of microwaves on asphalt pavements is presented. The review covers several applications of microwave heating on asphalt pavements and additives that enhance the microwave-absorbing capabilities of asphalt materials. Then, the results of a laboratory fatigue-heal cycle experiment are presented. The results demonstrate the ability of microwave heating to activate asphalt self-healing. Then, a 1D microwave heat transfer model is presented. A sensitivity analysis is performed on several model parameters. The analysis reveals that some parameters, such as thermal conductivity, do not significantly impact the microwave heating outcome, while some, such as applied microwave power density, do. Finally, recommendations are made for future work including field trials of discussed applications and implementation of the presented model in a computer application.

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CHAPTER 1: INTRODUCTION

The majority of roads worldwide are paved using asphalt materials.[1,2,3] With time and use, asphalt pavements deteriorate due to various factors. Temperature cycles, moisture penetration, sun exposure, and traffic loading can all cause the asphalt binder to harden, become brittle, and lose relaxation capacity and fracture resistance.[4] Deterioration leads to pavement distresses. Many visible distresses, such as potholes and alligator cracking, begin with less visible microcracks. It is important to deal with these microcracks before they develop into distresses that are more serious and more expensive to repair.

Asphalt self-healing is the natural tendency of asphalt materials to mend microcracks to varying degrees depending on the traffic level and internal temperature of the pavement.[5] Self-healing can occur through two different mechanisms. Depending on the amount of "resting time" from traffic loading, the diffusion of molecules between the two faces of a microcrack can create connection points and partially restore the continuity of the material.[5,6,7] This phenomenon is less likely to occur on busy roadways that experience continuous loading and are never traffic-free for the time required to heal cracks at ambient temperatures. Healing can also occur when asphalt reaches the necessary temperature to lower the viscosity of the binder to the point where it can act as a Newtonian fluid and flow through microcracks.[8] This capillary flow is caused by surface tension in the material, the gravity of liquid asphalt, and friction between aggregate particles and flowing asphalt.[9] The temperature at which self-healing begins (the critical temperature) depends on the binder in the mix and can range from 30-70°C.[8] Rapidly raising the temperature of asphalt binder tends to favor the latter healing mechanism, but it has been shown that the particle diffusion mechanism is activated by this practice as well.[10] Asphalts may naturally reach the critical temperature due to sun exposure or other factors; however, the amount of time they maintain this temperature cannot be controlled.

Much work has been done to accelerate and control the asphalt self-healing process through the application of external heating methods. The ability to successfully heal microcracks in a short time would surely benefit preventative maintenance efforts. Two main heating methods have been used for both laboratory and limited field applications: microwave heating and induction heating. Both methods use electromagnetic fields that alternate at high frequencies to rapidly raise the temperature of asphalt to the critical level required for self-healing and to sustain those temperatures for the amount of time necessary to heal the asphalt. However, the heating rate and efficiency of the two methods are very different.

Objective and Research Approach

The main objective of this thesis is to provide a state of the art of the applications of microwave heating of asphalt pavements including self-healing and to perform practical calculations using a simple heat transfer model. First, the principles of microwave heating and induction heating are introduced, with an emphasis placed on microwaves. Then, an extensive literature review on the use of microwaves on asphalt pavements is presented. The literature review also covers other applications of microwave technology on asphalt pavements and additives that enhance the microwave-absorbing capabilities of asphalt materials. The results of laboratory experiments that demonstrate the effect of healing from microwave heating are then presented. Finally, using a simple model of microwave heat transfer, a sensitivity analysis is performed to show how different physical and dielectric properties affect the microwave heating rate. The thesis ends with conclusions and recommendations for further work.

CHAPTER 2: PRINCIPLES OF HEATING METHODS

The induction and microwave heating methods are similar in the ways they generate heat in materials. Both methods apply an electromagnetic field to the target material to raise its temperature. The basic goal of both heating methods is the transfer of energy from the electromagnetic field to molecules in the target object and the dissipation of that transferred energy into heat. The two primary mechanisms for that energy transformation are dipolar orientation polarization (DOP) and conduction.[11] The former is dependent on the dielectric properties of the target object, while the latter is dependent on the magnetic properties of the target object.

The dipolar orientation polarization (DOP) mechanism is characterized by the rapid reorientation of dipoles within a material caused by the effort to align themselves with an applied oscillating electromagnetic field. The dipole alignment cannot keep pace with the rapid reversal of high-frequency fields because their motion is limited by inertia and resisting forces.[12] The effort of the dipole molecule motion against resisting forces creates friction and produces heat. This results in energy dissipation from the electric field into the material. This process is sometimes called “polarized relaxation loss”.[13]

The conduction mechanism is characterized by the induction of eddy currents within a material.[14,15] The oscillating electromagnetic field continuously redistributes charged particles along these eddy current paths.[11] Asphalt materials are poor electrical conductors and resist the flow of these currents. This resistance converts the electromagnetic field energy into kinetic energy which in turn creates heat. This heat generation is described as the Joule effect.[14] Although this mechanism relies on the target object not being a perfect conductor, it also requires the object to be at least partially conductive so the eddy currents may exist. This mechanism is observed more prominently at lower frequencies on the electromagnetic spectrum.[16]

The capability of materials to transmit and absorb field energy to convert it to heat through the DOP mechanism is described by their relative complex permittivity, as shown in Equation 2.1.[11] The capability of materials to transmit and absorb field energy to convert it to heat through the conduction mechanism is described by their relative permeability, as shown in Equation 2.2.

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \tag{2.1}$$

$$\mu^* = \mu' - i\mu'' \tag{2.2}$$

The real portion of the complex permittivity, ε', is the dielectric constant of the material. It is a measure of the material's ability to be polarized and store energy from an electromagnetic field through the DOP mechanism. It is defined as the ratio of the permittivity of the material and the permittivity of a vacuum or free space. The imaginary portion of the complex permittivity, ε'', is the dielectric loss factor. This loss factor is a measure of how efficiently a material can transform microwave energy into heat. The two components of complex permittivity can be used to find the dielectric loss tangent, $\tan(\delta) = \frac{\varepsilon''}{\varepsilon'}$.[11] Similarly, μ' is used to indicate how much energy can be stored by a material through the conduction mechanism, and μ'' is used to indicate how much of that energy can be converted into heat. Although the term "dielectric constant" implies a static value, the real and imaginary portions of both the complex permittivity and complex permeability can change with frequency and temperature.

Microwave and induction heating have several advantages over the more traditional industrial heating method of convection heating. Convection heating is performed by directing heat energy from the heat source through the skin of the heated material.[11] Depending on the properties of the target material, adequate temperature uniformity could take an extended period of convective heating to achieve. This brings a danger of overheating the surface of the material.

With microwave and induction heating, the heat is generated within the material, resulting in faster and safer outcomes of uniform heating. Microwave and induction heating can be operated with instantaneous and precise electronic control. This gives them an economic and environmental advantage over convection heating systems which require time and fuel to reach the necessary temperature to begin the heating process. Another environmental advantage of these two methods is that they don't involve combustion and thus don't create any secondary waste such as smoke or ash. On the contrary, these methods encourage the recycling and reuse of industrial waste products as additives. This will be expanded upon.

2.1 Induction

Induction heating is performed by sending a current through an inductor to create an electromagnetic field with a frequency on the order of kHz.[17,18] The frequencies of these waves are much lower than those used in microwave heating. With asphalt heating, the inductor is typically a coil that is placed directly above the material surface. The distance between the coil and the material has a significant effect on the heating rate.[17] Liu et al.[17] found that moving the induction coil closer to the asphalt surface will increase the heating speed but decrease the effective heating depth of the mixture. An example of asphalt induction heating can be found in Figure 2.1.

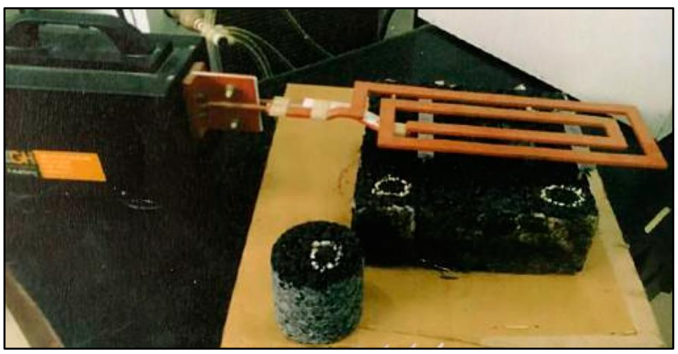


Figure 2.1 Induction heating of an asphalt sample.[17]

Because asphalts do not typically have strong magnetic or conductive properties, asphalt induction heating requires the addition of metallic additives such as steel wool fibers (SWF) or metallic fillers.[19] The metallic fillers form short-range electrical contact clusters while the fibers act as conductive bridges through the material.[20,21] Norambuena-Contreras et al.[22] identified different electrical conductivity phases associated with fiber content in asphalt. SWF is the most commonly used additive in asphalt induction heating efforts. However, metallic additives that cannot raise the electrical conductivity, such as steel slag, cannot increase induction heating of asphalt.[23,24]

Because induction heating does not work well on unmodified asphalt mixes and SWF-modified asphalts are not currently very common in road networks, microwave heating has more potential than induction heating to be incorporated as an effective maintenance tool.

Asphalt mastics with these additives that were heated through induction were shown to have reduced required rest time for self-healing and longer fatigue life.[25] The eddy currents present in induction heating also cause a “skin effect” in the asphalt where a large temperature gradient is observed between the asphalt surface and interior.[26]

Asphalt self-healing by induction heating has been thoroughly explored by the HEALROAD consortium, a European effort to maintain roads cost-effectively by healing asphalts with induction heating. This effort focused heavily on minimizing the transport flow disruption caused by the induction healing process, which they said causes the loss of 1% of the EU’s GDP each year.[27] Through extensive research that included binder optimization, the construction, and testing of a road section, and a life cycle assessment of maintenance operations, they found total savings in costs of around 4%.[28]

2.2 Microwave

Microwave heating is performed by placing an object within a reflective chamber then filling the chamber with an electromagnetic field with a frequency on the order of MHz. On the electromagnetic spectrum, microwaves can have frequencies between ~1GHz and ~1000GHz.[29] However, the United States Federal Communications Commission (FCC) has designated certain microwave frequency bands for industrial, scientific, and medical applications.[30] This is different than induction heating, which is not limited to a preselected set of frequencies.[17,25,31] The bands most commonly used for microwave heating have center frequencies of 915MHz and 2450MHz.[16] The 5800MHz band has recently been gaining interest. For reference, domestic microwave ovens operate at a center frequency of 2450MHz. Microwave heating is more energy-efficient than induction heating. Gallego et al.[5] found that microwave heating systems can achieve far greater heating rates than induction heating systems with the same power supply. Also, microwave heating can raise the temperature of unmodified asphalts while induction heating cannot.[23,31]

The majority of the heat generation from microwave heating comes from the DOP mechanism.[13] The contribution of the conduction mechanism is low, meaning a material doesn’t have to have high electrical conductivity to be effectively heated by microwave.[7] Most literature on microwave asphalt heating focuses on the DOP mechanism. In this thesis, in cases where microwave heating is discussed but the mechanism is not specified, the DOP mechanism will be assumed.

Because microwave heating depends mostly on the DOP mechanism, it also depends on the dielectric properties of the target materials. Materials with high dielectric loss factors are referred to as “lossy” and can be heated with microwaves most effectively. The dielectric properties of a material are dependent on various things. The dielectric constant and loss factor are dependent on the frequency of the applied electromagnetic field, as well as the temperature, density, and composition of the target material. The latter is particularly important in materials such as asphalt that tend to be made of many elements can have heterogenous compositions.[13] The fact that certain materials are more susceptible to microwave heating is a strength of the microwave heating method. It allows for selective heating of elements within materials, which is convenient for some industrial processing procedures.

The microwave penetration depth represents the depth of a material at which most of the microwave power has been absorbed. Materials with lower dielectric constants have deeper penetration depths. At the penetration depth, the microwave field will have been reduced to 36.8% of its original strength value.[32]

The microwave-absorbing abilities of a material also depend on its reflectivity to microwaves. A material with reflectivity lower than -10.0dB is considered to be highly effective at absorbing microwaves.[33]

Water has a relatively high dielectric loss factor at 2450MHz and 915MHz, so its presence in a material can significantly affect the microwave heating process.[11] Absorbed water that is in contact with other materials has a greater loss factor than non-absorbed water. However, water that exists free form in the cavities of a material can increase the loss factor of a material even more than absorbed water. This is because water molecules bound to the material have limited rotational movement which limits the DOP mechanism. Metaxas and Meredith[34] stated that once a material passes a critical moisture content, additional moisture comes in the form of free cavity water which increases the dielectric loss factor at a much higher rate.

Water has a moderately high dielectric loss factor, but it has an exceptionally high dielectric constant.[35] This imbalance leads water to be better at absorbing microwave energy than it is at converting that energy into heat. The presence of water in a material thus impedes efficient microwave heating. Because of water's high dielectric constant, increases in moisture content can significantly decrease the microwave penetration depth of the material.[36]

It has been shown that, at low moisture levels, an increase in temperature typically causes an increase in dielectric loss factor.[34] That response can cause a phenomenon known as "thermal runaway" in which increases in temperature and dielectric loss factor exponentially feed each other. An increase in temperature from microwave heating causes an increase in dielectric loss, which in turn causes greater microwave heating effects. This phenomenon can lead to uncontrollable increases in temperature that severely damage the material being microwaved. Thermal runaway has been called one of the largest challenges of the microwave heating method.[37] There is work that has been done to try to combat this phenomenon in asphalt, which is prone to runaway as a low-moisture material.[37,38]

Typical microwave equipment is made up of three major components: the power unit, the applicator, and the control circuitry.[16] The power unit provides power to the system and generates the electromagnetic field. The applicator is used to expose the target material to the field. The control circuitry optimizes and regulates the performance of the microwave.

Magnetrons are by far the most commonly used power source in industrial microwave applications today.[11] This is mostly due to the relatively low capital and operating costs of these kinds of power units. The core component of magnetrons is an electron-emitting cathode held within a hollow copper anode that has multiple cavities or "vanes".[34] The anode vanes protrude into the center, creating the cavities. A diagram of this component can be seen in Figure 2.2. The component is designed so that electrons emitted from the cathode will travel in a circular pattern in the space between the cathode and anode. This circular motion is both encouraged by and is the cause of polarity shifts on the faces of the anode vanes. The electrons are attracted to the positively charged faces of the vanes, but their presence causes the charge on the faces of the vanes to switch, which then propels the electrons to the next vane, and so on. Further discussion of this process can be found in Metaxas and Meredith[34].

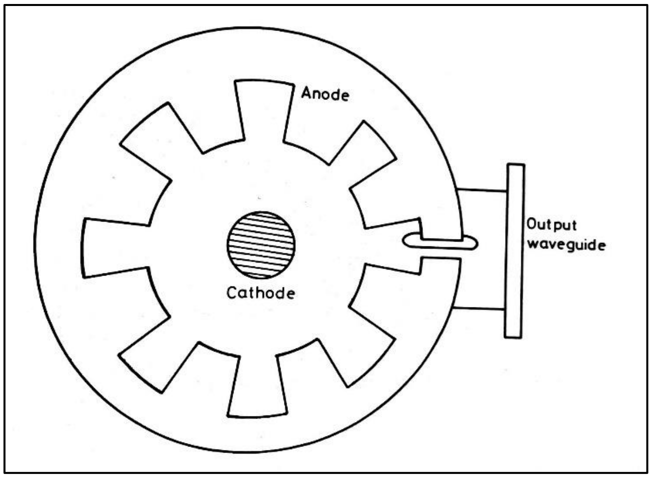
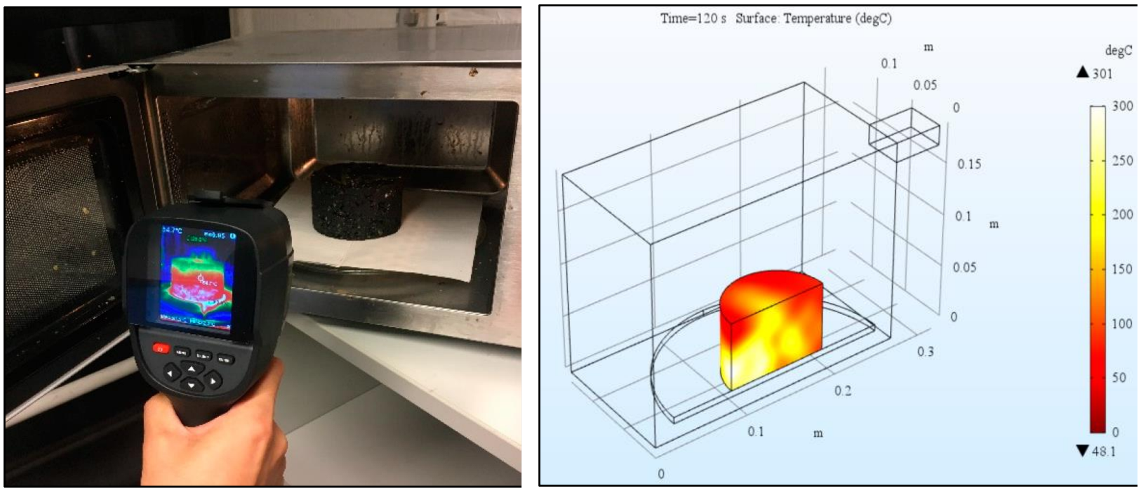


Figure 2.2 Diagram of the inner components of a magnetron.[34]

This continued motion creates a microwave electric field that can be extracted via a loop through one of the anode cavities and passed into a waveguide. Waveguides are circular or rectangular hollow metallic tubing that are used to guide the extracted electromagnetic field from the power unit to the applicator. Waveguides are often made of aluminum.[11] The material choice for the waveguide is important because it must be able to reflect the microwave field with minimal power loss and dissipate the significant amount of heat that can be generated from this reflection. Aluminum can do both of these things.

The microwave applicator is used to expose the target material to the microwave field. For domestic microwave ovens, the applicator is the chamber that food is placed in. The walls of the chamber are made of material that will reflect the microwave field with little power loss. This is meant to maximize the amount of energy available for absorption by the target material. The most common type of applicator is the “multimode” applicator.[16,39] Microwave systems with multimode applicators employ a microwave field with several standing wave patterns. Each of these standing wave patterns is called a “resonant mode” and has a frequency within the frequency band of the microwave system. These different frequencies allow the wave patterns to create different heating patterns within the material being heated. While this is meant to create a uniform heating environment, the patterns are not naturally different enough to achieve this. In fact, a defining characteristic of multimode applicators is non-uniform heating. These patterns have anti-nodes where the field intensity is zero and no heating can occur. This is why food heated in a microwave oven will often have hot and cold spots. Various actions are taken to combat this non-uniformity such as forced movement of heated material and the inclusion of “mode stirrers”. Mode stirrers are metal devices within the applicator (typically a rotating multi-blade fan) that perturb the field distribution continuously. They are usually placed near where the waveguide feeds into the applicator chamber to maximize the disruption.

In microwave heating research work, there are typically two kinds of microwave systems used. The first is the common domestic microwave oven unit. An example of this type of unit can be seen in Figure 2.3a. This type of microwave is often used in laboratory settings due to its accessibility and low price point. However, its effectiveness is limited by the heating distribution issues discussed previously and a typical lack of power level and frequency options. Most of these units operate solely at a frequency of 2450GHz and a power level of around 1kW.[40] Pitchai[15] presents an overview of the work done to model the heat transfer within domestic microwave ovens. These models face the common challenges of dielectric and thermal properties that change with temperature and frequency and difficulty in accounting for the reflection and refraction of microwaves in the material. Pitchai discusses the concept of coupled electromagnetic and thermal models. The outputs of one affect the inputs of the other. He also discusses various relevant modeling software including Microwave Studio by CST and COMSOL Multiphysics. These software are 3D finite element tools that are commonly used in the modeling of microwave heating. Wang et al.[41] used COMSOL Multiphysics to model the electromagnetic and thermal behavior of a modified asphalt specimen heated with a microwave oven. An example of surface temperature results from their model can be found in Figure 2.3b.



(a) (b)

Figure 2.3 Example of (a) the use of a domestic microwave oven in a laboratory application and (b) a 3D model of the oven in COMSOL Multiphysics.[41]

The second kind of microwave system used in microwave heating is the horn antenna system. This type of system is composed of a power unit, a waveguide, and an applicator that directs microwave energy in the direction of the “horn” opening. These applicators can have either the traditional horn shape or can have a box-like shape. Figure 2.4 shows an example schematic of a traditional pyramidal horn antenna system. Because horn antenna microwaves are not mass-manufactured commercial products, each one is somewhat unique. Different systems can operate at different power levels and frequencies, depending on the hardware of the system. While it is very common for horn antenna microwave laboratory tests to be run at 2450MHz, there has been laboratory and model work with 5800MHz horn antenna systems.[42,43] This work suggests that 5800MHz systems are more efficient at heating due to the faster oscillation of the electromagnetic field which leads to increased heat conversion from the DOP mechanism.[44]

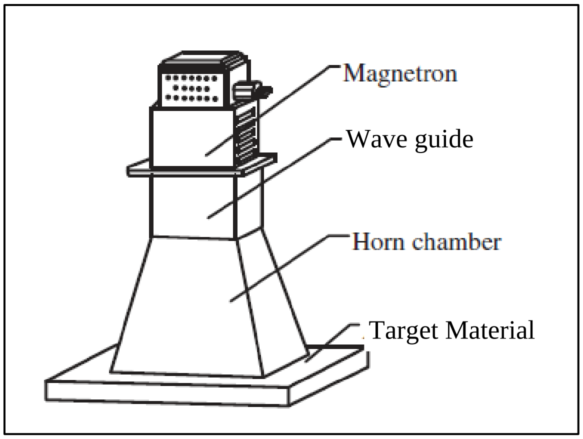


Figure 2.4 Example of a pyramidal horn antenna system.[45]

Sun has been a leading researcher in the field of horn antenna microwave temperature field modeling. He found that microwave heating temperature uniformity can be optimized through adjustments to the horn antenna structure.[23,46] Sun and Chen[47] found that horn antenna systems that feature applicators with similar long and short sides and that use intermittent heating have the greatest heating uniformity. They also found that horn antenna systems with higher-power magnetrons have worse heating uniformity. Sun has shown in multiple studies that when horn antenna systems are used on flat surfaces, the heating rate is highest near the center of the applicator footprint.[45,48,49]

Mobile microwaving systems have the same functional structure as horn antenna systems but are larger in scale and mounted on some kind of vehicle. These are the systems that are used to perform microwave heating in the field and are the practical evolution of most of the work done with microwave heating in a laboratory setting. Horn antenna systems used in laboratories typically operate on a power scale of 1-10kW while modern mobile microwaving systems typically operate at 50kW and beyond.[50] These mobile systems use much longer waveguide apparatuses as their applicator are typically extended from the vehicle on some kind of mechanical arm.

Some mobile microwaving systems operate at 915MHz instead of 2450MHz. Penetration depth is inversely proportional to the frequency of the wave, so 915MHz systems can effectively heat further below the surface than 2450MHz systems.[36,46] The penetration depth of 915MHz microwaves is approximately 2.7 times more than that of 2450MHz microwaves.[36] This is beneficial for things like thawing frozen soils but can make temperature control at shallow depths more difficult.[50] Most materials heated with mobile microwaving systems have similar dielectric properties at 915MHz and 2450MHz.[11]

An example of a mobile microwaving system can be seen in Figure 2.5. This system has a box-like horn antenna applicator, operates at 915MHz and 50kW, and was created by Microwave Utilities, Inc.

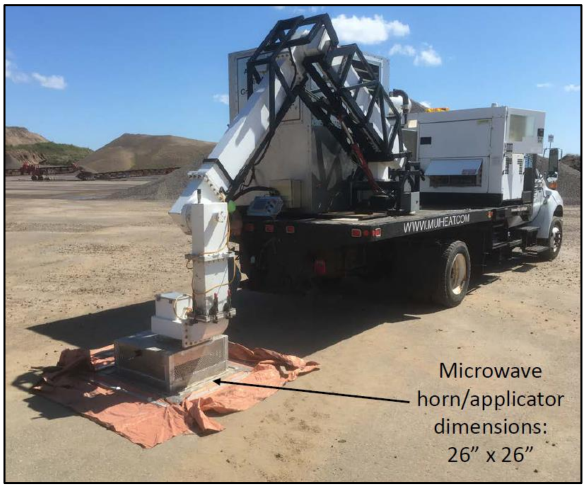


Figure 2.5 Example of a mobile microwaving unit.[51]

Zanko and Hopstock (2004) provide a history of the practical application of microwave technology for road repair in North America and Europe which doubles as a history of the innovations of mobile microwaving systems. In 1974, Renato Bosisio showed that microwave heating could be used to completely seal road cracks.[52] Their system operated at 2.5kW and 2450MHz. Their power unit was mounted on a 4-wheel carriage cart. This system was very inefficient in its power usage. The power unit was using 10kW to create a 2.5kW microwave field. Microwave power units would become more efficient with time. Morris Jeppson patented an early concept of the vehicle-mounted mobile microwaving system.[53] His truck-mounted power unit design is recognizable from today's mobile systems. In the 1980s, a Kentucky company called Microdry applied mobile microwave heating on a commercial scale for pothole patching and strip repair of asphalt highways.[54] Their truck-mounted system operated at 100kW and 2450MHz. In 1995, Lindroth[55] introduced a pickup truck-mounted mobile microwave system with a more compact horn antenna applicator. This system can be seen in Figure 2.6. This system represented a step forward in the flexibility of mobile microwaving systems. The mobile microwaving system found in Figure 2.5 is a natural evolution from and combination of the advancements outlined above. However, there are still advancements being made in this area. Recently, Salski[56] introduced a design for a new applicator that features a choke composed of a hexagonal pattern of cylindrical stubs. The choke reduces the amount of leakage by at least 35dB which makes the system safer and more energy-efficient. A prototype of this applicator can be seen in Figure 2.7.

Figure 2.6 Mobile microwave system with a more compact applicator.[55]

Figure 2.7 Microwave applicator with leakage suppressing choke.[56]

CHAPTER 3: LITERATURE REVIEW

3.1 Microwaving Asphalt

Every material reacts to microwave heating in a unique way. For that reason, it is important to discuss the microwave heating behavior of asphalt and how elements of the asphalt mix affect that behavior. There have been many studies over the years that have used microwaves to heat asphalts. Due to inherent variations in the methods, equipment, and mixes used in these studies, their results are not quantitatively presented in this thesis. Instead, qualitative findings established through these works will be discussed.

An asphalt mix has two main elements: asphalt binder and aggregates. Aggregates are the load-carrying component of the mix and are categorized by size (from largest to smallest) as coarse, fine, or filler. A variety of aggregate sizes and types (well-graded mix) can provide better pavement performance. Aggregates typically make up ~95% of the weight and ~80% of the volume of an asphalt mix. Filler aggregates are small enough to provide contact points between particles in the mix and to fit in the bituminous films that coat larger aggregates.[57] The combination of asphalt binder and filler aggregates is called asphalt mastic. Most asphalt mixes contain some amount of recycled asphalt pavement (RAP). Unless a rejuvenator chemical is applied to RAP, it has a more viscous binder due to the binder aging process.

Asphalt binder is typically the least microwave-absorbing element of an asphalt mix.[56] Wang et al.[58] found the dielectric constant of asphalt binder to be ~18 times less than that of the coarse aggregate and ~17 times less than that of the asphalt mix as a whole. This makes sense as aggregates are typically the most microwave-absorbing element of an asphalt mix. However, the microwave heating rate of an aggregate depends on its mineral composition. The minerals that compose common asphalt aggregates (quartz, basalt, limestone, etc.) have significantly lower microwave heating rates than ferric minerals like magnetite.[54] However, some common aggregates are better suited for microwave heating than others. Salski et al.[56] found basalt to be much more “lossy” than limestone and to have a microwave heating efficiency ~40 times higher. Benedetto and Calvi[12] also found the replacement of limestone with basalt to increase the microwave heating efficiency of asphalt. Common asphalt aggregates can contain metallic minerals that have high dielectric loss factors.[59] Trigos et al.[59] established a classification for aggregates based on their microwave-absorbing ability.

Examples of aggregates found in the upper classes are steel slag, andesite, and ophite. Examples in the lower classes are quartzite and limestone.

Aggregates are the microwave-absorbing element in asphalt mixtures, and therefore act as the primary heat source during microwave asphalt heating. Aggregates convert microwave field energy into heat then transfer that heat to the surrounding mastic through conduction. The heating rate of asphalt has been shown to increase with aggregate size.[60] This means that well-graded asphalt mixes will have different heating rates throughout the mix. This can lead to a lack of temperature uniformity. Sun[46] found that decreasing the weight share of aggregates in a mix would slightly increase the thermal conductivity but decrease the average microwave heating rate of the asphalt.

A lack of temperature uniformity is a commonly observed issue with asphalt microwave heating. Temperature variation within the asphalt has been found to grow with microwave heating time.[58] Temperature variation is minor at the beginning of heating due to the long-time influence of air temperature. Over time, the non-homogenous nature of the asphalt mix will ensure a somewhat non-uniform heating pattern. Different researchers have approached this non-uniformity in different ways. Some have deemed the temperature variation acceptable and an improvement over other heating methods such as direct frame or infrared heating.[58] Some have seen room for growth and moved to study additives (steel wool fiber, magnetite powder, etc.) that can reduce microwave heating temperature variation.

The dielectric constant and dielectric loss factor of asphalt vary with temperature.[38] Zhu and Shi[38] found that both parts of the complex permittivity of asphalt decrease nonlinearly with an increase in temperature. The decrease is initially severe but then tapers off as temperatures reach binder-softening levels. This implies that the microwave heating rate of asphalt would decrease as the temperature of the material rises. This has been observed by multiple studies although it is not always the case and can vary by depth.[12,58] Sun[46] found a near-linear relationship between the heating rate of asphalt mixtures and the microwave power applied.

As already mentioned, microwave heating of asphalts involves internal heat transfer from aggregates to mastic. Sometimes during this heat transfer, the binder film that coats the aggregates melts.[61] This melted binder is redeposited onto the aggregate surface and can fill permeable voids in the aggregates. This action increases the adhesion of the asphalt mix. Al-Ohaly and Terrel[61] also found that the DOP mechanism is beneficial to mix adhesion as it reduces the randomness of the polar molecule orientation on the aggregate-binder interface, allowing for a more uniform connection. This also boosts the performance of anti-stripping agents. The adhesion and water resistance benefits of microwave heating have been used as an argument for the use of microwave heating in the production of asphalt on a commercial scale.[62]

Unlike traditional heating techniques that pass all heat flux through the surface, microwave heating typically doesn't have the highest heating rate at the surface.[58] Wang et al.[58] found the "optimum heating depth", or the depth at which the microwave heating rate is highest, of unmodified asphalt to be between 5-13cm. While longer heating times increase the temperature throughout the asphalt, they also increase the temperature disparity between the optimum heating depth layer and the surrounding layers. However, Wang et al.[58] say this lack of uniformity is a positive for activities such as hot in-place recycling where keeping the pavement interior warm is a priority. The optimum heating depth can be moved closer to the surface with the inclusion of microwave-absorbing additives.[40]

Franesqui et al.[63] noticed that asphalt mastic specimens with identical contents but different lengths had different microwave heating speeds and determined that the microwave heating rate of asphalt depends on the specific energy applied. Specific energy is the amount of microwave energy applied to the asphalt per unit of mass. They found the rate of temperature increase against applied specific energy to be consistent across three different asphalt types. Similarly, it has been found that an increase in asphalt layer thickness leads to a reduction in microwave heating rate.[49] This reduction follows an inverse exponential trend with an increase in thickness.

As already mentioned, water has a relatively high dielectric loss factor and can impede efficient microwave heating. Water typically has a dielectric constant value in the 70's while asphalt typically has a dielectric constant value in the 30's.[58] The presence of water on the asphalt surface can reduce the microwave penetration depth. Sun and Sheng[49] found that pavements with higher initial moisture content take much longer to reach a certain temperature because the asphalt heating will be stalled until sufficient evaporation has occurred. The energy required to raise the temperature of a unit of water is five times more than that required to raise the temperature of a unit of asphalt pavement.[64] This is due to the difference in specific heat between water (1.0) and elements of an asphalt mix (0.2-0.3).

Water's high microwave-absorbing abilities can be taken advantage of, as shown by Benedetto and Calvi.[12] They showed that microwave heating is more effective at drying aggregates than conventional heating methods because of those abilities. They argued that this meant microwave heating could be effectively utilized in the production process of asphalt mix. This study also showed that the optimum water content of aggregates for efficient microwave heating is the Saturated Surface Dry (SSD) condition. Any extra present moisture would create a film of water on the surface of the aggregates which would hamper microwave heating. Terrel and Al-Ohaly[64] also found SSD to be the optimum aggregate water content. Their tests showed SSD aggregate can achieve a microwave heating rate almost double that of dry aggregate. They described the optimum water content of an asphalt mix as the point where the cooling effect of evaporation outweighs the increased heating rate provided by the water.

3.2 Microwave-absorbing additives

When the practice of asphalt microwave heating was young, standard asphalt mix was considered to have good microwave-absorbing qualities.[52] Today, most researchers would say that asphalt mix is a poor microwave absorber. This is evidenced by the volumes of work done testing the effects of microwave-absorbing asphalt additives. Microwave-absorbing additives are materials that are added to an asphalt mix that increase the ability of the mix to be heated by microwave. This section will give an overview of many of these additives. The qualitative advantages and disadvantages of each will be discussed. The only time direct comparisons will be made between different additives is when they are included in the same study. The inherent fact that each additive increases the microwave heating rate of asphalt will not be repeated in each section. Also, the effects of each additive on the physical and mechanical properties of asphalt generally will not be discussed. This review will focus on the effects that impact the microwave heating process.

Osborne and Hutcheson[65] were one of the first parties to discuss the benefits of microwave-absorbing additives in their patent for an asphalt compound that incorporated a "lossy microwave material". Their definition of lossy materials was broad and included things from semi-conductors to ferromagnetic materials to metals "in powder or particle form".

An environmental benefit of microwave-absorbing additives is that many of them are industrial waste products that would be disposed of otherwise. Metallic waste products such as steel fibers, steel shavings, and steel slag persist in the environment for a long time before oxidizing and degrading.[22] Low-grade pyrite cinder (LPC) is a waste product generated during the manufacturing of sulfuric acid.[66] LPC contains significant quantities of hazardous heavy metals and acids that could potentially cause serious environmental damage when disposed of. In China, over 12 million tons of this waste is dumped onto land without any pretreatment. This has led to considerable use of land resources, dust problems, and contamination of soil and water. The use of LPC as a microwave-absorbing additive reduces these environmental harms. Activated carbon powder (ACP) is commonly used to absorb pollutants in air pollution control and wastewater treatment.[67] Once used, ACP is typically disposed of. However, it has been shown that used ACP can be used as a microwave-absorbing additive for asphalts instead. The reuse of readily available waste products in asphalt production will also reduce the number of virgin materials that need to be mined or manufactured. In places where a majority of the paved roads are asphalt, the substitution of natural virgin aggregates is urgently needed to alleviate issues with supply and dwindling natural resources.[1,2,3] Increased heating efficiency from the use of these additives results in significant environmental and cost savings.[1] Gulisano et al.[7] found that their use of additives allowed them to halve the amount of expended energy to reach a target temperature. Increased microwave heating efficiency can also reduce maintenance costs and traffic closure time.[68] Researchers have used increases in efficiency to justify the high price of some additives. Most waste products (e.g., steel slag, metal shavings) are relatively cheap, but products manufactured for first-time use (e.g., carbon nanotubes, ferrite, graphene) are more costly.[1,71]

Microwave-absorbing additives come in the form of aggregates (coarse and fine), fillers, and fibers. Aggregate additives are used as a substitution for a portion of the coarse or fine aggregates in a mix. However, because asphalt mixes don’t always feature fillers or fibers, those types of additives are truly an addition to the mix. Some materials can fit both the aggregate and filler labels. Examples of these are taconite and steel slag, both of which can either be included in a mix as a coarse, fine, or filler aggregate. However, not all filler additives are aggregates. Engineered particulates such as carbon nanotubes and graphene are fillers as well.

As already mentioned, fiber additives can improve induction heating by creating conductive pathways that encourage the conduction energy conversion mechanism. Likewise, they can improve microwave heating through the DOP mechanism. They act as effective thermal conductors due to their small diameters, which allows them to rapidly dissipate the heat generated through the DOP mechanism to the surrounding mastic.[31]

It has been shown that fiber additives can be damaged during the mixing and compaction processes. Norambuena-Contreras and Concha[21] showed that thicker fibers are more prone to damage because they have a large specific contact surface. Damage to the fibers can reduce their electrical various mechanical and electromagnetic benefits. Franesqui et al.[63] observed that asphalts with shorter fibers are more efficient at microwave heating than asphalts with longer fibers.

Fiber clusters are a much-discussed issue with the use of fiber additives. They are a concentration of fibers in the mix caused by tangling during the mixing process. An example of fiber cluster formation can be seen in Figure 3.1. Several factors can increase the likelihood of cluster formation. The most well-known factor is excess fiber content in the mix.[3,6,31,70] High fiber content can increase air voids and make proper fiber distribution difficult, both of which encourage cluster formation.[31] Another factor is the shape and size of the fibers. Thinner and longer fibers have been found to increase cluster formation.[2,5,63,71] Fiber clusters can impede microwave heating in multiple ways including decreased thermal conductivity (from increased air voids), increased microwave reflectivity, and increased chance of local overheating.[22,71] Local overheating occurs when the binder exceeds its flash point temperature and can cause binder damage.[17] It can also cause excessive expansion and loosening of the asphalt mix which can result in asphalt specimens breaking apart in laboratory settings.[17,23] Overheating has been identified by some as a point of impracticality of using microwave heating as a common construction tool.[23] Zhao et al.[68] argue that limiting microwave heating periods will prevent binder damage and make field operations more viable.

Clusters can also make asphalt compaction difficult which in turn weakens various mechanical properties of the mix. Although some studies mention the tendency of filler additives to agglomerate, it seems that distribution within the mixture is much better for fillers than it is for fiber additives.[72]

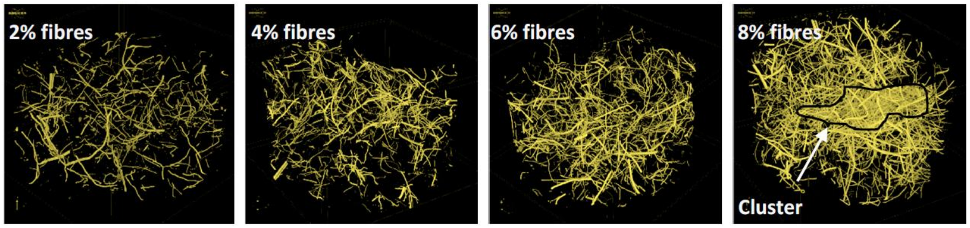


Figure 3.1 3D reconstruction of the fiber spatial distribution in an asphalt specimen with varying fiber content. Bounding box dimensions are 25x25x12mm, approximately.[70]

An increasingly common area of interest is the use of multiple microwave-absorbing additives in a single asphalt mix. Several studies have shown that different additive types (aggregate, filler, fiber) can work well together to maximize the microwave heating potential of asphalt.[6,13,73]

3.2.1 *Steel Slag*

Aggregate

"Steel slag" is a generalized term for the main solid by-product of the iron and steel smelting industry.[1,74] Steel slag used in microwave-absorbing additive research is typically electric arc furnace (EAF) slag, which is produced during the oxidation of steel pellets in an electric arc furnace.[74] EAF slag makes up 15-20% of the weight of iron produced in this process. Steel slag, in general, makes up 10% of the raw steel output around the world.[75] This product will just be referred to as "steel slag" hereafter. Steel slag has a recycling rate of less than 50% and typically ends up in large storage facilities and can lead to environmental problems such as land occupation, water pollution, and heavy metal soil contamination.[1,74] Worldwide, approximately 100 million tons of steel slag are produced each year, making its reuse an international concern.[75] Researchers have attempted to increase steel slag's recycling rate by using it as an ingredient in asphalt pavements. Another environmental benefit of this is that coating steel slag in asphalt binder reduces its heavy metal leaching.[1]

The microwave-absorbing ability of steel slag can be explained by its chemical makeup and mineral components. Gao et al.[1] found the most active chemical ingredient in steel slag during microwave heating to be white iron-magnesium, which has a very high iron content. They also found prominent magnetite content in the additive. Lou et al.[75] also found high iron content in steel slag. Both magnetite (Fe_3O_4) and iron are considered hyperactive for microwave heating. Lou et al.[75] found the dielectric constant and dielectric loss factor of steel slag to be highest under microwave frequencies close to 2450MHz, meaning the additive is most effective as a microwave-absorber at the most commonly used microwave frequency.

Sun et al.[74] first tested the use of steel slag as a microwave-absorbing additive in asphalt. They found promising results for the replacement of limestone aggregates with steel slag. Steel slag aggregates are well-performing asphalt aggregates with high stiffness and hardness, and good fatigue, aging, polishing, and abrasion resistance.[1,7] Steel slag also has good interlocking characteristics which increase the skid resistance, moisture stability, and fatigue life of steel slag-modified asphalts.[6,73] Steel slag is sometimes treated with the "six months processing method" to prevent volume expansion and pavement cracking caused by the existence of free lime in the aggregate.[6]

Steel slag is produced in large, dense blocks that must be crushed before use in asphalt.[1] For that reason, its size is versatile and can be used as a coarse, fine, or filler aggregate. Like with typical aggregates, the microwave heating rate of steel slag increases with an increase in particle size and volume.[1,76] Most steel-slag-modified asphalt mixes either use steel slag as the coarse or fine aggregate, but not both.[6,23,74]

As already mentioned, steel-slag-modified asphalts sometimes experience nonuniform microwave heating temperature distribution. This is partially caused by the poor thermal conduction of typical asphalt binders which require long heating periods to achieve desired temperatures across the mix.[73] These long heating periods result in portions of the mix that are in danger of local overheating which can critically soften the asphalt binder surrounding the steel slag aggregates and lead to a collapse of the asphalt.[73] There are conflicting findings on whether the inclusion of large quantities of steel slag can improve temperature uniformity. Sun et al.[23] found that when steel slag is used as a coarse aggregate replacement, the temperature uniformity is good. Phan et al.[6] found that replacing even 30% of coarse aggregate with steel slag can increase temperature uniformity. However, Gao, et al.[1] found that increasing the steel slag content of a mix will continuously decrease the temperature uniformity, even with 100% aggregate replacement. Lou et al.[73] had similar findings. Because steel slag is a waste product, the amount of microwave-hyperactive elements may vary in each piece of aggregate.[68] This may explain why certain studies found large quantities of steel slag to increase the temperature uniformity while others did not.

The common occurrence of cold air pockets within steel slag aggregate can cause it to decrease the overall thermal conductivity and diffusivity of asphalt.[1,23,74] This should only slightly affect the microwave heating process as most of the heat transfer is within the mastic. Small additions of steel slag can significantly increase the electrical conductivity of asphalt.[7,69]

One major benefit of steel slag over other microwave-absorbing additives is its cost. In a comparison of the cost increment of various additives, Gao et al.[1] found steel slag to be the only additive that decreased the construction costs of asphalt pavements. However, this low cost is likely location-dependent given that it is most abundant in regions with steel and iron manufacturing like Northern China or Korea.

The porous nature of steel slag particles can cause them to consume high amounts of asphalt binder, significantly increasing production costs.[6] Phan et al.[6] recommend that steel slag not be used as a fine aggregate as the smaller particles are particularly binder-absorbing. Wang et al.[41] warned that excessive binder absorption could lead to a loss of adhesion and rutting resistance. However, it has been suggested that the steel slag's porous nature increases its microwave heating ability as it allows microwaves to be reflected multiples times within the steel slag pores.[75,77]

Coprecipitation Method

In 2017 and 2018, a group of researchers from Southeast University performed a series of studies that improved the microwave-absorbing qualities of steel slag. They did this by increasing the share of magnetite on the surface of the aggregates. The steel slag was modified with the activated-carbon-reduction method, which involved the chemical reaction found in Equation 3.1.[26] This reaction transformed the non-magnetic ferric oxide (Fe_2O_3) on the surface of steel slag into magnetite (Fe_3O_4).

$$C + 3Fe_2O_3 \xrightarrow{500℃} 2Fe_3O_4 + CO \quad (3.1)$$

Liu et al.[78] were able to modify steel slag aggregates to the same end using the coprecipitation method. This process is explained in various studies and essentially comes down to the chemical reaction found in Equation 3.2.[78,79]

$$2Fe^{2+} + Fe^{3+} + 8OH^{-} \rightarrow Fe_3O_4 + 4H_2O \quad (3.2)$$

Asphalts containing modified steel slag had much higher microwave heating rates and efficiencies than those containing normal steel slag or typical aggregates.[26,78] The modification of the steel slag greatly increased the magnetic loss factor (μ'') of the aggregate. This, in turn, greatly increased the effectiveness of the conduction mechanism during microwave heating.[26,78] Miao et al.[26] simulated microwave heating of an asphalt specimen containing modified steel slag using Microwave Studio. They found the overall temperature uniformity to be improved compared to typical steel slag asphalts.

Filler

Some studies have used steel slag in filler form to modify asphalts.[72,77] Steel slag filler (SSF) has been shown to have superior rheological properties to the commonly used limestone filler.[77] As mentioned earlier, the porous nature of steel slag allows microwave radiation to reflect multiple times within steel slag particles. Li et al.[77] found that SSF reflects less microwave energy and refracts more microwave energy than limestone filler, meaning microwaves can "be attenuated repeatedly and consume more energy in the inner parts of SSF".

3.2.2 *Steel Wool Fiber (SWF)*

Steel wool fiber (SWF) is an industrial waste product and the most commonly studied microwave-absorbing fiber additive. The microwave-absorbing abilities of SWF come from its primary chemical component, iron.[80] Like steel slag, SWF is typically disposed of in landfills where it takes decades to decompose.[22] Recycling this material as an additive is an environmental benefit. As already mentioned, SWF is commonly used as an additive for induction heating.[5] However, researchers have found that microwave heating is more effective than induction heating for SWF-modified asphalts.[5,31] Gallego et al.[5] showed that a unit mass of SWF is ten times more effective as a microwave heating aid than as an induction heating aid. An example of SWF can be found in Figure 3.2.

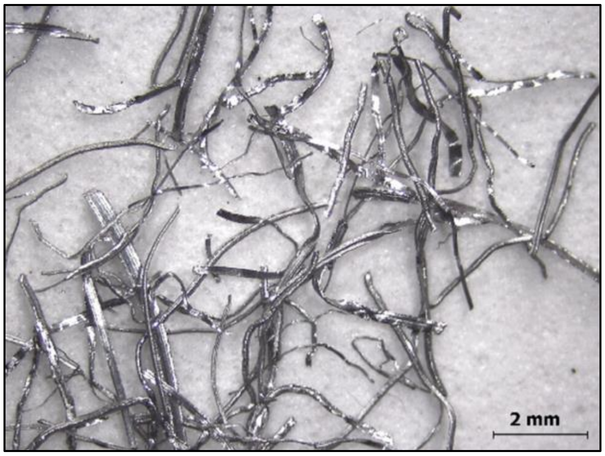


Figure 3.2 SWF that would be included in an asphalt mix.[3]

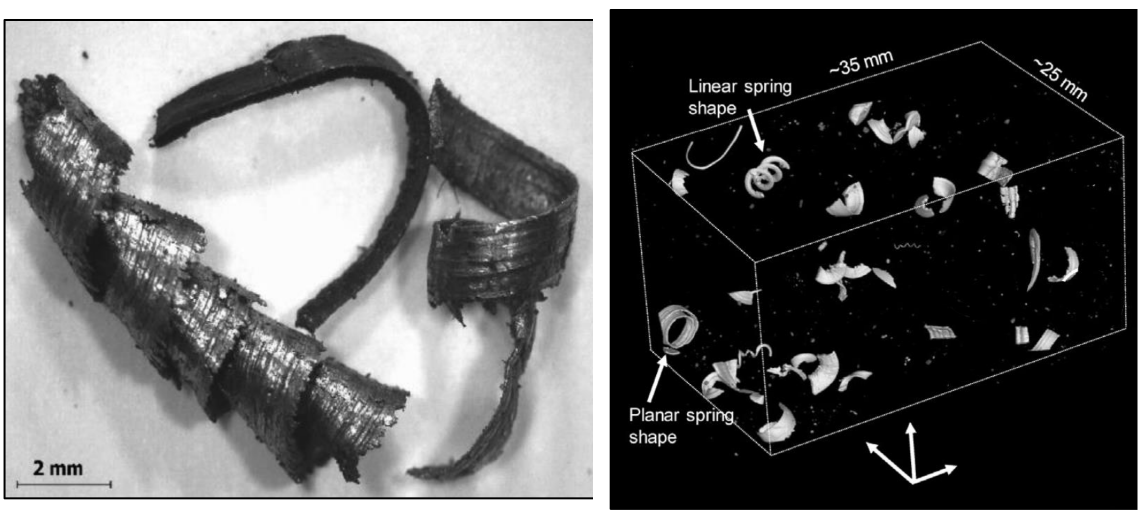
The longer an SWF thread is, the more it can increase the microwave heating efficiency of asphalt.[5] A variety of thread lengths are typically used but mixing and compaction damage tend to reduce the average thread length.[2,23] Thicker fibers tend to retain their length the best. SWF is often produced by being cut from larger steel wires.[2] The blades used during this process are subjected to vibrations which cause variation in the diameter of fibers. As already mentioned, fibers with smaller diameters can more easily dissipate generated heat to the surrounding mastic.

Sun et al.[23] found SWF to have almost no effect on the thermal properties of asphalt (conductivity, diffusivity, and specific heat). SWF itself has a higher thermal conductivity than asphalt binder, but it usually makes up a small proportion of the volume of the mix (around 1%) and doesn't have a large impact on the overall thermal conductivity.[13] In some cases, the air voids created when SWF keeps its shape during compaction can decrease the thermal conductivity of the mix.[2,13,22] This does not affect the ability of SWF to increase the microwave heating rate of asphalt.[31] The effectiveness of SWF as a microwave-absorbing additive is dependent on its distribution and content in the mix. The high length to thickness ratio of SWF allows it to quickly and efficiently transfer microwave-generated heat to the surrounding mastic. Thinner SWF threads are more efficient while thicker threads tend to have higher microwave heating rates.[5,71] So, while uniformly distributed SWF cannot effectively increase the transfer of heat from one area of the mix to another, it can increase the microwave heating rate and temperature distribution of the asphalt. While well-distributed SWF typically increases microwave heating temperature uniformity, the clusters that can form with excess SWF content decrease that temperature uniformity.[6] Temperature uniformity can also decrease if the SWF content is too small and thus only heating disparate areas of the mix.[23]

The appropriate SWF content depends on the goal of including the additive. As discussed, excess SWF can reduce microwave heating efficiency. However, higher amounts of SWF are required to significantly improve the electrical conductivity of asphalt.[22] Researchers have proposed an optimal SWF content for increasing microwave heating rates without severely reducing the flexural strength of the asphalt or increasing the formation of fiber clusters.[2,6]

3.2.3 *Steel Shavings*

Steel shavings are another industrial waste product recycled as a microwave-absorbing additive. They are produced from metal turnery or machining and pose the same environmental issues of land occupation and pollution as the other waste products mentioned so far.[81] Because they are a byproduct, steel shavings don't have a standard form and can vary in length and shape. They are commonly either helicoidal or curled. Examples can be seen in Figure 3.3a. Helicoidal shavings fall into one of two shape categories: planar spring or linear spring. Examples of both can be found in Figure 3.3b.



(a) (b)

Figure 3.3 Examples of (a) steel shavings with different shapes and lengths and (b) different helicoidal shapes visible in a CT scan of an asphalt specimen.[81]

As a microwave-absorbing additive, steel shavings have mostly been studied in relation to SWF.[22,81] Therefore, most observations made about them are direct comparisons to SWF. Although they can vary greatly in length, the average length of steel shavings is about the same as SWF.[81] They are much wider than fiber additives and feature edge flaws and a complex geometry that can increase adhesion to the asphalt matrix. The variation in shape and geometry is due to different types of equipment vibrations during the production of the shavings. Due to their cylindrical shape, steel shavings generally increase the air voids in asphalt, although less so than SWF.[22] That is because steel shavings are relatively brittle and can be crushed during the mixing process. The shape of steel shavings prevents them from creating conductive channels and increasing the electrical conductivity of asphalt as well as SWF. Additionally, the high exposed surface area per volume of steel shavings decreases the thermal properties of asphalt (conductivity, diffusivity, specific heat capacity) even more than SWF. The standalone thermal conductivity of steel shavings is lower than that of SWF. The tendency of steel shavings to concentrate in the mix also decreases the microwave heating temperature distribution. González et al.[81] said the high surface area of steel shavings made it more susceptible to microwave heating than induction heating.

Another form of steel shaving is steel filings that are produced from metal lathe machines and can be used as a filler.[63] The smaller size of filings makes it easier to homogenously spread them throughout the mix which in turn increases the temperature uniformity. It also prevents the filings from inhibiting asphalt compaction as larger steel shavings might.

3.2.4 *Taconite*

Taconite is a metallic ore mined and processed primarily in the Mesabi Iron Range of Minnesota. Taconite byproducts have been studied as a microwave-absorbing additive by researchers from the University of Minnesota – Twin Cities and the University of Minnesota – Duluth.[50] Around 125 million tons of taconite byproduct is produced in Minnesota annually, making it a cheap additive option for the surrounding areas.[82] Additionally, taconite is known to have “excellent aggregate properties” and has been used as an aggregate in asphalt in the past.[54]

The microwave-absorbing abilities of taconite come from its high iron content in the form of grains of magnetite.[40,82] Similar to steel slag, the content and distribution of magnetite grains in each aggregate particle are variable.[40] This can affect the microwave heating rate and temperature distribution of taconite-modified asphalts. Unlike most aggregates, the microwave heating rate of taconite doesn't depend on the aggregate particle size. Also, the inclusion of taconite aggregate has not been found to have a large effect on the thermal properties (conductivity, diffusion, etc.) of asphalt.

Le et al.[82] proposed the use of taconite concentrate as a microwave-absorbing filler additive. They theorized this would lower the potential transportation costs of the material and also allow for more targeted heating of the mastic. In addition to enhancing microwave heating and healing, taconite concentrate was found to increase the electrical conductivity of the asphalt when added to asphalt with graphite nano-platelets (GNP). Tests from this study that display the self-healing benefits of taconite concentrate and GNP will be detailed in Chapter 4.

3.2.5 *Magnetite*

Some studies use microwave-absorbing additives that are referred to simply as "magnetite". Magnetite has been mentioned numerous times as the mineral that gives additives like taconite and steel slag their microwave-absorbing abilities. Because of this, researchers seem to use the label "magnetite" quite fluidly. Even though additives are separated into categories like "steel slag" and "ferrite" in this thesis, the materials that fit these labels are not unrelated.

Wang et al.[83] describe "magnetite" additives as "rich magnetite materials, whose main component is Fe_3O_4". Guan et al.[84] add that "magnetite" additives are cheaper and more widely available than additives such as steel fiber, carbon fiber, and low-grade pyrite cinder.

The mineral magnetite is a stronger microwave absorber than water by 4.7 times on a mass basis and by 24 times on a volumetric basis.[40] "Magnetite" additives generally contain a larger proportion of this ferric mineral than additives such as steel slag and taconite. Guan et al.[84] found magnetite powder to have a 47.5% ferric composition while Phan et al.[6] found steel slag to have a 23.3% ferric composition. This gives "magnetite" additives very good potential to enhance microwave heating. Additionally, magnetite-modified asphalts display minimum microwave reflectivity around 2450MHz.[83]

"Magnetite" has been used as coarse, fine, and filler aggregates in asphalt mixes. As a coarse or fine aggregate, it has an angular and crystalline structure that allows it to interlock with other aggregates and increase the resistance to deformation.[83,84] As a filler aggregate, “magnetite” has a relatively clean face that results in less binder absorption.[84] While this decreases the asphalt production costs, it also decreases the aggregate-binder adhesion. This limits the “magnetite” filler content allowed in a mix.

3.2.6 *Ferric Powders*

Ferrite

Ferrite is a particulate ceramic compound composed of iron oxide chemically combined with one or more additional metallic elements.[68] Ferrites are labeled as hard ferrites, which are difficult to magnetize, or as soft ferrites, which are easy to magnetize. Zhao et al.[68] and Zhu et al.[10] were the first to demonstrate the use of ferrite as a microwave-absorbing filler additive in asphalt. Zhao et al.[68] found soft ferrites (NiZn) to have greater microwave heating potential and efficiency than hard ferrites (barium). Ferrite particles are spherically shaped with a large surface area and small volume that ensures speedy heat transfer to the surrounding mastic.[68,73]

Ferrite can be used as a partial replacement for mineral fillers like limestone.[68] Ferrite is less reflective of microwaves than limestone although there is no consensus on the optimal frequency for minimum reflection. Lou et al.[73] found 5800MHz to be the optimal frequency while Zhao et al.[68] found it to be 915MHz. Regardless, both studies observed good reflectivity values at the commonly-used microwave frequencies.

Ferrite has been found to increase the thermal conductivity of asphalt binder which allows the heat generated by the particles to diffuse rapidly throughout the asphalt.[73] This decreases the range of temperatures observed after asphalt microwave heating.[68] Zhu et al.[10] suggested adding ferrite particles to certain layers of asphalt pavement for targeted heating. However, Zhao et al.[68] found that adding either too much or too little ferrite could decrease the temperature uniformity. Excess ferrite can lead to particle agglomeration which prevents uniform distribution of ferrite throughout the mix.[73] Agglomeration is possible due to the small particle size, high density, and porous nature of ferrite. It can lead to the same temperature distribution and overheating issues as fiber clusters. Lou et al.[73] found ferrite agglomeration to limit the overall microwave heating rate of asphalt.

Carbonyl Iron Powder

Carbonyl Iron Powder (CIP) is an often-cited ferric-based microwave-absorbing filler additive. Wang et al.[33] found CIP to have higher saturation magnetization than ferrite and to have minimum microwave reflectivity at 2450MHz. Like other ferromagnetic additives discussed in this review, CIP increases the utilization of the conduction mechanism during microwave heating.

3.2.7 *Activated Carbon Powder*

Activated carbon powder (ACP) is another microwave-absorbing filler additive. It is very absorptive due to its porous nature and high surface area.[14] This allows for exceptional binder infiltration of the filler particles.[41,85] By absorbing the lightweight fraction of binder in a mix, ACP can also increase the ultraviolet light aging resistance of asphalt.[14] However, this absorption deteriorates the aggregate-binder adhesion of the mix and requires more binder to be added to the mix, increasing production costs.[14,85] In addition to an increased microwave heating rate, Karimi et al.[14] found ACP to improve the thermal properties (conductivity, diffusivity) and electrical conductivity of asphalt.

ACP is created through electron cloud rearrangement in the carbon skeleton of agriculture and forestry waste particles. As already mentioned, ACP can be reused as an asphalt additive after its use in environmental measures such as air pollution control, wastewater treatment, and solvent recovery.[85] ACP's high absorption also allows it to act as a decontaminating agent in asphalts.[14,67,85] ACP has been shown to reduce the volatile organic compound (VOC) emissions of asphalt and has been proposed as a way to absorb vehicle pollution.[67] So, although ACP is an engineering material, its use has various environmental benefits.

Although ACP is relatively expensive compared to other asphalt fillers, it also has a relatively low density, meaning the increased cost of equal volume substitution is not that significant.[85] The mass unit cost of ACP is less than that of filler additives such as carbon black and ferrite.[67]

3.2.8 *Coal*

Coal was studied early on in the search for ideal microwave-absorbing additives. In 1993, Wuori[86] said coal was the best performing microwave-absorbing additive he had seen up to that point. In 1995, Long[87] proposed the use of anthracite coal as a microwave-absorbing aggregate additive for asphalt in a patent. Coal is relatively cheap and easy to access. However, its use as an asphalt aggregate replacement has been questioned due to its low fracture strength.[54] No work has been done in the past 20 years using coal as a microwave-absorbing aggregate additive.

3.2.9 *Carbon Fiber*

Carbon fiber (CF) is a microwave-absorbing fiber additive that has been known to improve the mechanical and electromagnetic properties of asphalt.[88] Dispersion of CF in an asphalt mix has traditionally been a challenge due to a lack of moisture. Wang et al.[88] found that CF can easily be clustered. Along with the clustering issues mentioned, these clusters decrease the compressive strength of the asphalt. CF dispersion can be improved with the use of a dispersing agent. A microscopic picture of microsurfacing asphalt reinforced by CF can be found in Figure 3.4. CF has also been shown to increase the electrical conductivity of asphalt. Along with the conduction mechanism microwave heating benefits this entails, researchers have tried to use this added conductivity to monitor for pavement damage.[9]

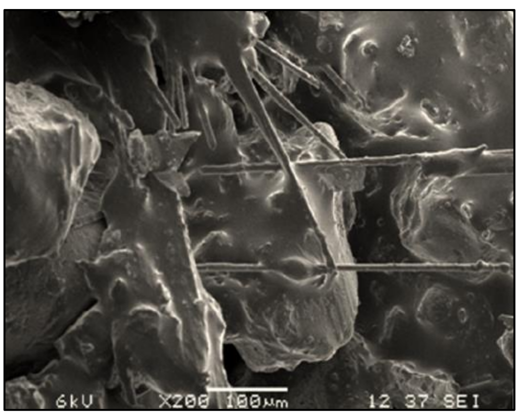


Figure 3.4 Microscopic picture of microsurfacing asphalt reinforced by CF.[88]

Wang et al.[88] found that when CF mass fraction reaches a certain point (0.45%), its peak microwave absorption occurs around 2450MHz. When that mass fraction is surpassed, the absorption grows with frequency. Wang et al.[9] observed this as well. They also found that microwave absorption of carbon fiber composites varies with the thickness and temperature of specimens.

3.2.10 *Graphene-Based Nano-Additives*

Graphite

Graphene and graphite are nanometer-scale materials that have been used as microwave-absorbing filler additives. Graphene is a layer of carbon atoms arranged in a 2D honeycomb lattice structure while graphite is made of layers of graphene.[89] Researchers tend to use the two names interchangeably. Graphene itself is extremely difficult to isolate. Most studies in this field that use "graphene" additives are actually using some form of graphite. For simplicity, these additives will be referred to as graphite hereafter.

Graphite's microwave-absorbing abilities come from a combination of the small size effect, surface and boundary effect, and quantum size effect.[90] It has a lamellar crystal structure with a smooth surface. This structure allows for folds, cracks, and flaws which can affect the mechanical properties of the material. An electronic microscope picture of a graphite particle can be found in Figure 3.5.

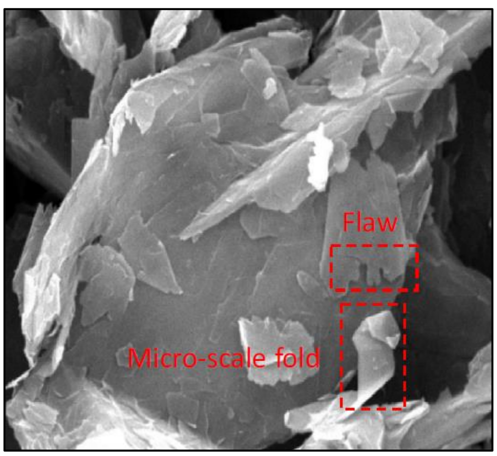


Figure 3.5 Electronic microscope image of a graphite particle.[90]

While graphite itself has a much higher thermal conductivity than asphalt, it is usually added in quantities too small to improve the thermal properties of the mix.[13] However, its addition can increase air voids in the mix, negatively affecting the thermal conductivity. Graphite can increase the electrical conductivity of asphalt when added in substantial amounts.[7,69]

Graphite nano-platelets (GNPs) are a subset of graphite microwave-absorbing filler additives. GNPs consist of stacks of graphene nano-discs.[82] They have been shown to have strength approximately 100 times that of steel and electrical conductivity higher than copper. Their price falls below that of other engineered nanostructure additives like carbon nanotubes, but far above that of waste products like steel slag.[69] Despite their small size, it is difficult to uniformly distribute GNPs throughout a mix, especially at higher content levels. This causes issues with microwave heating uniformity and limits its ability to improve electrical conductivity. Also, as a powdered filler, GNPs increase the viscosity of the binder and can make compaction efforts difficult.[7]

Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are another graphene-based nanometer-scale microwave-absorbing filler additive.[91] The structure of CNTs is similar to sheets of graphene rolled into a tube. Depending on the degree of rolling and the original form of the sheet, CNTs can have different diameters and internal geometry. CNTs can be formed as single tubes (single-walled) or as multiple concentric tubes (multi-walled). CNTs used as microwave-absorbing additives are typically multi-walled. An image of a multi-walled CNT can be found in Figure 3.6. CNTs also have a high length-to-diameter aspect ratio which results in them having a very high specific surface area. This leads to good binder absorption and adhesion between CNTs and binder.

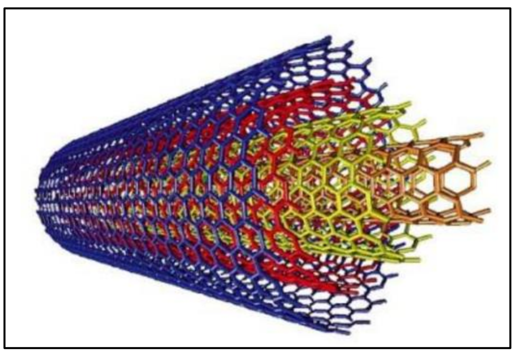


Figure 3.6 The structure of a multi-walled CNT.[91]

As with graphite particles, the microwave-absorbing abilities of CNTs come from a combination of the small size effect, surface and boundary effect, and quantum size effect.[90] CNTs increase the microwave heating rate more than graphite particles. Additionally, CNTs can improve the conduction mechanism of microwave heating.[91] They form a percolation network within the binder which increases the electrical conductivity and allows for the flow of eddy currents throughout the asphalt. However, there is an optimum CNT content level for effective microwave heating. Excess CNT content results in higher microwave reflection at the asphalt surface.

A motivation for the study of graphene-based microwave-absorbing additives like CNTs and GNPs is the fear that iron-based additives would increase the mass of the material and would gradually rust under the erosion of water and oxygen.

3.3 Applications of Microwave Technology on Asphalts

3.3.1 *Self-Healing*

The use of microwave heating to accelerate the asphalt self-healing process (a.k.a. "microwave healing") has been one of the most heavily researched applications of microwave technology on asphalts over the past two decades.

Self-Healing with Induction and Microwave Heating

Gallego et al.[5] were the first to show the viability of microwave healing. At the time, self-healing acceleration by induction heating (induction healing) had been established as a viable, field-proven technique. Induction healing was therefore often used as a benchmark for microwave self-healing studies. While induction and microwave heating both result in a temperature gradient along the depth of the asphalt, the gradient is less severe for microwave heating.[17] Liu et al.[17] found this improved temperature distribution to be instantaneous and to lead to better healing results and a larger effective healing depth for microwave heating. However, controlling the asphalt mixture temperature is easier with induction heating, especially in cases with high additive fiber content. In such cases, microwaving can lead to local overheating in the asphalt. Local overheating, whether caused by fiber or aggregate additives, can cause binder damage which restricts binder flow during the healing process.[17,23] However, Norambuena-Contreras and García[31] theorized that binder decomposition from overheating helps the microwave self-healing process by producing gases that increase pressure within the mix and help binder flow. However, the less severe temperature gradient of microwave heating prevents prolonged heating periods to heat deeper layers that could cause overheating at the pavement surface.

A difficulty in healing asphalts with external heating methods (both induction and microwave) is that optimal healing conditions exist when a mix is consistently kept at a temperature that is high enough to induce good binder flow but low enough to avoid overheating.[23] These external heating procedures are not designed to keep asphalt at a consistent temperature, but to steadily increase the temperature. This issue should be addressed in future work.

Microwave Self-Healing Considerations

In laboratory testing, healing is often measured through a series of fatigue-healing cycles where specimens are fatigued through procedures like the three-point bending test then heated to induce healing.[23] The specimen is then fatigued again, and the healing level is determined by its strength retention. The duration of microwave heating an asphalt experiences has a large effect on its healing level. Norambuena-Contreras and Gonzalez-Torre[70] showed that increasing the heating time from 20s per cycle to 40s per cycle can improve the initial healing level of the specimen by almost 2.5 times. This is because specimens that are heated for longer periods achieve higher temperatures and stay above the binder flow-inducing ("critical") temperature longer. Binder flow occurs not only while heating is being applied, but also during the long cooling period that occurs afterward until it returns to the critical temperature.[13] The heating period length has more impact on the healing rate of asphalt than variation in fiber content.[2,70] Various sources have proposed an optimal heating time that attempts to maximize the healing effect while minimizing damage to the binder.[6,13,19,70] García[19] found that heating asphalts beyond the optimal time causes the binder to continue to flow through cracks and reopen them.

Although self-healing can fully heal cracks, it can't necessarily return an asphalt's original fatigue strength. Studies have found that fatigue-healing cycles show reduced restored strength each cycle.[3,6,8,9,14,22,31,70,77,91,92] This is true no matter the amount of resting time the material receives.[77] Repeated microwave heating oxidizes and ages the binder, making it more brittle, weaker, and less ductile.[6] While longer heating periods result in higher healing levels in early cycles, they also greater reductions in healing levels each cycle.[22] Longer heating periods lead to higher temperatures and possibly more binder damage. This trend is an indication that if microwave healing was to be applied as a maintenance practice, the number of times it could be applied to a stretch of pavement would be limited. However, González et al.[81] found that asphalts with a certain type of steel shaving and RAP content had greater healing during the second and third cycles than the first one.

Self-healing effectiveness also depends on crack formation. Microwave healing can effectively repair microcracks that appear in early fatigue-healing cycles.[6] However, as these cycles continue, the sizes of these cracks grow, and the healing action is diminished. Cracks through coarse aggregates are unlikely to be quickly repaired through self-healing because of a lack of present binder.[6,17] Binder flow during the healing process may rearrange the binder matrix, displacing filler and fiber additives and air voids.[2,31,67] This rearrangement can affect the microwave healing capabilities and the mechanical and thermoelectric properties of the asphalt. It could increase the healing capabilities if fiber additives become aligned with the orientation of the crack as can be seen in Figure 3.7.[3] The heat generated by the fiber would be applied directly to the face of the crack. This would improve binder flow through the crack. Franesqui et al.[63] found that microwave healing of top-down cracks begins at the crack tip, where the opening is smallest, and spreads towards the surface until fully healed. They found that cracks up to 40mm deep could be completely healed after brief exposure to microwave heating.

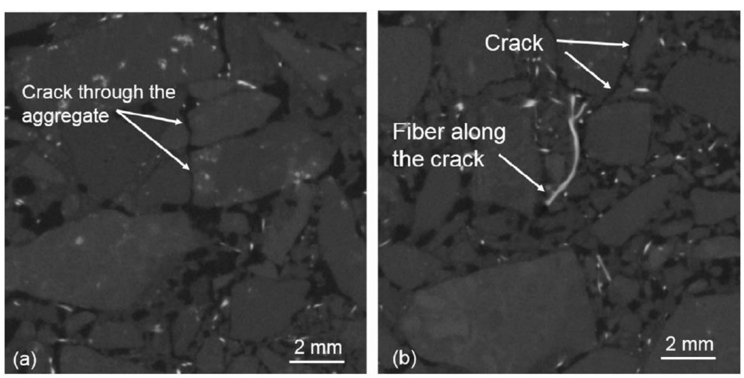


Figure 3.7 Cross-section of an asphalt specimen that shows (a) cracking through the aggregate and (b) fiber orientation through the crack after binder flow.[3]

Wang et al.[13] compared the healing effects of consecutive and intermittent microwave heating. Consecutive heating involves continuously heating the asphalt to the desired temperature. Intermittent heating involves cycles of heating and cooling until the asphalt reaches the desired temperature. An example of the heating curves from these methods can be seen in Figure 3.8. Asphalts exposed to intermittent heating had higher healing rates. Because microwave heating rates are higher at relatively low temperatures, intermittent heating allows asphalts to absorb more energy during the microwave heating period. Also, intermittent heating keeps asphalts above the self-healing critical temperature for a longer period. This can be seen in Figure 3.8.

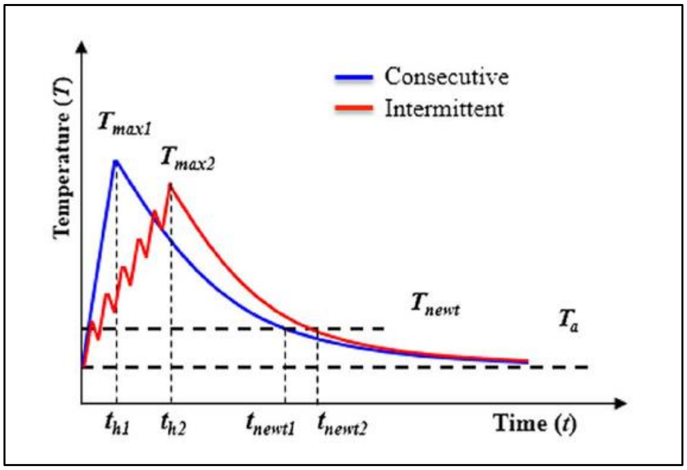


Figure 3.8 Consecutive and intermittent microwave heating curves.[13]

Effects of Additives on Microwave Self-Healing

Excess fiber content can be detrimental to the microwave healing process in multiple ways. The fiber clusters that accompany excess fiber content can block binder flow and cause local overheating which damages the binder. Poor fiber distribution in mixes with excess fiber results in poor heating uniformity which hurts the healing process.[6] Excess fiber content creates air voids in the mix that help the material dissipate heat.[22] This makes it difficult to uniformly achieve adequate healing temperatures in the mix.

Carbon fiber (CF) has been used to accelerate asphalt self-healing. Wang et al.[9] showed that the increase in electrical and thermal conductivity caused by CF improved the microwave healing potential of asphalt. They found an optimal CF content that would enhance microwave heating without limiting binder flow during the healing process. Well-distributed CF can act as a bridge network to prevent the occurrence and free expansion of microcracks.[88] Activated Carbon Powder (ACP) is another carbon additive that has been used to accelerate the self-healing process.[14]

Graphene-based nanometer additives have also been used to increase the microwave healing rate of asphalt. Li et al.[90] showed that CNTs and graphite particles improve the microwave healing of asphalt. Although these additives increased the critical binder flow temperature of the mix, they also increased the microwave heating rate so the asphalts could rapidly reach that critical temperature.[13,90] The microwave healing rate was improved with increased resting time after heating. The healing rates of specimens that rested for 12hr were ~10% higher than those that rested for 3hr. CNTs showed slightly better microwave healing capabilities than graphite. Pérez et al.[91] also showed that carbon nanotubes (CNTs) can improve microwave healing of asphalt. CNTS can also bridge across microcracks to prevent their free expansion.[90] Gulisano et al.[7] also found graphite to improve the microwave healing efficiency of asphalts. Wang et al.[13] discussed the disadvantages of using graphite powder to do this. The high oil absorption and surface area of these powders allow them to absorb the lightweight fraction of binder from the mix which in turn stiffens the binder and prevents flow. Le et al.[82] found that graphite nano-platelets (GNPs) and taconite concentrate can improve the microwave healing capability of asphalt.

Ferrite powder has also been used to increase the microwave healing abilities of asphalt.[68,73] Zhao et al.[68] showed that ferrite-modified asphalts could achieve microwave healing levels greater than 100%. This is possibly due to the healing of initial defects in the specimens that formed during preparation. Zhu et al.[10] also observed this behavior. However, similarly to graphite powder, excess ferrite powder can stiffen the binder and prevent healing due to the powder's porous structure.[73] Wang et al.[33] found that carbonyl iron powder (CIP), close in composition to ferrite, makes binder more viscous and asphalt harder to heal.

The idea of using steel slag aggregates to increase the microwave healing rate of asphalt was first proposed by Sun et al.[74]. This idea has been proven successful by several subsequent studies.[6,7,23,73] Steel slag asphalts consistently show stronger healing performances than typical asphalts. Some studies attribute this to the good temperature uniformity displayed by asphalts whose coarse aggregates were fully substituted for steel slag.[6,23] Partial aggregate substitution resulted in worse temperature uniformity.[73] Steel slag filler (SSF) has also been used to improve the microwave healing of asphalt mastics and mixtures.[63,77] SSF-modified mastics have a slightly lower critical binder flow temperature and better healing performance than limestone filler mastics. SSF-modified mastics also displayed superior complex modulus and fatigue life recovery after several fatigue-healing cycles.[77] Lou et al.[73] used the COMSOL Multiphysics software to simulate microwave heating of steel-slag-modified specimens in a domestic microwave oven. These simulations helped them determine the effect of frequency on the microwave heating distribution in the specimen. They concluded that the use of multiple microwaves, each with a different frequency, would improve the heating uniformity and healing efficiency.

While they typically decrease the thermal properties of asphalt, steel shavings have been used to increase the asphalt microwave healing efficiency.[22,81] In a study comparing the use of steel shavings and SWF, Norambuena-Contreras et al.[22] showed that shorter microwave heating periods benefit the healing of SWF-modified asphalts while longer periods benefit the healing of steel-shaving-modified asphalts. González et al.[81] found the optimal steel shavings content for microwave healing to be relatively low (1% volume of binder). Increased shavings content generally decreased the healing level of the asphalt.

Recycled asphalt pavement (RAP) decreases the microwave healing rate of asphalts.[3] The aged, viscous binder in RAP prevents binder flow during the healing process. However, González et al.[3,81] showed that the healing detriments caused by RAP can be overcome with the addition of microwave-absorbing additives like steel shavings or SWF.

An often-cited method of accelerating asphalt self-healing is the inclusion of rejuvenator capsules in the asphalt mix. When these capsules are broken by cracks in the pavement, the rejuvenator speeds up the natural self-healing process by restoring binder components lost to aging.[93] However, it isn't possible to control when the capsules will rupture, and the rejuvenator moves through the binder slowly. On the other hand, while microwave heating can heal microcracks, it cannot de-age binder. This leaves microcracks more likely to reform. Shu et al.[93] created an asphalt additive called the multi-responsive fiber (MRF) to combine the strengths of the microwave and rejuvenator capsule healing methods. MRF is a non-organic fiber composed partially of graphene oxide that contains droplets of rejuvenator. A microscopic view of the droplets within the fiber can be seen in Figure 3.9. The presence of graphene in the fiber increased the microwave heating and healing rates of the asphalt. Upon rupture from asphalt cracking, the rejuvenator could flow out of the MRF, soften the binder and partially heal microcracks. These combined actions showed significant healing results.

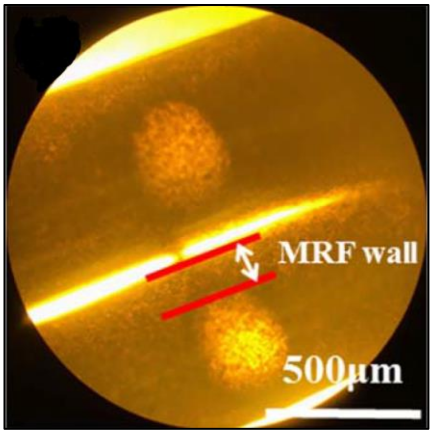


Figure 3.9 MRF fiber with rejuvenator droplets inside.[93]

There has been work done to determine if conventional asphalt pavements without microwave-absorbing additives could be healed through microwave heating. González et al.[92] found that microwave healing could be performed on asphalts that contained naturally metallic aggregates. However, Zhu et al.[60] found that asphalts with non-metallic aggregates could achieve adequate microwave healing in a relatively short amount of time. This study used AC-13 asphalt mixtures with SK-70[#] and Shell styrene-butadiene-styrene polymer-modified asphalt binders. No reasoning was presented as to why these unmodified mixtures were able to achieve something that those in past studies could not.

3.3.2 *Deicing*

The second most common area of study for microwave asphalt heating is the application of microwave heating to remove ice from pavement surfaces ("deice"). The need for an alternate method of roadway deicing is emphasized by the inefficiencies of current chemical deicing practices. Sodium chloride, the most common chemical deicing agent, is estimated to cause user automobile corrosion damage of more than $10 billion per year in the United States.[94] Deicing salt also corrodes pavements and lakes, streams, and groundwater.[54,95] This damage is worsened by the tendency of maintenance programs to use massive amounts of it on each application. China uses over 100,000 tons of deicing salt each year.[88] Finally, sodium chloride has been found to be ineffective at temperatures below -10°C, rendering it useless for much of the wintertime in some cold regions. Other innovative deicing methods, such as buried electric heating cables or embedded hydronic devices, are expensive to install, operate, and maintain.[54,85] Microwave heating has been proposed as a viable asphalt deicing alternative that doesn't produce corrosive residual material, can be applied at any temperature, and is relatively inexpensive to implement (compared to buried cables).

Attempts at deicing through microwave heating are not focused on fully melting the ice on the pavement surface, but rather breaking the bond at the pavement-ice interface so the ice may be removed mechanically. Breaking the bond requires melting an ice thickness of approximately 2-10microns at the interface.[86] This bond is often too strong for mechanical methods of pavement deicing (i.e., scraping) to overcome.[83] The bond strength of ice to Portland cement concrete at -60F is approximately 60,000psi.[87] It is possible to break this bond with microwave heating without fully melting the ice because ice has insignificant dielectric properties.[86] Microwave energy can pass through the ice with almost no loss and heat the pavement underneath. However, ice has low (but nonzero) reflectivity of microwaves.[88] This decreases the microwave deicing efficiency as a portion of the microwave power isn't able to reach the asphalt. Thicker ice layers of ice are more reflective of microwave radiation and slow the microwave deicing process.[43,66,88] Additionally, impurities such as sand can increase the dielectric properties of ice and slow the microwave deicing process more so.[43]

At the start of microwave deicing, the heated asphalt surface melts an incremental layer of ice at the pavement-ice interface. This creates a film of water between the pavement and surface. As already mentioned, water is highly absorptive of microwave power due to its high dielectric constant. Its presence increases the microwave heating rate at the interface.[24] This is helpful as the surface layer (top 1cm) of unmodified asphalt only absorbs ~4-5% of the microwave energy directed at the pavement. As more ice melts, the water layer becomes thicker which further increases the heating rate at the interface. However, once microwave heating is stopped, the temperature of this water layer quickly decreases. It is important to remove the ice layer soon after the bond is broken to avoid refreezing of the water film.[1,85] Lower atmospheric temperatures have been found to slow the microwave deicing process.[83]

Sawyer et al.[96] were the amongst the first to suggest that microwave heating could be used to remove ice from roadways. They observed that microwave heating allowed for the removal of ice from a concrete pavement without melting the entirety of the ice. Lindroth et al.[55] found that microwave energy could penetrate an ice layer 50mm thick to heat the soil below. Wuori[86] suggested that microwave-absorbing additives be used to make microwave deicing more practical as a maintenance tool. They found that thin overlays (3mm) that contain lossy materials could theoretically absorb most of the microwave energy directed at them. This idea of using microwave-absorbing additives to improve microwave deicing has been a common thread in the literature since this study.

The inclusion of lossy materials in asphalt reduces its microwave penetration depth and concentrates the bulk of the microwave energy conversion near the surface of the pavement. Wuori[86] found the use of coal aggregate to reduce the ice disbonding time (the time it takes to break the bond at the ice-pavement interface) by a factor of ten. Long[87] patented an asphalt compound that contained 10-30% anthracite coal filler and could be used to reduce the ice disbonding time by several times. Hopstock[40,54] showed that taconite aggregate could be used to improve microwave deicing and developed a 1D model to simulate the heat transfer that occurs during the microwave deicing process.

Shortly thereafter, Long[87] received a patent on an asphaltic concrete compound that was to be used for pavement-ice disbonding. This compound, which he proposed to contain 10-30% by weight of anthracite coal particles and fines, could be applied as an overlay on existing pavement and make microwave deicing several times faster. Laboratory tests performed by Hopstock[40] showed that taconite aggregate, which contains a large proportion of magnetite, can be added to asphalt to assist in microwave deicing. This work was continued by Zanko and Hopstock[54] in a study that resulted in a 1D model to simulate the heat transfer that occurs during the microwave deicing process.

Wang et al.[88] showed that carbon fiber (CF) is an effective microwave-absorbing additive for deicing and found an optimal CF content (within emulsion) that achieved minimum microwave reflectivity at 2450MHz and minimum deicing time. This study was one of several that took a more literal view of deicing, where “deicing time” was the time necessary to fully melt the ice from the surface of the pavement. Thus, their reported deicing times fell on the scale of minutes rather than the scale of seconds reported by studies that focused on ice disbonding. This is an important distinction when reviewing the literature on this subject. Liu et al.[85] showed that activated carbon powder (ACP) is an effective microwave-absorbing additive for deicing. They found that deicing time decreased linearly with increases in the ACP content of the binder.

Wang et al.[83] showed that "magnetite" aggregate could be used as a microwave-absorbing additive for deicing and the optimal "magnetite" content for minimum microwave reflectivity and deicing time. "Magnetite" powder is also an effective microwave deicing additive.[84] Thicker layers of the magnetite-containing asphalt show greater deicing performance. However, Guan et al.[84] found that magnetite powders can lower the water stability of asphalt. Water stability is important when performing deicing due to the abundance of free water involved in the process. Guan et al.[84] suggested an optimal "magnetite" powder content to balance deicing efficiency and reduced water stability. Microwave heating ceramics (MHC), a magnetite-containing material created by inducing a chemical reaction in low-grade pyrite cinder, can also be used as an aggregate additive for microwave deicing.[66]

Sun et al.[23] investigated whether microwave heating could be used for deicing and self-healing applications at the same time. They found that the film of water that developed at the pavement-ice interface during deicing penetrates the cracks in the asphalt and prevents any healing. Their findings suggest that microwave self-healing and microwave deicing must be performed separately.

Sun et al.[23] showed that steel slag aggregates and SWF could be used as effective microwave deicing additives. SWF showed better deicing results of the two. This study is one of few that also looks at the use of microwave heating to melt snow on the pavement surface. They found that the snow melting process was also benefitted by the formation of free water at the snow-pavement interface. They found microwave heating is more effective than induction heating at both deicing and snow removal. Gao et al.[1] also found that steel slag aggregate can be used as a microwave deicing additive.

Contradictions arise between the theoretical application of microwave energy for deicing in the field and how microwave deicing is often studied in the laboratory. In the field, microwave radiation would be applied straight down into the pavement surface/ice layer. In laboratory settings, researchers typically use domestic microwave ovens to heat their specimens. These ovens are designed to evenly apply microwave radiation to the entire surface of the object being heated. The entirety of the microwave energy is not being applied to the top of the specimen as it would be in the field. Therefore, the microwave heating rate at the pavement-ice interface is likely underestimated by these studies. This is another important consideration when reviewing the literature on this subject.

Computer modeling and numerical simulations have shown that microwave deicing efficiency can be quadrupled by replacing a 2450MHz microwave system with a 5800MHz system.[43,44] Tang et al.[43] and Ding et al.[44] confirmed these findings through laboratory experiments. Studies have also found that the penetration depth of 5800MHz systems is less than that of 2450MHz systems.[43,44] This is beneficial to microwave deicing efforts as it generates more heat near the surface of the pavement. However, 5800MHz systems are much more expensive than 2450MHz units (up to 100 times more in China).[44]

Various parties have proposed designs for mobile microwave deicing systems. The ability to perform microwave heating at moving speeds is especially important for this application as deicing is a regular maintenance activity during the winter. These systems also need to feature some way to mechanically remove the disbanded ice from the asphalt surface. One of the first mobile microwave deicing system designs comes from a patent by Long.[97] He proposed an all-in-one vehicle that would have attached, from front to back, a snow removal blade, a microwave generator and applicator, and an ice scraper. Hopstock[40] proposed a similar microwave-mounted vehicle with ice-removal brushes located behind the microwave generator to remove disbonded ice. Researchers in China have come closer to developing working units. This makes sense as microwave heating is used in the maintenance practices of some regions of the country.[98] A diagram of a design proposed by Gao et al.[1] can be found in Figure 3.10a. This design is fairly similar to the designs proposed in earlier studies. However, not all mobile microwave deicing system designs have the all-in-one style. Liu et al.[85] suggested a design that incorporates a second vehicle that would be able to both scrape and store the disbonded ice. This design can be seen in Figure 3.10b. Li et al.[95] proposed a system with an extended trailer that could hold a longer applicator. This would allow for the formation of a “heating wall” and would increase the heating time of each point on the road.

(a) (b)

Figure 3.10 Schematic diagram of (a) an all-in-one mobile microwave deicing unit[1] and (b) a mobile microwave deicing unit that uses two vehicles[85].

3.3.3 *Asphalt Recycling*

Asphalt recycling is the practice of reusing old asphalt pavements as part of a new asphalt mix. It occurs either during construction (in-place recycling) or at RAP production plants. While it has traditionally been done with conventional heating methods, researchers have used microwave heating in both the in-place and plant recycling processes.

In-Place Recycling

Wang et al.[58] found that temperature variation along the depth of a slab of typical asphalt was very low with microwave heating when compared to traditional heating methods. Methods like convection heating that pass all energy through the pavement surface, will often result in an overheated surface and underheated internal layers. Wang et al.[58] found that 20min of microwave heating could bring the internal temperature of an asphalt slab to an adequate level for hot in-place recycling.

Various studies have modeled the heat transfer that would occur during microwave hot in-place recycling. Zhu et al.[99] created a 2D heat transfer model that simulated the effects of horn antenna structure on the microwave power density applied to the pavement surface. From this work, they were able to identify a lack of surface temperature uniformity that could lead to decreased recycling efficiency and repair quality. Their simulation results reasonably matched their experimental results. Sun created several models to simulate and optimize microwave hot in-place recycling of asphalt. His 2009 temperature control model showed that the dielectric loss factor of the asphalt and the microwave power applied have significant impacts on the heating uniformity and maintenance effectiveness.[100] His 2013 thermoelectric-coupled model showed that the efficiency of microwave hot in-place recycling increases linearly with an increase in applied microwave power.[46] He later built onto this model so that it could simulate the mass transfer of water in liquid and vapor form during the asphalt heating process.[48] Through this updated model, he was able to observe a gradually increasing (with heating time) pressure gradient within the asphalt that increased the moisture mass transfer rate. In 2019, Sun and Sheng[49] created a 3D heat transfer model for microwave in-place recycling using the COMSOL Multiphysics software. They found the average heating temperature to decrease with an increase in pavement thickness and initial moisture content, giving valuable insight on the ideal conditions for microwave hot in-place recycling. Zhu et al.[10] created a 1D coupled heat and mass transfer model for microwave hot in-place recycling that is similar to the one presented by Sun[48]. This is a fairly complex 1D model that relates temperature, penetration depth, moisture content, heat generation, and variations in humidity. They found their numerical results to be consistent with their experimental results and concluded that their model could be used to simulate hot in-place recycling of asphalts or drying of asphalt.

Plant Recycling

Several studies have focused on the effects of using microwave heating in the industrial production of recycled asphalt mix. Zhu et al.[101] compared the mechanical properties of asphalts created with microwave heating and asphalts created with conventional heating methods. They found that RAP produced with microwave heating showed superior pavement performance characteristics including increased water resistance and low-temperature flexural strength. They concluded that this method would be useful in cold climate regions. Zhang et al.[102] found that RAP produced with microwave heating showed improved penetration strength, water stability, and fatigue resistance. However, Shoenberger et al.[103] found microwave-produced RAP to have increased viscosity and a lower complex modulus. These changes are especially pronounced in older binders.

3.3.4 *Pavement Patching Maintenance*

Many applications of microwave heating on asphalt pavements discussed in this thesis are more or less theoretical. Applications like microwave self-healing and microwave deicing have been shown to be possible through extensive laboratory tests and modeling work. However, there is little actual fieldwork that has been done to support them. Pothole repair and asphalt patching are the two applications that have been supported by significant fieldwork thus far. They will be discussed together as they are very similar and typically overlap. Each requires the rapid heating of asphalt to temperatures where the pavement softens and can be easily manipulated.

Bosisio et al.[52] were the first to show that this kind of repair can be made with microwave heating. They were able to repair substantial cracks in asphalt pavement with microwave heating and in-situ mixing of the asphalt. Their repairs showed promising results as 50% of the cracks did not reappear over the winter season. They used a 2450MHz microwave system, but they suggested further research be done with 915MHz due to greater heat penetration and "microwave economics". However, Hopstock[36] later says that shallower penetration depth is preferable and that lower frequency microwave units (915MHz) should only be used if the penetration depth is reduced through the inclusion of some microwave-absorbing additive. The Microdry company, mentioned earlier, used microwave heating to perform pothole patching and continuous strip repair on a commercial scale in the early 1980s.[54] Researchers at the Oak Ridge National Laboratory (ORNL) developed a microwave system that could more effectively repair potholes than conventional methods. Microwave pothole repair has been adopted as a maintenance practice in some regions of China.[98] Lu et al.[98] introduced a microwave pothole repair vehicle capable of repairing potholes within 30min of arriving at them.

Various parties have designed microwave-absorbing patching compounds that can be used in pothole and crack repair. Osborne and Hutcheson[65] patented the concept of this kind of patching compound although they did not propose the use of a specific additive. However, Long's[87] patent for a microwave-absorbing compound suggests the use of anthracite coal and details its use as a patching compound. Before the patching compound is added to the damaged pavement, the damaged surface should be cleaned out and sprayed with a preheated anthracite coal-containing emulsion. The coated surface should then be microwaved until a 0.5in depth is softened. The patching compound is then added and microwave heated, with the emulsion coating acting as a bonding agent between the pavement and the compound. This method applies to concrete pavements as well, although the pavement itself will not be softened by microwave heating. Marbet-Wil, Ltd. developed a process for pothole repair called "Sul-Fix-Mix".[54] This process is similar to the one described by Long[87] except instead of coal, the compound incorporates a sulfur polymer called "Sulcem" and microwave heating is not applied until after the patch had been roller-compacted.

Microwave patching repair can be performed in all seasons and still achieve good results. Patches that are laid during winter months typically don't perform well because the damaged pavement is cold and damp. This benefit is reiterated by Zanko and Hopstock.[54] They explain that in cold climate regions, potholes that develop during winter months are traditionally repaired twice. An initial "throw and go" repair is made, then a more permeant repair is made in the spring. They say that microwave heating with a taconite-based patching compound can produce a permanent repair the first time under any weather conditions. Hopstock[36] supported these claims through experimental work. Finally, Zanko et al.[50] demonstrated the use of their taconite-based patching compound in a series of microwave pothole repair field tests in sub-freezing conditions. The repairs lasted beyond the winter season until the roads were further rehabilitated. This is a significant improvement over the traditional "throw and go" two-step winter patching maintenance practice.

3.3.5 *Alternative/Less Common Uses of Microwaves on Asphalt*

Joint Sealing

In addition to pothole repair, the ORNL "microwave repair technique could also be used to seal joints that occur when utilities have to be installed into existing pavement or when highway lanes are paved individually.[104] However, there is not much publicly available information on their system. Salski et al.[56] designed and tested a mobile microwave applicator specifically designed to heat technological joints. These joints occur when lanes are paved next to each other and they need to be bonded down through the entire pavement structure to mitigate longitudinal cracking and other defects at the joint. These joints are typically welded with a gas jet then compacted with a roller. This welding process is done manually which can lead to issues in the consistency of the bond. Microwave heating of the joint provides better repeatability, heating efficiency, and bond uniformity at the joint. The concept of improving joint bonding through microwave heating was proven viable by Zanko et al.[50]. During a series of field tests with a mobile microwaving unit, they attempted to anneal a butt joint (a transverse joint from asphalt being placed at two different times). They heated the joint in one lane so that the pavement reached a temperature of ~200F at a depth of three inches. The pavement was then worked with shovels and compacted. The condition of the joint was monitored over the next 2.5 years and while a crack developed along the joint in both lanes, the crack was significantly narrower in the microwave-bonded lane. A visual comparison of the joint in both lanes 2.5 years after the microwave repair can be found in Figure 3.11.

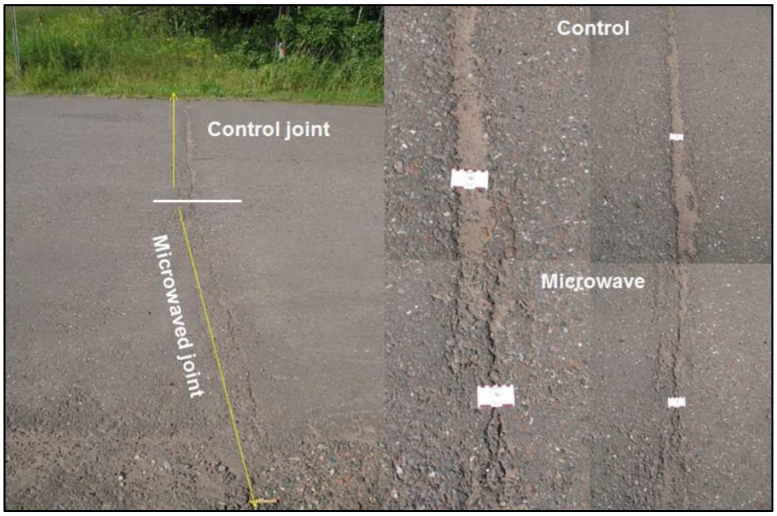


Figure 3.11 Comparison between a control joint and a joint bonded with microwave heating.[50]

Binder Aging

There have been attempts to use microwave heating to rapidly age asphalt specimens and binder samples. Bishara and McReynolds[105] proposed a set of microwave heating procedures that could be used to replace common binder aging techniques. They found that by microwave heating asphalt binder in a quartz petri dish with a domestic microwave oven for specific amounts of time, one could effectively simulate thin film oven (TFO) aging, rolling thin-film oven (RTFO) aging, and combinations of TFO and RTFO aging and pressure aging vessel (PAV) aging. They found their technique to reasonably align with the results of traditional techniques. Their technique was also much faster than those they were simulating. Mitchell et al.[106] attempted to develop a similar technique for aging asphalt specimens. While their results were inconclusive, they found some potential in their observation that repeated microwave heating led to a reduction in the stiffness of the specimens. These efforts were meant to gauge the possibility of substituting very costly laboratory equipment with inexpensive conventional microwave ovens. The success of these methods would lead to greater access to various testing techniques for many. Further research needs to be done to test the viability and accuracy of these methods.

Emulsion Curing

Microwave heating has been found to accelerate the curing process of asphalt emulsions through a higher demulsification rate, a higher dehydration rate, and a better demulsification effect.[76] The rapid rise in temperature from microwave heating can quickly destroy the electrical double layer structure of the emulsion, reduce the repulsive force between emulsion particles, and rapidly release water in the emulsion. The addition of microwave-absorbing additives like steel slag aggregates accelerates this process even further. Microwave heating can also reduce the heat dissipation in the emulsified asphalt and increase the energy utilization rate.

CHAPTER 4: LABORATORY EXAMPLE OF MICROWAVE HEALING

Most of the documented experiments on the healing of asphalt materials are based on qualitative observations and not on a rigorous approach based on mechanical testing. As a result, an investigation was performed to demonstrate the presence of healing.

The semi-circular bend (SCB) test was used to evaluate damage and healing effects in the asphalt specimens. The SCB test determines the fracture energy of asphalt mixtures at low temperatures. The testing procedure is detailed elsewhere[107]. All SCB testing was performed at -12°C. An MTS servo-hydraulic testing system equipped with an environmental chamber was used to perform the SCB test. The SCB samples were symmetrically supported by two fixed rollers and had a span of 120mm. The specimen contains a 20mm notch at the midspan. The load line displacement (LLD) was measured using a vertically mounted Epsilon extensometer with 38 mm gage length and ±1mm range; one end was mounted on a button that was permanently fixed on a specially made frame, and the other end was attached to a metal button glued to the sample. The crack mouth opening displacement (CMOD) was recorded by an Epsilon clip gage with a 10mm gage length and a +2.5 and -1mm range. The clip gage was attached at the bottom of the specimen. The CMOD signal was used as the control signal to maintain the test stability in the post-peak region of the test.

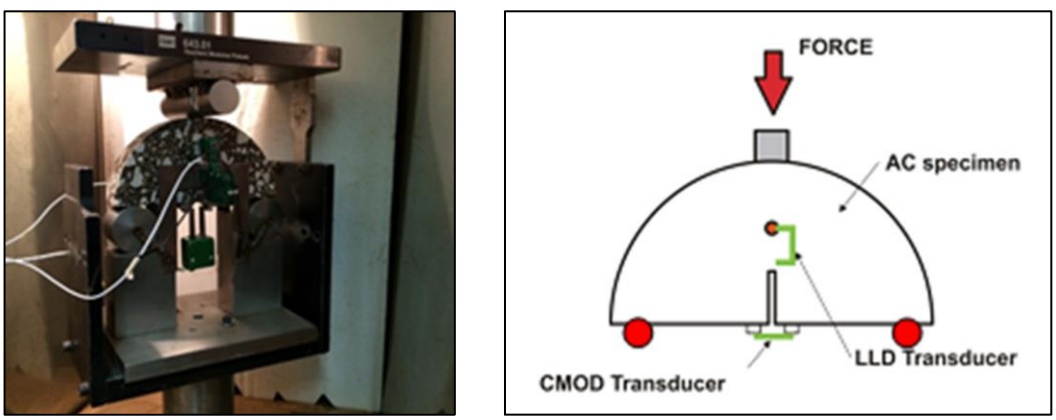


Figure 4.1 SCB test setup.

Two modified Superpave loose asphalt mixtures were used to prepare the test specimens, namely Mixture 60-SPL, which was prepared with loose mix and 6% GNP (by weight of binder), and Mixture 61-SPL, which was prepared with loose mix and 6% GNP (by weight of binder) and 1% taconite concentrate (by weight of mixture). Taconite in “concentrate” form is taconite aggregate reduced to the particle size of filler. For the first mixture, the GNP was added to the heated loose mix (at 135oC) and mixed for 4 minutes. For the second mixture, both the GNP and taconite concentrate were added to the heated loose mix (at 135oC) and mixed for 4 minutes. Two gyratory cylinders were compacted at 4% air void and then were saw cut to obtain six SCB samples. Each SCB sample is 31mm thick, with a radius of 150mm. A 15mm notch was cut in the center, perpendicular to the base, with a 0.5mm thick diamond blade.

The SCB experiments involved the following three steps:

1) First loading test (for all samples):

Testing was done following the AASHTO TP-105 protocol using CMOD control.[107] The test was performed at -12^{o}C. Before the testing, all the samples were conditioned at the testing temperature for two hours. The test was stopped when the load has decreased to 80% from the maximum (peak) load value. At 80% post-peak strength, the specimen is expected to experience considerable damage. Based on the peak value, the samples (by type) were ordered in ascending order. The samples with the lowest, third, and fifth values were not treated in the microwave (labeled NON). The samples with the second, fourth and highest peak were treated in the microwave oven to heal (labeled Micro).

2) Microwave Treatment:

The "Micro" samples were heated, seating on the semicircular side, one by one in the microwave oven for 90 seconds. The goal was to heat the crack ligament to a surface temperature of around 50°C. At the end of the treatment, each sample was seated on a flat surface, on the same side, at room temperature for one hour, and then returned to the fridge at 6^{o}C. Temperatures measured after the test (with a non-contact thermometer) oscillated between 55°C and 70°C, depending on the target point (aggregate or mastic).

3) Reloading test (for all samples):

All modified SCB specimens were tested again under load control to prevent damage to the CMOD and LLD gages. Based on the average time needed for the first loading test to reach 80% of the peak value, a loading rate of 0.9kN/min was used. This minimizes the influence of the loading rate on the fracture process. Before testing, all the samples were conditioned at the testing temperature for 2 hours. For each specimen, the test ended with a "catastrophic" failure due to the load-control protocol. The fracture load was recorded.

Table 4.1 summarizes the results of the SCB tests, which include the peak load of the specimen attained in the first loading test, the value of 80% of the peak load at which the specimen was unloaded, and the peak load capacity measured in the second reloading experiment. These results are also presented in Figure 4.1.

Table 4.1 SCB Test Results

Sample	First test, CMOD control			Treatment	Second test, Load control
	Peak Load, kN	80% post peak measured, kN	0.8% peak calculated		Load at fracture, kN
60-SPL 1 Micro	4.03	3.23	3.22	Microwave	3.68
60-SPL 2 Micro	4.08	3.29	3.26	Microwave	3.73
60-SPL 3 NON	3.76	3.01	3.01	NON	3.13
60-SPL 4 NON	4.24	3.4	3.39	NON	3.62
60-SPL 5 Micro	4.27	3.42	3.42	Microwave	3.86
60-SPL 6 NON	4.05	3.24	3.24	NON	3.35
61-SPL1 NON	4.02	3.22	3.22	NON	3.15
61-SPL2 NON	4.51	3.64	3.61	NON	3.34
61-SPL3	4.18	3.37	3.34	Didn't Fail	
61-SPL4 Micro	4.28	3.43	3.42	Microwave	4.02
61-SPL5 Micro	4.33	3.49	3.46	Microwave	3.9
61-SPL6 Micro	4.89	3.92	3.91	Microwave	4.14

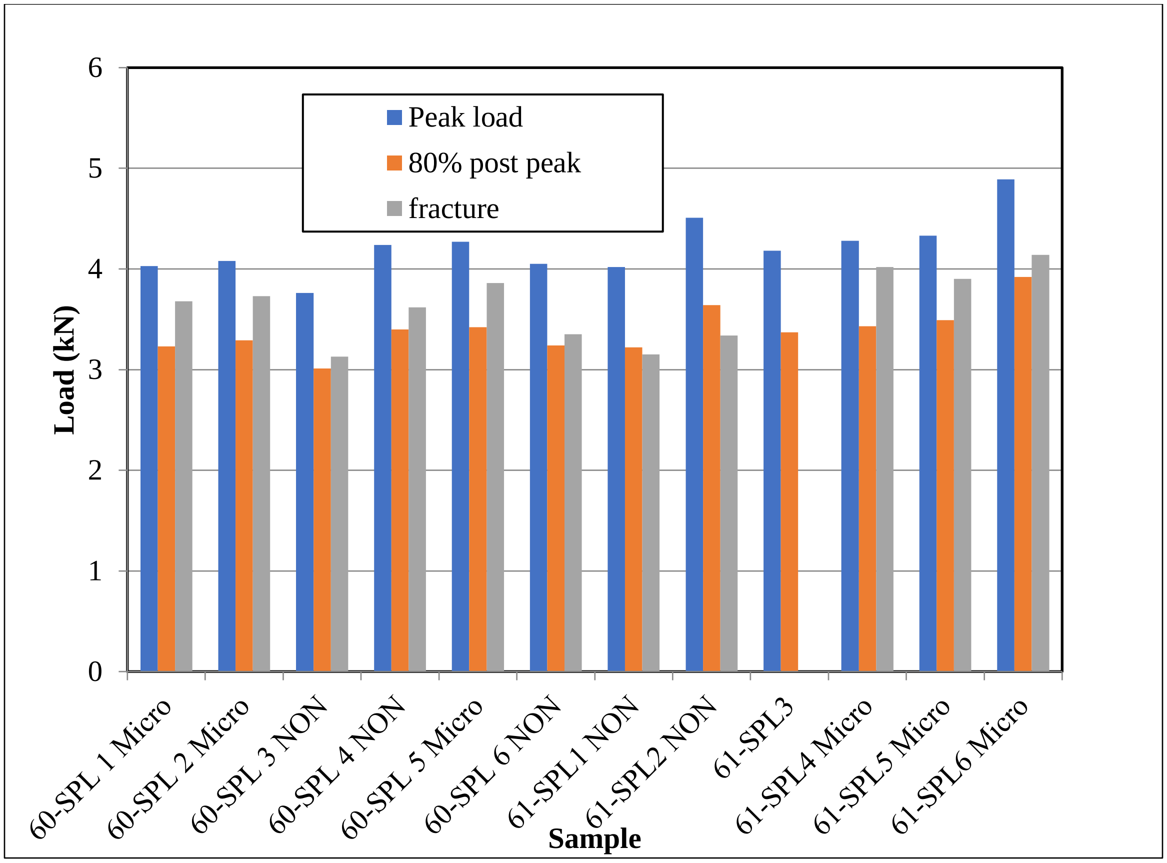


Figure 4.1 Comparison of peak loads, 80% post-peak loads, and final fracture loads.

Table 4.2 presents the average ratio between the peak load capacity measured in the reloading process and the load level at which unloading occurred during the first loading test (80% of the original load capacity).

Table 4.2 Fracture load to post peak load ratios

Sample	Average Ratio between the peak load measured in the reloading test and 80% of the original peak load
ALL 60 and 61 SPL Micro	1.125
ALL 60 and 61 SPL NON	1.006
ALL 60-SPL Micro	1.133
ALL 60-SPL NON	1.043
ALL 61-SPL Micro	1.116
ALL 61-SPL NON	0.95

For the samples without treatment (NON), the peak load measured in the second experiment is very close to the load level at which the specimen was unloaded at the end of the first test.

The overall difference is about 0.6%. This indicates that, without microwave treatment, the damage extent in the specimen remains unchanged. Therefore, the specimens can only reach the load level at which the previous unloading process begins but cannot regain the original load capacity. This is typical behavior of quasi-brittle materials.

For specimens undergoing the microwave oven treatment (Micro), the load capacity measured in the reloading experiment is about 12.5% higher than the load level at which the previous unloading occurs. After microwave treatment, the specimen can regain, on average, 90% of the original load capacity. This indicates that the damage incurred in the first loading experiment was partially healed by the microwave treatment. This confirms the findings of past researchers that microwave heating can be used to heal macrocracks as well as microcracks.[60]

To further investigate the healing effect, the measured load-deflection curves of specimens with and without microwave treatment are plotted in Figures 4.2 and 4.3. The dark grey markers show the load-deflection response of the specimen during the first loading process, and the red markers show the response during the reloading process.

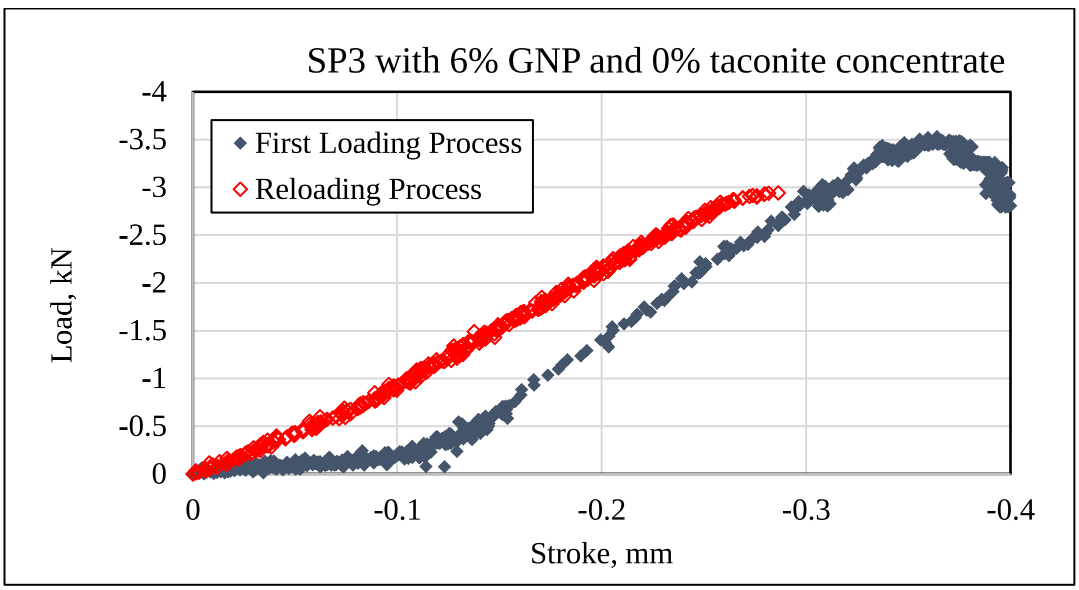


Figure 4.2 SCB results from a specimen with 6% GNP that was not microwaved.

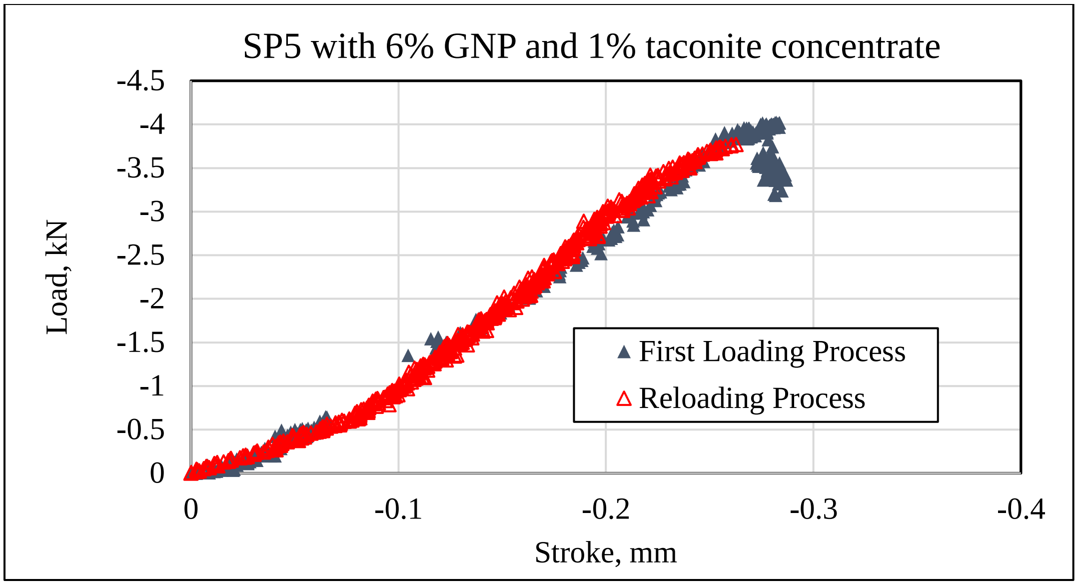


Figure 4.3 SCB results from a specimen with 6% GNP and 1% taconite concentrate that was microwaved.

CHAPTER 5: APPLICATION OF MODELING

Modeling heat transfer provides researchers with the necessary tools to predict the microwave heating uniformity in the asphalt and to determine whether there is a danger of overheating the material.[15] It also allows them to understand how different aspects of the asphalt mix will affect the microwave heating rate and uniformity without having to go through the expensive and time-intensive process of performing laboratory or field tests.

Several examples of modeling asphalt microwave heating were presented in Chapter 3. This modeling work typically involves 2D or 3D modeling software that requires extensive training and exhaustive computing power. In this chapter, a simple 1D microwave heat transfer model is presented then used to perform a sensitivity analysis of microwave heating to different material property changes and microwave settings.

In 2004, Hopstock[54] introduced a 1D heat transfer model for the asphalt microwave heating process that was described as a "reasonable first approximation". The model assumes the microwave field enters the roadway from the normal direction and that the lateral transfer of thermal energy is negligible. The effects of moisture on the heating process are ignored. The modeling results represent the heating that occurs directly below the center of a microwave applicator.

The model was based on a basic heat balance concept at each incremental thin slab of material on a per unit time and unit volume basis, as described in Equation 5.1.

$$\{Thermal\ Energy\ Stored\} = \{Microwave\ Energy\ Absorbed\} + \{Net\ Heat\ Input\ By\ Conduction\} \tag{5.1}$$

The three components of this heat balance equation are defined mathematically as shown in Equations 5.2 - 5.4. The resulting heat balance equation can be found in Equation 5.5.

$$\{Thermal\ Energy\ Stored\} = \rho C_p \frac{\partial T}{\partial t} \tag{5.2}$$

$$\{Microwave\ Energy\ Absorbed\} = 2\alpha P(z) = 2\alpha P_0 e^{-2\alpha z} \tag{5.3}$$

$$\{Net\ Heat\ Input\ By\ Conduction\} = k \frac{\partial^2 T}{\partial z^2} \tag{5.4}$$

$$\rho C_p \frac{\partial T}{\partial t} = 2\alpha P_0 e^{-2\alpha z} + k \frac{\partial^2 T}{\partial z^2} \tag{5.5}$$

Where:

ρ = material density (kg/m^3)
C_p = heat capacity on a mass basis (J/kg/°C)
T = temperature (°C)
t = time (s)
α = microwave absorption coefficient (m^{-1})
P_0 = power density of the microwave energy entering pavement surface (W/m^2)
k = thermal conductivity (W/m/°C)

The "microwave energy absorbed" term describes how much microwave energy is converted into heat flux in each incremental slab of material. This depends on the attenuation of the microwave field as it travels deeper into the material. This attenuation is described by the function for power density available at a certain depth. This function is derived from Lambert's law and is found in Equation 5.6.[15]

$$P(z) = P_0 e^{-2\alpha z} \tag{5.6}$$

The microwave absorption coefficient, α, is the reciprocal of the microwave penetration depth. This model assumes a constant α. The heat capacity and thermal conductivity were also assumed constant.

Hopstock used a factor of two for the "microwave energy absorbed" term while some researchers, such as Lindroth et al.[55], do not. This is because those researchers define the penetration depth to be one-half of Hopstock's definition. The "net heat input by conduction" term is derived from a 1D version of Fourier's law of thermal conduction.[54]

Materials with high microwave-absorbing abilities will consume most of the available microwave power in the top layers of the material. This is desirable for applications like deicing that are reliant on the rapid heating of the pavement surface.

Hopstock provides methods for calculating nearly all of the properties required for this heat balance equation. Those methods can be reviewed in Zanko and Hopstock[54]. Because this is a 1D model that poses a partial differential equation problem, Hopstock recommends the numerical solution be performed using an explicit finite difference approximation in a spreadsheet tool like Microsoft Excel.

Hopstock substantially revised his model in 2016 to make it more realistic for infield applications.[50] The updated version of the model retained the same governing heat balance equation for the pavement interior (Equation 5.5), but it added more complicated boundary conditions at the pavement surface. These boundary conditions try to account for environmental elements that may affect the heat balance such as absorbed solar energy, energy lost to convection (wind), and energy lost to the atmosphere. These three elements are formulated in Equations 5.7-5.9. The heat balance equation used at the surface of the asphalt can be found in Equation 5.10.

$$\{Radiant\ Energy\ Absorbed\} = AH_{ri} \tag{5.7}$$

$$\{Energy\ Loss\ By\ Convection\} = (7.4 + 6.39v^{0.75})(T_s - T_a) \tag{5.8}$$

$$\{Energy\ Loss\ By\ Radiation\} = \varepsilon\sigma[(T_s + 273.15)^4 - (T_a + 273.15)^4] \tag{5.9}$$

$$\frac{\Delta z}{2}\rho C_p \frac{\partial T}{\partial t} = 2\alpha P_0 e^{-2\alpha z} - k\frac{\partial T}{\partial z} + AH_{ri} - (7.4 + 6.39v^{0.75})(T_s - T_a) - \varepsilon\sigma[(T_s + 273.15)^4 - (T_a + 273.15)^4] \tag{5.10}$$

Where:

A = Radiation absorption coefficient
H_{ri} = Incident radiant energy per unit area per time (W/m^2)
v = Air velocity (m/s)
T_s = Temperature at the surface (°C)
T_a = Ambient temperature (°C)
ε = Thermal emissivity
σ = Stefan-Boltzmann constant, 5.669×10^{-8} (W/m^2/K^4)
Δz = Thickness increment used in the finite difference solution (m)

The “thermal energy stored” term is multiplied by $\frac{\Delta z}{2}$ because the heat at the pavement surface is considered to be stored in a thin layer of thickness $\frac{\Delta z}{2}$. This is necessary because Hopstock’s finite difference solution features a node at the surface of the pavement, meaning the thickness of pavement accounted for by that top node is half of that of the other nodes in the solution. The “net heat input by conduction” term is changed to reflect the fact that conduction will only be occurring in one direction along the z-axis at the top node. Conduction at the surface is considered a heat loss because the surface layer always has the highest temperature. The bottom node of the asphalt layer was treated the same as the internal points except it only considered conduction from the nodes above it. No heat was lost to the layer beneath the asphalt.

The addition of these surface conditions brings Hopstock’s model closer to the model laid out by Chadbourn et al.[108] in their creation of the PaveCool application. PaveCool is a tool that can predict the cooling curve of asphalt based on a certain set of parameters. The governing equation and surface boundary conditions used by this tool are the same as Equations 5.5 and 5.10, respectively, but without the "microwave energy absorbed" terms. The other major differences between the two models are that PaveCool assumes a constantly shrinking Δz to account for the compaction of the asphalt and that PaveCool accounts for changes in the thermal properties of the asphalt with changing temperatures. Because these models are so similar, there is an opportunity to create a new tool based on PaveCool that can predict the microwave heating time necessary to raise asphalt to a certain temperature.

A sensitivity analysis was performed on the 2016 version of Hopstock's 1D microwave heat transfer model to determine which parameters have the greatest impact on the microwave heating process. An explicit finite difference method was used that is slightly different than the method used by Hopstock.

In the finite-difference solution, the top node is at a depth of $\frac{\Delta z}{2}$, meaning that the node accounts for the same pavement thickness as all other nodes in the solution. For this reason, Equation 5.10 is modified for this solution so that the "thermal energy stored" term is multiplied by Δz instead of $\frac{\Delta z}{2}$. This solution assumes uniform temperature along with the depth of the pavement at the beginning of heating. It does not account for heat transfer into the base layer from the bottom of the pavement layer.

The base parameter values used for this analysis, shown in Table 5.1, are similar to the values used by Zanko et al.[50]. However, certain values are changed from those provided in the paper. Namely, H_{ri} (solar radiation) and v (wind speed) are set to zero. This was done to better simulate the microwave heating process that would occur when the horn antenna is placed flat on the pavement surface, as is the case with the mobile microwaving unit used by Zanko et al.[50] in their fieldwork.

Table 5.1 Base parameter values used in the model sensitivity analysis.

Quantity	Symbol	Units	Value
Ambient air temperature	T_a	ºC	5
Initial temperature of pavement	T_0	ºC	7
Pavement Density	ρ	kg/m^3	2435
Specific heat capacity of pavement	C_p	J/kg/ºC	889.6
Thermal conductivity of pavement	k	W/m/ºC	1.78
Microwave absorption coefficient	α	m^{-1}	3.559
Wind speed	v	m/s	0
Emissivity of pavement	ε	dimensionless	0.95
Microwave power density at surface	P_0	W/m^2	98852
Solar energy	H_{ri}	W/m^2	0
Radiation absorption coefficient	A	dimensionless	0.85
Time increment	Δt	s	20
Distance increment	Δz	m	0.0127

Five parameters (P_0, α, T_a, k, and C_p) were chosen for sensitivity analysis. One at a time, these parameters were varied with 0.5, 0.75, 1.25, and 1.5 multipliers while the other parameters were kept as they appear in Table 5.1. The parameters were varied by the same multipliers to better determine which parameters have the greatest proportional impact on the heating process. The temperature profile of the pavement after 2 minutes of simulated microwave heating was calculated for each variation. The results are shown in Figures 5.1 - 5.5.

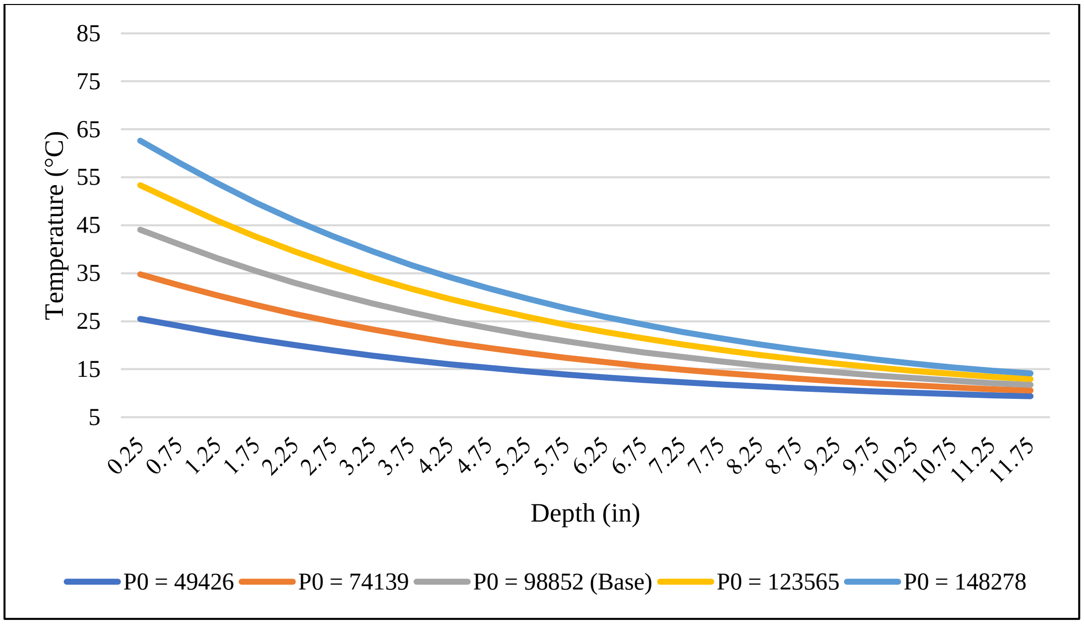


Figure 5.1 Change in temperature profile (after 2 minutes of heating) due to variation of microwave power density (P_0).

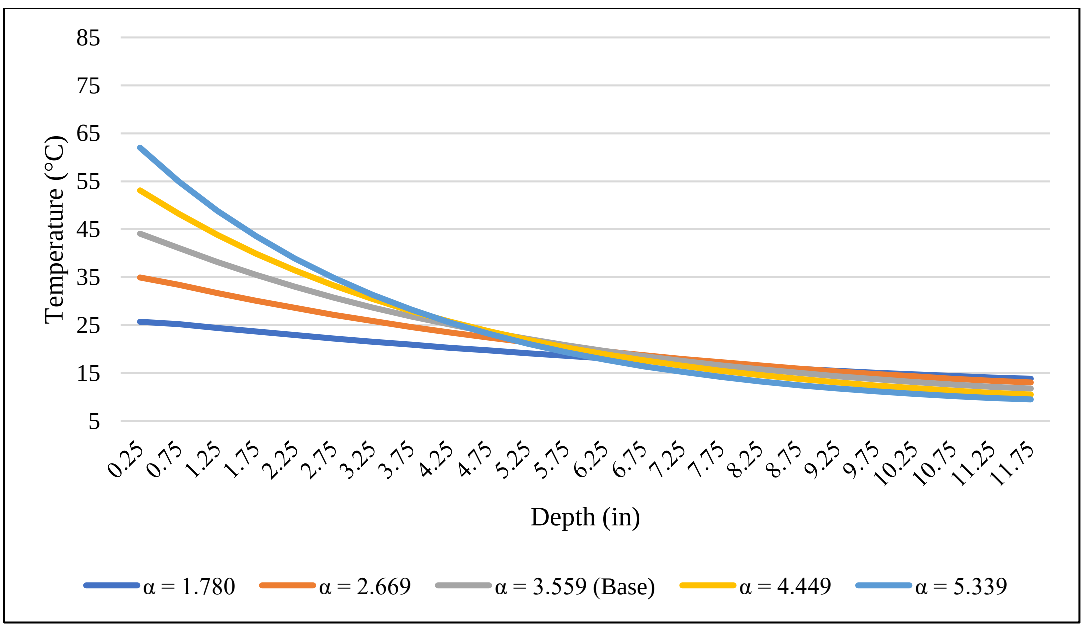


Figure 5.2 Change in temperature profile (after 2 minutes of heating) due to variation of microwave absorption coefficient (α).

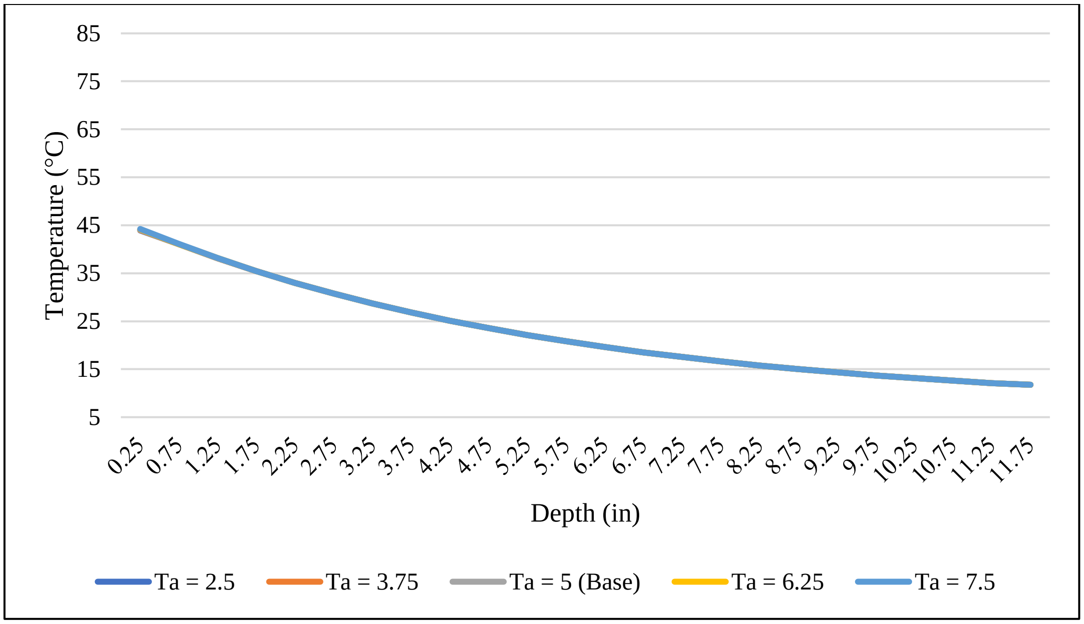


Figure 5.3 Change in temperature profile (after 2 minutes of heating) due to variation of ambient temperature (T_a).

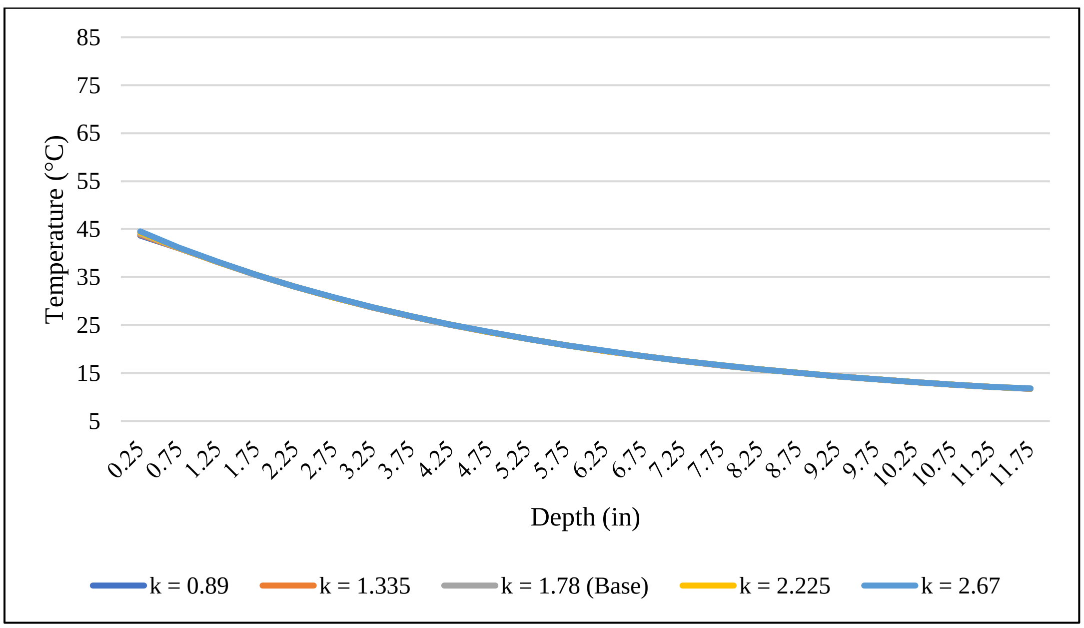


Figure 5.4 Change in temperature profile (after 2 minutes of heating) due to variation of thermal conductivity (k).

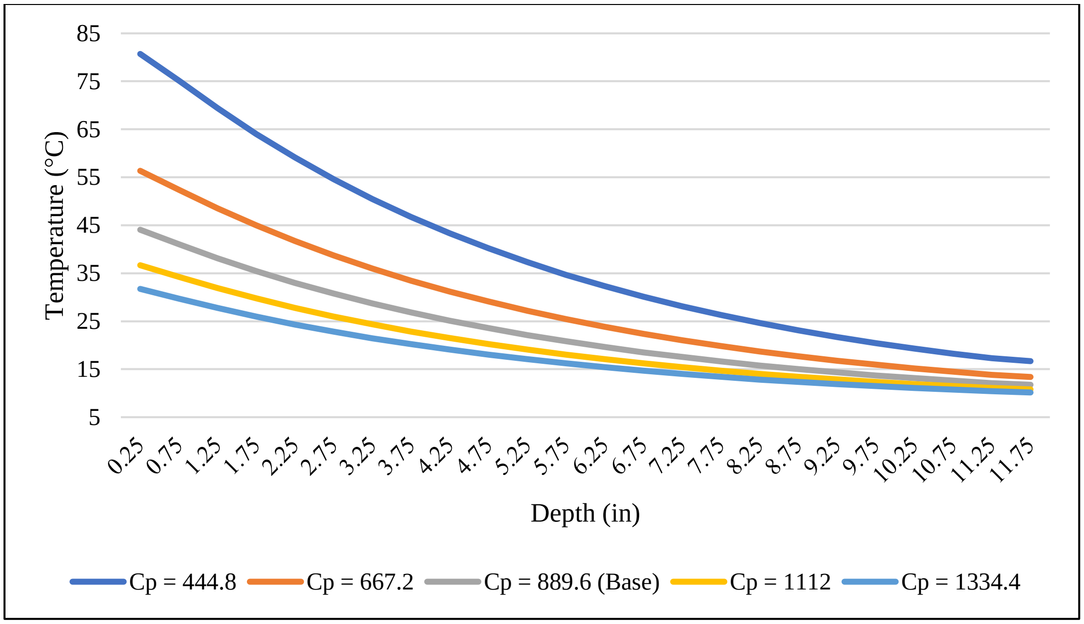


Figure 5.5 Change in temperature profile (after 2 minutes of heating) due to variation of specific heat capacity (C_p).

Several conclusions can be drawn from the plotted results. As observed in Figures 5.3 and 5.4, the ambient temperature and thermal conductivity do not have any significant impact. This indicates that the increase in temperature is mostly due to the heat generated from microwave energy and not from thermal conduction and that the amount of heat lost from the pavement surface to the atmosphere is fairly inconsequential.

Figure 5.5 shows that a reduction in the specific heat capacity of the pavement causes the microwave heating rate to greatly increase. This makes sense as the specific heat capacity of a material is the amount of energy that must be dissipated in one unit mass of the material to raise the temperature by one degree.

The microwave power density at the pavement surface, P_0, is shown to have a large impact on the microwave heating rate. This parameter is dependent on the strength of the microwave generator used and the geometry of the microwave applicator. These two factors can be changed by those doing the heating provided they have money for the proper equipment.

Variation of the microwave absorption coefficient has an interesting effect on the pavement temperature profile. Raising the absorption coefficient will increase the heating rate near the top of the pavement but decrease the heating rate near the bottom of the pavement. This makes sense as the absorption coefficient is the reciprocal of the microwave penetration depth, which is the depth at which ~87% of the applied microwave energy has been absorbed. An increase in absorption coefficient means a greater portion of the applied microwave energy is consumed by the upper portions of the pavement.

Specific heat capacity seems to be the tested parameter with the greatest impact on the microwave heating rate. However, the specific heat capacity of asphalt is not as variable as the options selected for the simulation. The specific heat capacity of asphalt is typically around $900\frac{J}{kg℃}$ and would not be expected to reach values in the range of 400-$600\frac{J}{kg℃}$. However, P_0 is highly impactful on the microwave heating rate and can be adjusted more easily than any of the other tested parameters. The microwave absorption coefficient can be changed with the inclusion of more or less microwave-absorbing elements into the asphalt mix.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this thesis, a state of the art of applications of microwave heating of asphalt pavements was performed. In addition, limited experimental work, demonstrating the occurrence of healing, and practical calculations, using a simple heat transfer model, were presented in support of the potential use of microwave heating in asphalt pavements.

First, the principles of microwave heating and induction heating were introduced, with an emphasis placed on microwaves. The two mechanisms responsible for the conversion of energy from microwave electromagnetic fields into heat in the asphalt were discussed. The dipolar orientation polarization mechanism was identified as the primary mechanism for microwave heating. The basic concepts of microwave heating were then covered, including complex permeability and permittivity and how they affect the microwave heating process, the different components of a microwave system, and different types of microwave systems used for research.

Then, an extensive literature review on the use of microwaves on asphalt pavements was presented. The literature review included several applications of microwave technology on asphalt pavements and additives that enhance the microwave-absorbing capabilities of asphalt materials. The microwave heating, environmental, and cost-saving benefits of microwave-absorbing additives were explained. Different applications of microwave technology on asphalt pavements were discussed including self-healing, deicing and snow removal, asphalt recycling, and pavement patching.

The results of laboratory fracture experiments that demonstrated the effect of healing from microwave heating were then presented. These results showed that microwave heating can effectively repair asphalt macrocracks.

Finally, the 1D microwave heat transfer model developed by Hopstock was solved with an explicit finite difference method to perform a sensitivity analysis of several of the model parameters. The results showed that certain parameters, such as ambient temperature and thermal conductivity, do not have a significant impact on the microwave heating outcome, while microwave absorption coefficient and applied microwave power density have a significant effect.

The vast majority of the work discussed in this thesis was done in a laboratory setting. The potential implementation of this technology requires field trials of these applications and the practical development and demonstration of a mobile microwave unit that could effectively heat pavements at a moving speed. The simulation results obtained in this thesis can be used as a good starting point for the experimental design of such a future field study. In addition, the simple 1-D model can be easily combined with the PaveCool[109] computer application to create an accessible microwave heating simulation tool.

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