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MICROWAVE DE-ICING OF ASPHALT PAVEMENT WITH STEEL FIBERS AND MAGNETITE AS AN ADDITIVE AGGREGATES

And its implications for the Finnish road infrastructure

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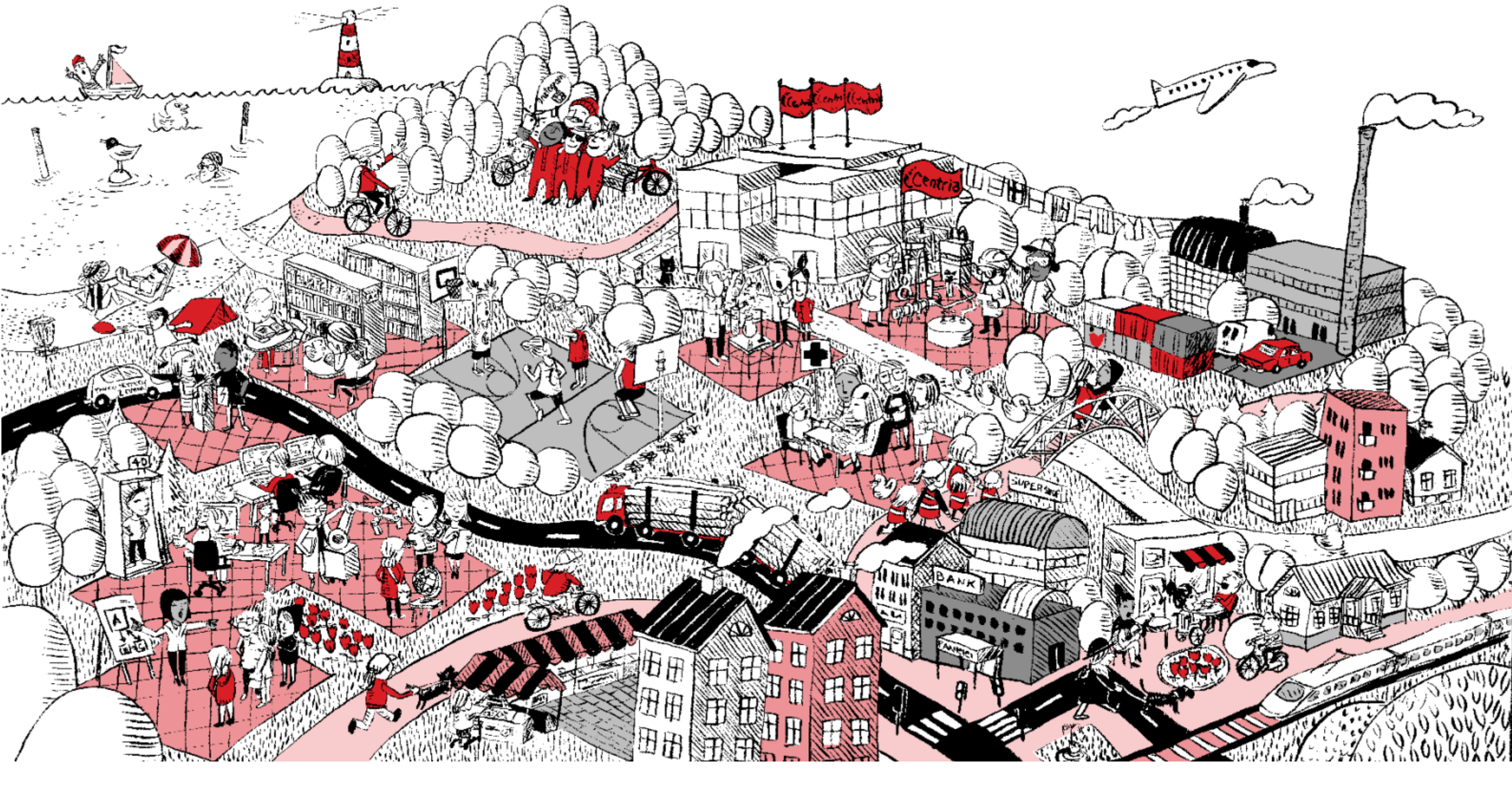

ABSTRACT

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Abstract

Over half a century, salt and gravel beside mechanical practice are used for de-icing the roads in winter. Consequently, using this traditional method for an extended period weakens the asphalt pavement, causing environmental and health effects with high costs. In order to tackle the de-icing problems with the traditional approach, a novel method is highlighted in this thesis with Microwave Heating (MH) of asphalt pavement. The new approach shows several feasible benefits, mainly environmental, and more so, economical. The findings of this thesis are based on a critical review of recent experimental studies on magnetite and steel fibers as additive aggregates in asphalt pavements. Compared with the other additive aggregates, steel fibers and magnetite showed a high microwave heating efficiency (MHE) due to high MH sensitivity. Furthermore, several aspects of these aggregates and their behavior were investigated with different compositions and under different environmental/laboratory conditions based on the thesis's methodology. Finally, the key findings were grouped under several themes to unpack the research question and address the impact of the new approach. Hence, the principal practical implication from the findings of this thesis has been proposed as a framework and action plan for maintenance of the Finnish road infrastructure.

Key words
Aggregates, asphalt pavement, microwave de-icing, microwave heating, snow and ice melting

ABBREVIATION

AC	Activated Carbon
ACP	Activated Carbon Powder
IARC	The International Agency for Research on Cancer
ICNIRP	The International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
MALT	Magnetite Layer Thickness
MDT	Microwave De-icing Time
MH	Microwave Heating
MHE	Microwave Heating Efficiency
MP	Mineral Powder
SAR	Specific Energy Absorption Rate
TSR	Tensile Strength Ratio
WHO	World Health Organization

ABSTRACT
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1 INTRODUCTION

The traditional de-icing process is causing environmental damage besides having a high operational cost of chemicals (mainly salts). Recently, researchers have shown an increased interest in developing more enhanced de-icing approaches to asphalt pavement with additive aggregates by Microwave Heating (MH) than ever before. Although several types of research have been conducted on MH of asphalt pavement and several new additive aggregates were examined, little is known about investigating and evaluating the feasibility of using a different additive's effects on MH of asphalt pavement. Guo, Wang, Huo, Wang, Liu & Li (2020); Sun, Wu, Liu, Hu, Yuan, & Ye (2018) argued that using particular additive aggregates in a specific composition showed high de-icing efficiency by using MH. However, the findings from the literature review revealed that the new technology of MH of the asphalt mixture shows an auspicious outcome of de-icing on the laboratory scale.

This study intended to explore the different properties of magnetite and steel fibers as additive aggregates under Microwave Heating Efficiency (MHE) in the de-icing process. The thesis seeks to address several questions, which are presented in (TABLE 1). Hence, this thesis's primary aims is to gain a fundamental overview of the influence of newly developing de-icing technology on the engineering properties of the asphalt mixture. Another target of this thesis is to propose an implementation approach to the Finnish road infrastructure about the feasibility of using this technology based on the findings of the thesis.

2 THEORETICAL BACKGROUND

Asphalt has been known for five millennia for its properties, such as its high boiling point, being non-volatile under the conditions of use (stable), having a high viscosity. Ever since, there have been different usages for asphalt, namely, waterproofing, adhesives for jewelry, caulking, mastic asphalt for construction purposes, and many others. Asphalt, by definition, is a residuum of the bottom fraction of an oil refinery treated by air blowing or by a solvent process, the product of which meets the requirements as a material for diverse road and highway construction. By and large, the use of asphalt increased from the beginning of the twentieth century as the popularity of vehicles increased. (Speight, 2016, 1-8.)

When snow falls on pavements, highways, and airfields as winter approaches, especially in the Nordic regions, it causes traffic issues and delays, resulting in increased traffic congestion. In that case, the increased traffic load triggers ice layers to melt, reducing skid resistance and complicating winter road maintenance; these problems have been addressed for decades. Traditional methods of solving these include mechanical equipment and chemical treatment (usually salts) (Liu, Yang, Wang & Luo 2019, 50.) The traditional way used for over half a century is to remove the snow using snowplows and sweepers. Although this method provides satisfactory results, it lacks in efficiency and requires professional staff, besides the high cost of these mechanical devices. Another drawback is the severe damage to the surface (pavement/road/airfield) caused by the intense shoveling force of these mechanical devices (FIGURE 1). Similarly, when the temperature drops rapidly below zero degree Celsius, and the snow becomes ice, the mechanical devices are incapable of tackling these conditions. (Ma, Geng, Ding, Zhang, & Huang 2016, 653.)

Chemical treatment, on the other hand, generally with salt, typically sodium chloride (NaCl) and magnesium chloride ($MgCl_2$), is the other traditional method for removing snow. Technically, when rock salts are distributed on the top of the pavement, they dissolve in melting snow, causing a decrease in the solution's freezing point and delaying the forming of bonds between the pavement and the ice layers. Granted that, the opposite effect occurs when using a significant amount of salt, such as corrosion on asphalt pavement, besides hazardous effects on road condition and environmental pollution (Liu et al. 2019, 51.) Similarly, the effectiveness of salt (NaCl) in melting snow diminishes when the temperature drops below 3.9 °C (Sun et al. 2018, 871). In the Nordic region, the snow regularly falls combined with a severe drop in temperature; therefore, the mechanical and chemical methods go hand-in-hand to tackle this issue. However, these methods are time and resource-consuming and affect flora and fauna. With this in mind, a study conducted by Wang, Zhao & Chen (2008, 1538) concluded that China's annual de-icing salt consumption is around 100 thousand tons on average, which appears to have increased in recent years but worldwide is estimated to be over 30 million tons.

FIGURE 1. The outcome of using the traditional method of de-icing asphalt pavement

Under those circumstances, many existing studies have examined hydronic heating by burying pipe systems under the asphalt pavement to melt snow and ice. For instance, Sun et al. (2018, 872) summarized many research articles on hydronic heating by a pipe system, where some researchers suggested a hybrid system for snow melting and air conditioning. The main aim of this approach was to stop the freezing of a pavement surface, where the exposure rate for road surface is roughly 90%. Furthermore, other researchers highlighted the utilization of geothermal tailwater (roughly 40 ºC) for melting ice and snow on the pavement. Other researchers confirmed that the use of the high temperature of fluid does not result in better performance in melting ice/snow. (Sun et al. 2018, 872.)

Moreover, a mathematical model provided evidence that the arrangements of pipe and fluid operation parameters and material thermophysical characteristics are critical factors that affect the efficiency of the geothermal pipe system process. Nevertheless, Sun et al. (2018, 872), argued that all previous studies neglected preventing melting snow on the pavement from freezing; also, these processes are time-consuming. Therefore, the same authors suggested that this process should be further advanced. Although the authors review the literature critically, they pay little attention to energy consumption, cost analysis, and environmental effect.

The aggregate "is the hard inert material, such as sand, gravel, crushed stone, slag, or rock dust that is mixed with the asphalt (binder) for the construction of roadways" (Speight 2016, 34-39). The selection of aggregates depends on the properties of the binder and the condition requirements, such as weather and traffic, to be fulfilled after completing the construction of the road. Likewise, there are several criteria to fulfill when choosing the aggregates, such as; the type of construction for which it is intended, cost, availability, and material quality, as well as several other criteria for aggregate suitability. Ultimately, the most common aggregate used to build asphalt pavement is limestone (calcium carbonate, $CaCO_3$); other materials such as gravel and granite types are also used to construct roads. Slag aggregates, on the other hand, are made by crushing smelter slag or treating fire-liquid slag melt with special treatment (molten slag aggregates). In addition, metallurgical slags are used as binding parts and fillers in many concrete forms, currently being produced and used in construction. Finally, construction waste (i.e., concrete, bricks, and asphalt) which come in the form of crushed material, are considered secondary aggregates. Secondary aggregates are used when promoting low costs; however, they are inferior when considering frost resistance. (Speight 2016, 34-39.)

In recent years, many researchers showed profound interest in new sophisticated methods of de-icing. The method proposed here includes MH for the asphalt mixture, which is characterized by the wavelength of the irradiation energy. This method has extensive heating efficiency, environmental protection, and lower costs than traditional methods or hydronic heating by burying pipe systems under the pavement. Various asphalt mixtures were investigated in combination with MH, and there is a wide choice of asphalt additive aggregates presented in (FIGURE 2).

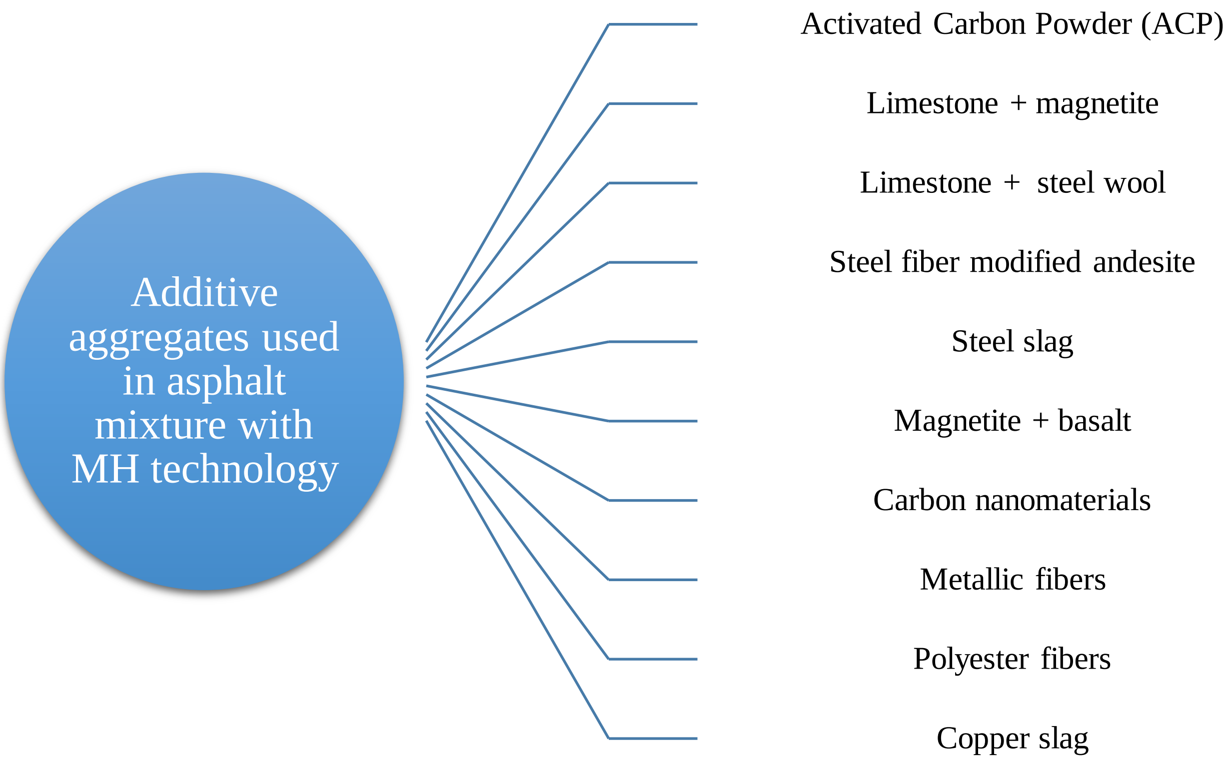

FIGURE 2. Several types of additive aggregates coupled with MH technology

MH of an asphalt mixture with additives aggregates is now well-established in the literature, and various laboratory-scale studies have been conducted in this domain. For instance, Liu et al. (2019, 51), provided evidence that MHE enhances twice with Activated Carbon Powder (ACP) comparing with asphalt pavement without additive aggregates. Likewise, a study conducted by Gao et al. (2017, 41), concluded that the MHE would increase even up to three times when an equal volume of steel slag and limestone was replaced in an asphalt mixture. On the other hand, Guo et al. (2020, 8), demonstrated that the proportion of 30% (magnetite with limestone) for the upper layer and 70% limestone for the lower layer in an asphalt mixture showed an increase in the complex dielectric constant and loss angle of the mixture with increasing electromagnetic waves absorbance. Furthermore, steel fiber and steel slag show 10 g/min of ice melting comparing to a pipe system of 1 g/min (Sun et al. 2020, 882). Overall, the addition of aggregates in the asphalt mixture has shown an effective result with MH. (FIGURE 3) shows the specimen of asphalt mixture with additive aggregates.

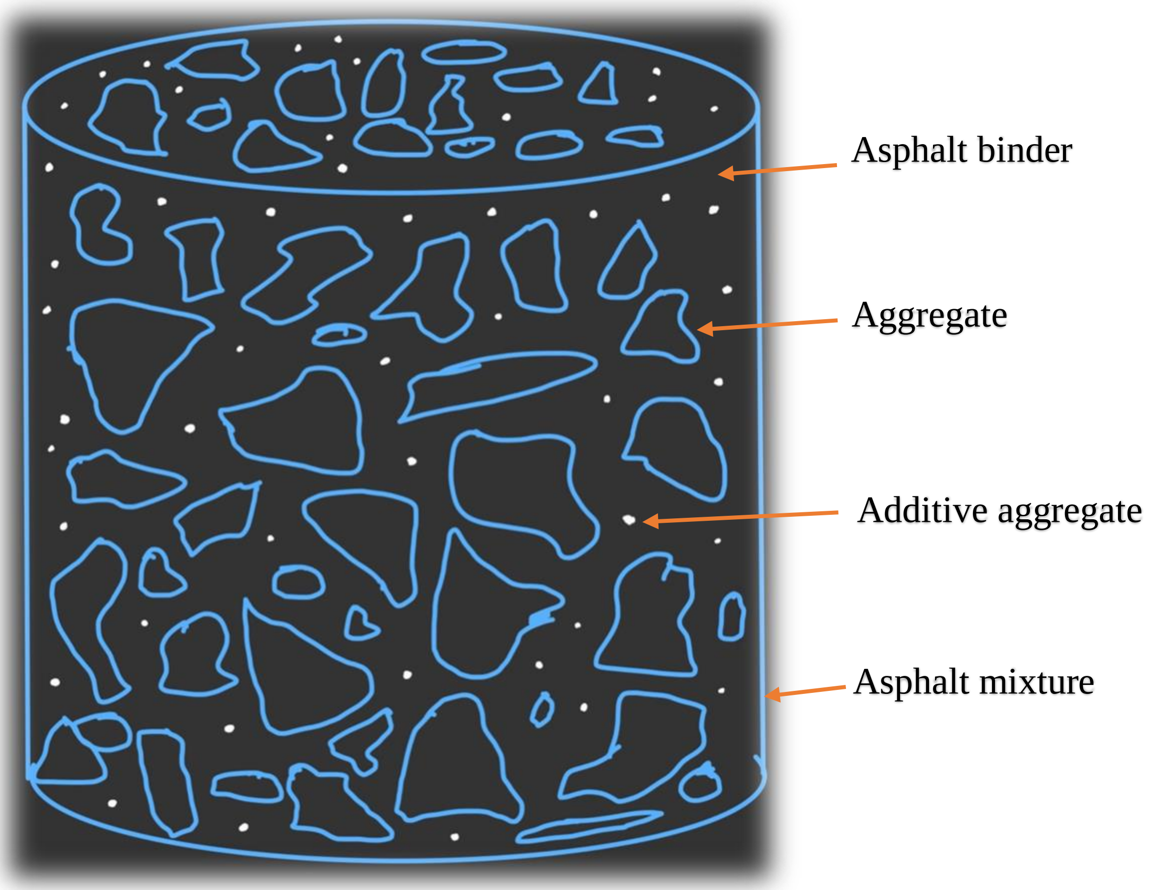

FIGURE 3. Asphalt specimen with additive aggregates

Similarly, Gao, Guo, Wang, Wang, Wei, Wang, Huang & Yang (2019, 1118) observed that with increases in steel wool content, the surface temperature increases, whereas this increase in the temperature will decrease if the steel wool content continues to increase. On the flip side, Yalcin (2020, 13) points out that MH increased the temperature of waste metal particles and the temperature of bitumen around them; hence, the waste metal shows a promising result as an asphalt aggregate. (FIGURE 4) demonstrates several experimental findings in the literature which addressed these aggregates and their feasibility with MH.

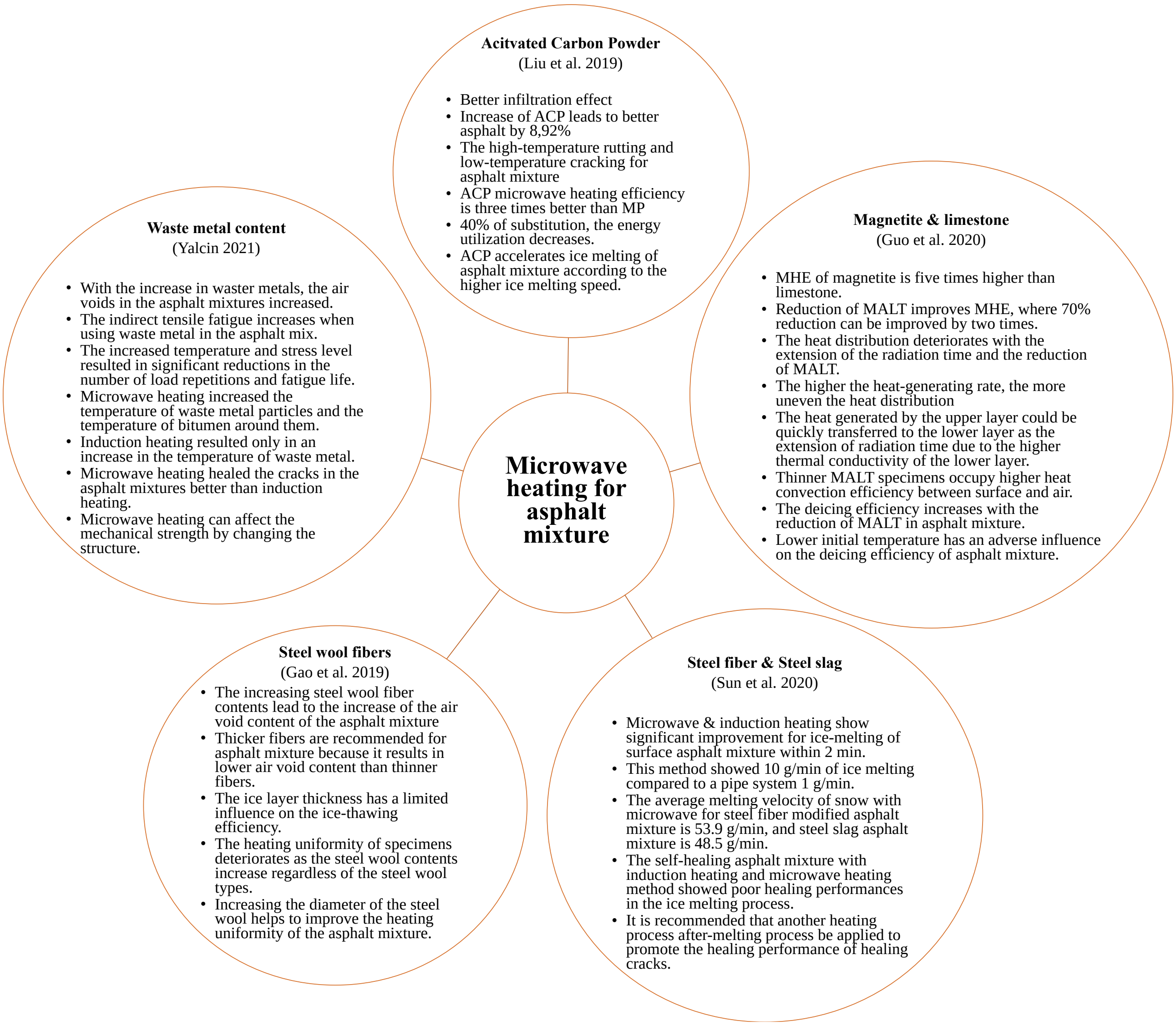

FIGURE 4. A diagrammatic overview of key findings from recent studies in the literature review

Based on the findings from the literature review, the methodological criteria are created and presented in (TABLE 1). Thus, the objective of this thesis is obtained based on this methodology which are listed in (TABLE 1). Where five different criteria represent various factors affecting the de-icing process. The following chapters briefly illustrate the MH process. Furthermore, the MH principles that state the full-scale equipment and safety issues of microwave technology are discussed. Additionally, the policy of winter road maintenance and their categories were covered in detail. Finally, all things considered, a hypothesis is made for the implication of this thesis's findings.

TABLE 1. Methodological criteria for evaluation the additive aggregates with MH technology

Criteria (what)	Justification (why)
(1) **Characteristic of aggregates with various quality testing methods**	To what extent the aggregates are suitable. How do these factors give optimal engineering properties in asphalt content for future substitution?
(2) Characterization of the microwave heating efficiency of asphalt mixture including the aggregates and bitumen (based on different laboratory experiments)	To find out the behavior of the mixture under microwave heating.
(3) The effect of aggerates thickness, percentage, time, and frequency of MH process in asphalt pavement	How does that influence the ice melting on asphalt pavement?
(4) Reflection losses, radiation depth, and effect of air voids on MH process	Negative aspects of MH by addition of aggregates and their effects.
(5) The effect of initial pavement temperature and ice layer thickness on the ice-thawing times of asphalt mixtures with different aggregates	How does that correspond to energy utilization efficiency?

3 TYPES OF HEATING PROCESSES

Induction heating is the phenomenon of heating conductors (primarily metals) by electromagnetic induction. Bonding, hardening, or softening the conductive materials are some of the applications of this process. Thus, due to its non-conductive nature, induction heating cannot be used for melting ice and snow. (García, Schlangen, van de Ven & Liu 2012, 38). However, in an experiment conducted by Sun et al. (2018, 881-882), they used steel fiber as an additive aggregate and the asphalt mixture showed moderate melting of snow. Furthermore, the average melting velocity of steel-modified fiber asphalt mixture using induction heating was observed to be 19.9 g/min, while the microwave was found to be 53.9 g/min. Hence, MH showed more significant potential for de-icing the road due to the higher rate of snow melting and cost-efficiency; this thesis work essentially focuses on MH with the addition of several aggregates on MH asphalt mixture.

3.1 Microwave heating principles

Microwaves are electromagnetic waves capable of transmitting through the medium, with a frequency range from 0.3 GHz (300 MHz) to 300 GHz and wavelengths from 0.001 meters to 1 meter. The difference in range of frequency and wavelength depends on the substance's complicated permittivity and strongly on tan δ, which is the loss angle constant. Therefore, the capacity of the material to absorb the microwave energy is directly proportional to the loss angle constant tan δ. (Ding, Wang, Cui, Zhang & Chen 2021, 2.)

The process of MH in dielectric matters depends on the electric field's capacity to polarize the charges in the material and the incapability of polarization to follow the rapid change of the electric field. The phenomenon of the transformation of electromagnetic energy to thermal energy causes MH. Thus, the induced microwave heats the material equally during penetration. In contrast, the process of conventional heating differs from microwave regarding the transfer of energy, wherein conventional heating, the pre-generated heat is transferred by conduction, convection, and radiation to the surface of the material. (Jin, Guo, Lu, Zhang, Wang & Jin 2017, 32-33; Fernández, Arenillas & Menéndez 2011, 723-724.)

Additionally, penetration depth during MH is another fundamental parameter as it determines the overall efficiency of the uniform heating process; thus, allowing for an increase in the surface heating rate. Due to energy consumed on the surface, the amplitude of the electromagnetic waves gets lower as it penetrates deeper into the material. As a result, the smaller the loss factor and frequency, the greater the penetration depth of the material. (Meredith 1998, 5.) Similarly, Sun & Tongsheng (2013, 353-363) reached the conclusion that 23 cm was the minimum penetration depth on the asphalt specimen when testing with various aggregates, as diorite, limestone, and quartz with two different frequency ranges of 915 MHz and 2450 MHz. The result showed that pavement with additive aggregates led to a higher penetration depth of 12 cm than pavement without additive aggregates.

The dielectric nature of bitumen lowers the heat generation in traditional asphalt pavement without microwave-sensitive additives. Under such circumstances, heat transferred conduction occurs from aggregates to bitumen, as the process is depicted in (FIGURE 5). As the microwave heats the aggregate particle first, the sequential convection of heat from aggregates to bitumen occurs and is diagrammatically presented in (FIGURE 6). (Wang, Zang, Feng, Lu & Cao 2019, 146).

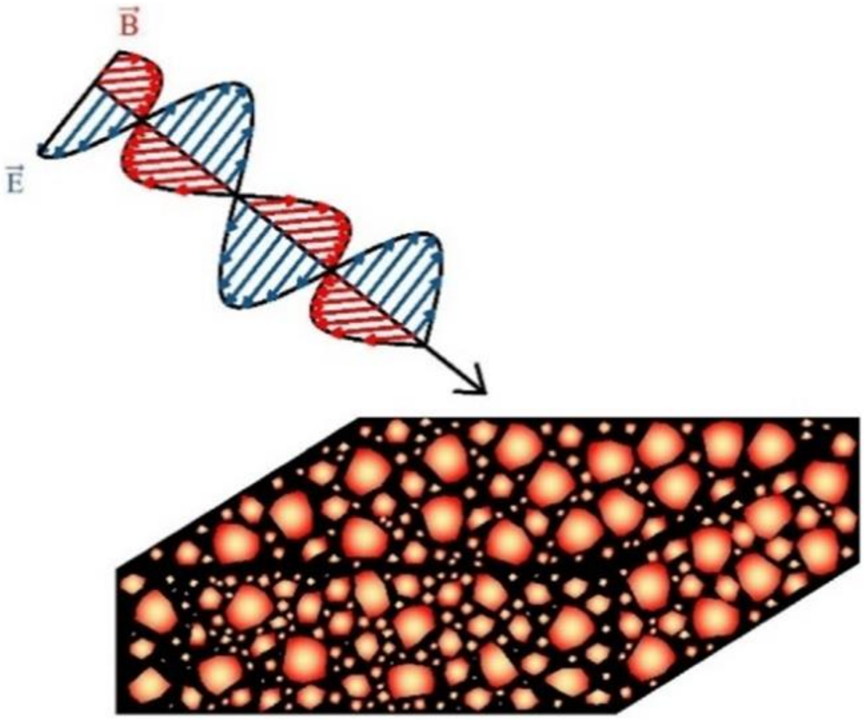

FIGURE 5. Microwave heating of asphalt pavements: primarily, the radiation heats the aggregates, (Gulisano & Gallego 2021,3).

The process of MH is the power consuming operation according to MH theory and practice. The required microwaves power consumption to heat a unit volume of material is given in Equation 1. Thus, the value of loss angle (tanδ) can be enhanced by adding microwave-sensitive additives to asphalt pavement. However, during penetration, microwave efficiency diminishes as the radiation passes in the vertical direction through the pavement (Gao et al. 2019 1113). Moreover, Jahanbakhsh, Karimi, Jahangiri & Nejad (2018, 656-666) concluded that the thinner specimens of asphalt pavement containing microwave sensitive additives have higher heating rates than that of specimens with the lower content of additives under similar heating conditions.

$$P = 0.556 f \varepsilon'_r \tan\delta \bullet E^2 \times 10^{-12} \qquad (1)$$

Where,

P = Power consumed on a per unit volume

f = Microwave frequency

E = Electric field intensity

ε'_r = Relative dielectric constant (a measurement of how much energy is contained in a substance as a result of an external electric field)

tanδ = loss angle constant (the material's ability to dissipate accumulated electromagnetic energy by turning it to heat)

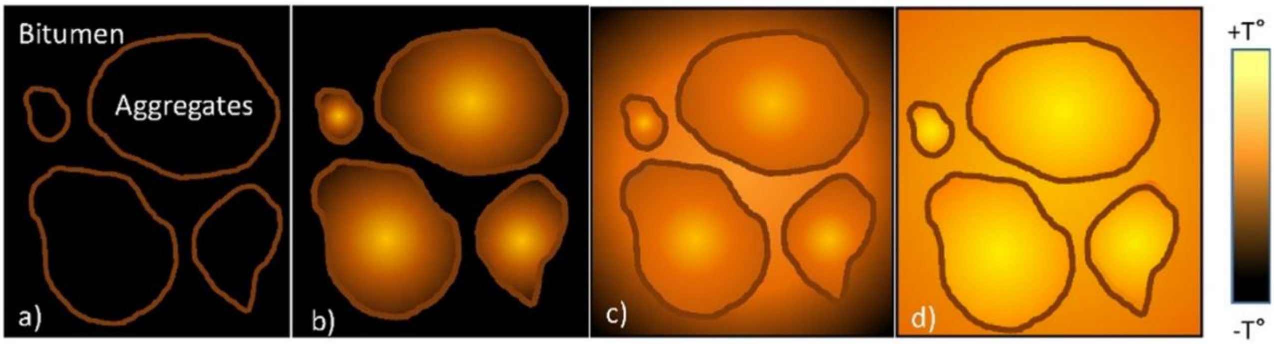

FIGURE 6. Scheme of the phases for the microwave heating of an asphalt mixture: a) Before radiation; b) The radiation heats the aggregates; c) The aggregates conduct heat to the bitumen around them; d) The entire asphalt mixture is heated (Gulisano & Gallego 2021)

(TABLE 2) shows the relative dielectric constant and loss angle constant of various materials. It shows that the relative dielectric constant of ice is only 3.2, and the value of the loss angle constant is 0.0009, which is relatively small. Therefore, it can be known from Equation (1) that when $\tan\delta$ is 0.0009, the power loss of microwaves in ice is minimal. However, the large portion of energy penetrated through the ice layer is absorbed by the surface of the road, a comparatively higher value of loss angle constant and relative dielectric constant. A certain percent of absorbed energy gets converted into heat energy, which detaches the layer between two surfaces. (Li, Sun, Liu, Fang, Wu, Tang, & Ye 2017, 1.) Moreover, if the asphalt mixture contains microwave energy absorbing components, the heat generation rate gets higher, resulting in quick ice melting (Ding et al. 2021, 2-3).

Furthermore, once the layer between ice and road gets weakened (which becomes slush), the melted water absorbs more microwave energy, raising its temperature, leading to an increase in the melting rate of snow. As a result, the bond stress on the two-layer contact surface decreases and eventually disappears, allowing snow to be separated from the asphalt surface with equipment or human resources. (Ding et al., 2021, 2-3.)

TABLE 2. Relative dielectric constant and loss angle constant of material (Ding et al., 2021, 2)

Material	Relative dielectric constant	Loss angle constant
Water	76.7	0.157
Ice	3.2	0.0009
Asphalt Concrete	4.5–6.5	0.015–0.036

3.2 Full-scale equipment and the procedures of microwave heating

MH technology in asphalt pavement has found several applications, including the heating of the asphalt mixture in the manufacturing process of asphalt pavement. In addition to that, the heating (healing or de-icing) of asphalt pavement is another proposed MH application in asphalt mixtures. However, not any practical implementation has been carried out so far. Nevertheless, several researchers have proposed procedures for studying MH in asphalt mixtures and patents and prototypes for large-scale operation. For the first time, the idea of using MH in the manufacturing process was proposed by Pickermann in 1981. The idea was to use the microwave heater for heating aggregates and bitumen in the manufacturing plant. In addition, the compact design of the microwave heater can make it transportable on-site whenever needed. In another prototype, in-service heating of asphalt pavement can be achieved when a vehicle equipped with a microwave generator is moved along the road. A pyramidal horn antenna is preferred mainly for heating the pavement. The MH device with different chambers is presented in (FIGURE 7). (Gulisano & Gallego 2021,8.)

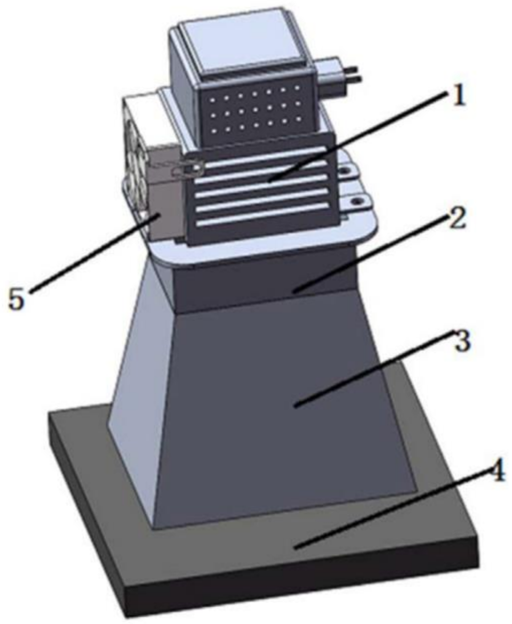

FIGURE 7. Microwave heating device with a single working chamber: 1) Magnetron, 2) Rectangular metal waveguide, 3) Radiation cavity, 4) Asphalt pavement, 5) Cooling fan (Gulisano & Gallego 2021,8)

The de-icing process using MH is completed in two principal stages. Firstly, voltage is generated using a transformer which helps in supplying power driving the magnetron to work. Then microwaves are radiated into the surface of the asphalt pavement through the rectangular metal waveguide. MH barely maintains the adhesion force of the freezing-thawing interface between asphalt pavements and ice. Heating time plays a vital role in de-icing the road, as lower heating time has less force to break the interface between two layers, and higher heating time leads to the refreezing of melted water under a lower temperature of the atmosphere. Secondly, the pulverized by crusher ice is removed from the road. The principal application of this process is for de-icing the road; however, with further research, a similar heating system can be used in other heating applications. (Gao et al. 2021, 1113.)

Sun and Chen (2017, 59-70.) investigated how different antenna conditions influence the temperature field distribution of an asphalt mixture. According to the findings, the antenna arrangement plays a significant role in asphalt heating. Furthermore, uniform heating necessitates antennas of similar short and long side dimensions. However, since the energy supply is directly proportional to the increase in temperature, heat is distributed unevenly across the asphalt pavement. Surprisingly, intermittent heat supply (at various times) resulted in uniform heating of the material but led to higher energy consumption. Finally, the author proposed that antenna criteria should be chosen based on parameters such as energy savings, maintenance quality specifications, and on-site work performance.

Academic researchers and industries jointly designed the MH de-icing prototype vehicle in China in 2000, and a commercial model is now available in the Chinese market (Yu, Li, Feng & Yi 2011, 933-940). A typical demonstration of an MH generator attached to the vehicle is presented in (FIGURE 8). The vehicle is equipped with essential equipment required for heating asphalt pavements such as crusher, shovel, magnetron matrix, and generator unit. Among various equipment, the magnetron matrix comprising 70 to 120 magnetrons is critical in heating the pavement with an area above $3m^2$. (Gao et al. 2021, 1113.)

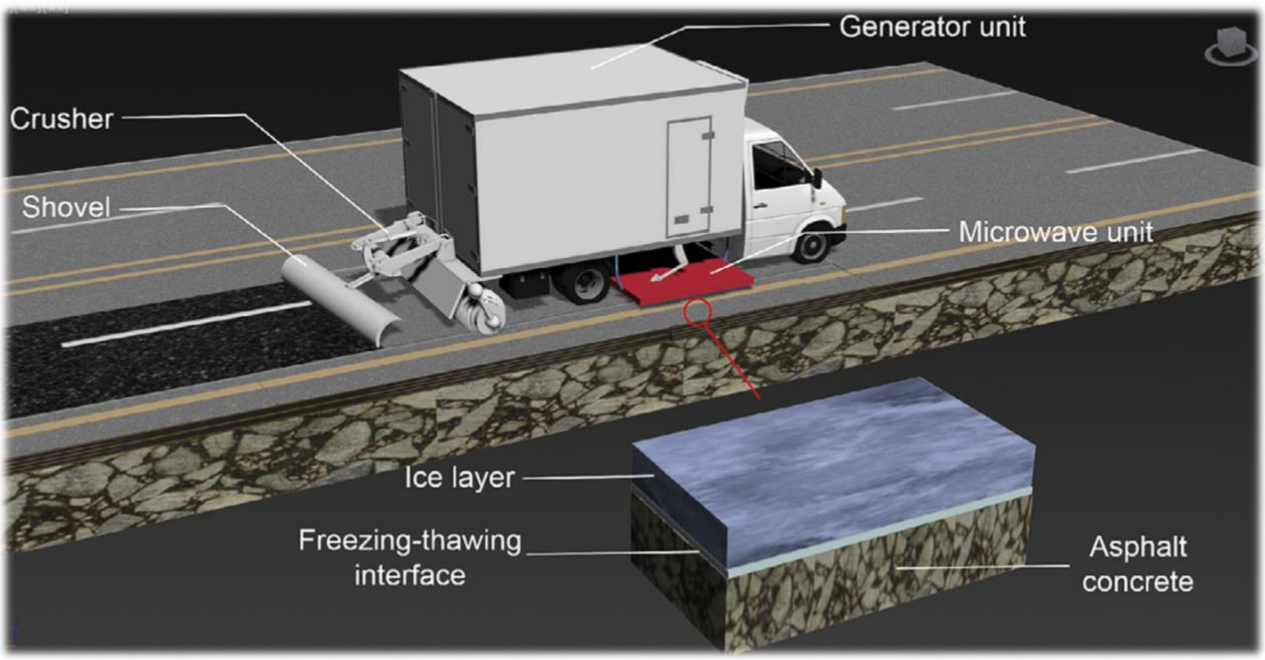

FIGURE 8. Prototype design for microwave heating de-icing vehicle (Gulisano & Gallego 2021,8)

Despite it being true that researchers have proposed prototypes for de-icing the asphalt pavement containing additives aggregates by means of MH, large-scale implementation and standards have not been developed yet. The effectiveness of the healing process, the thickness of the aggregates, and required heat distribution on the pavement on the full scale are based on laboratory-scale research. Even without implementation at the industrial level, the proposed prototypes and patents show a bright future in their approach to de-icing the asphalt pavement. (Gao et al. 2021, 1113.)

3.3 Safety issues of microwave technology

When carrying out microwave technology at an industrial level, the primary concern is for health issues of radiation exposure. Temperature-sensitive organs such as male testes and organs with low blood supply such as the eyes, according to World Health Organization (WHO), have a higher risk of absorbing heat leading to the damage of soft tissue (organs) on a long period of exposure to microwave radiation. In addition, the International Agency for Research on Cancer (IARC) in 2011 categorized 30 kHz to 300 GHz frequency spectrums as being carcinogenic to humans. In contrast, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) updated comprehensive literature on the subject in 2020, concluding that no evidence of the impact of radiofrequency electromagnetic fields on the induction or spread of cancer has been found. (Gulisano & Gallego 2021, 9.)

The maximum length of exposure to a microwave-radiated atmosphere and the maximum release or emission of microwave radiation are also important considerations in microwave radiation safety. ICNIRP defines the maximum amount of energy consumed per kilogram of tissue as 0.4 W/Kg. The human exposure limit for microwave radiation is expressed as a specific energy absorption rate (SAR). The International Electrotechnical Commission (IEC) defined a maximum power density of 5 mW/cm^2 when measured at 5 cm from the point where the leakage is at its highest degree. (Gulisano & Gallego 2021,9.)

4 NEW METHODOLOGY OF ASPHALT MIXTURE

Several aggregates such as waste metal content, ACP, steel and wool fibers, and magnetite are addressed in (TABLE 1) with their key findings from the literature review study. Although, most of the aggregates show a significant potential to be used in an asphalt pavement for the de-icing process. However, among these aggregates, this thesis focuses on the depth study of magnetite and steel fibers. In addition, more research and study of other aggregates in the future might show better MHE with lower cost and environmental impacts. Thus, every possible aggregate should be examined before choosing one to be used in the pavement for de-icing mechanism in winter road maintenance.

4.1 Steel fiber, steel slag and steel wool fibers asphalt mixture

Various authors have recognized the importance of steel slag, steel wool, and steel fiber modified andesite as aggregates in asphalt pavement. Ultimately, the term steel-modified fiber will be used in the following chapters to simplify the original term (steel fiber modified andesite). To date, some authors have also suggested that steel-modified fiber is a better substitute in asphalt mixtures as an aggregate prior to steel slag while other authors have further developed the idea of steel wool. By and large, those aggregates have been discussed by a considerable number of authors in literature. In the following sections, these aggregates are covered based on several tests, including the surface temperature test, ice-thawing time test, heating durability, and three-point bending.

4.1.1 Characteristics of steel aggregates

Gao, Sha, Wang, Tong & Liu (2017, 433), compared the advantage of steel slag over carbon fiber, carbonyl iron powder, low-grade magnetite, and steel fiber and concluded that steel slag asphalt aggregate is environmentally friendly and has a lower construction cost. In contrast, a recent study conducted by Gao et al. (2019, 1111) identified the advantages of steel-modified fiber. A recent study noted, “the asphalt concrete containing an optimal amount (0.4 wt%, 0.1 mm diameter) of steel-modified fibers has seen significant improvement in specimen stability, rutting resistance, indirect tensile strength, and low temperature cracking resistance compared to conventional asphalt concrete” (Gao et al. 2019, 1111). Another form of steel fiber is steel wool with a slight difference in physical properties (has a smaller diameter). The particle loss resistance and flexural strength of dense asphalt concrete are other advantages of steel fiber and steel wool. However, a slight difference in the physical properties causes clustering in steel wool; in this case, the MHE deteriorates. Therefore, it is essential to prevent high air voids in the asphalt mixture by adjusting the percentage of aggregates and bitumen used to avoid clustering when steel wool is used. On the other hand, the use of steel slag can be employed from industrial waste; thus, the asphalt pavement containing steel slag not only gives better performance for MH application it can also help alleviate the supply shortage of natural raw materials besides improving road traffic safety in the winter (Gao et al. 2017, 432).

In their literature review, Gao et al. (2017, 436.) deduced that MH behavior for common minerals are classified as "hyperactive (Fe_3O_4), active (Fe_2O_3 and FeS), difficult-to-heat (MaO and Al_2O_3), and inactive (SiO_2 and CaO)." Furthermore, the authors pointed out that higher iron content in inorganic or mineral compounds shows a higher conversion rate of microwave energy to heat energy (see FIGURE 9). Additionally, steel slag consists of black calcium silicate phase ($3CaO \cdot MgO \cdot 2SiO_2$, $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot 2SiO_2$, $CaO \cdot SiO_2$), gray calcium-iron phase ($CaO \cdot Fe_2O_3$,), and white iron-magnesium phase (Fe_2O_3, MgO). With this in mind, steel slag involves several minerals, including magnetite, considered hyperactive for MH. Finally, the authors provide evidence that the amount of iron in steel slag is between (43.60%–83.54%), which is the highest among the compounds mentioned earlier. Hence, the most active ingredient for microwaving is white iron magnesium in steel slag. Since, magnetite is the hyperactive component which shows promising heating rate efficiency. Chapter 4.2 of this thesis describes the characteristics of magnetite for microwave heating for the de-icing mechanism in depth.

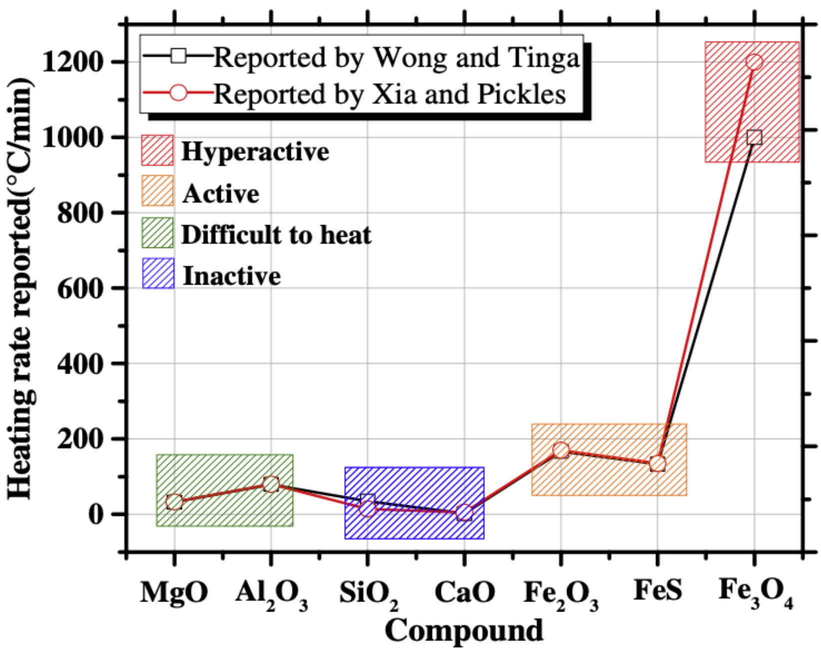

FIGURE 9. Microwave heating behavior of common metal oxides (Gao et al. 2017, 433)

4.1.2 Examination of asphalt specimen via various test

Gao et al. (2019, 1112) conducted several tests, including the surface temperature test, ice-thawing time test, heating durability into the asphalt mixture containing steel wool. These tests were carried out to simulate a similar environment whereby the MH of pavement is experienced in the de-icing process for the asphalt pavement. The ice-thawing efficiency of MH is decreased with lower initial temperature; however, the ice layer thickness has only a minor impact on the ice-thawing efficiency. Other researchers made the same test on asphalt mixtures containing steel slag, where tests show the initial surrounding temperature directly affecting the microwave thawing efficiency. It was found that the lower initial temperature has lower microwave thawing efficiency than that of the slightly higher initial surrounding temperature.

Moreover, the addition of steel slag showed higher microwave thawing efficiency in the contact surface between ice and tested specimen (Gao et al. 2017, 441). Prior researchers by Gao et al. (2019, 1112) provided evidence that despite the steel wool type, the heating uniformity of specimens declines as the steel wool content increases. Consequently, the heating uniformity of the asphalt mixture can be enhanced by increasing the diameter of the steel wool. Although results appear consistent with prior research, they seem inconsistent with the durability of the heating capacity test. Their review highlighted that the steel wool is wrapped in the asphalt mortar, isolating it from its surrounding environment. Therefore, the authors assumed that a steel wool asphalt mixture is durable under adverse conditions. Additional studies are required to understand the crucial tenets of the durability of asphalt pavement containing steel wool content on a large scale.

However, other researchers (Sun et al. 2018, 874), have looked at the ice thawing efficiency for asphalt mixtures containing steel-modified fiber and steel slag, including 5 mm, 10mm, and 15mm ice thickness on the surface of specimens. In contrast, only 15 mm snow thickness was placed on the top surface of tested specimens. The initial temperature of specimens holds roughly at –20 ºC, then MH was applied at room temperature 9 ºC for 120s. The heat was applied for 120s on the specimens by maintaining a break of 10s every 20s. Given that, the authors argued, “this is because the microwave oven was a closed environment during heating. It needs some time to measure and record the test data during the microwave heating test” (Sun et al. 2018, 874). If the bonding force between the bottom surface of the ice and the top surface of asphalt pavement detaches, ice can be easily removed from the pavement. In addition to this, immediate removal of ice after being separated from the pavement before it gets frozen again will lead to lower energy and cost consumption. (Sun et al. 2018, 874.)

Nevertheless, it is well-known from the literature that steel wool or steel fiber gets corroded in coastal atmospheric environments due to (NaCl) and acidic rain ($NaHSO_3$), (Marcos-Meson, Michel, Solgaard, Fischer, Edvardsen, & Skovhus, 2018, 5). Under such circumstances, applying asphalt mixtures with steel wool aggregates as a road pavement does not serve well for lower maintenance category (i.e., Ise, Is, I), mainly when slightly more slippery conditions may occur, and NaCl treatment should be used instead of MH treatment. When asphalt pavement is confronted by acid rain, it might be truer that it will deteriorate the pavement's life span due to the corrosion of the additive aggregates. However, this assumption needs to be verified, as also noted by the authors in their work.

Other researchers (Sun et al. 2018, 876) employed a three-point bending test methodology on steel fiber and steel slag, which prescribes the measure of the healing performance on a self-healing asphalt mixture. The volume of bitumen and mixing ratio of steel-modified fiber and steel slag were kept at 6.0% and the asphalt-aggregate ratio at 5.3% in the preparation of two types of specimens. The test was done under 80 ºC for 30 min, and the result showed that the samples fractured at -20 ºC with Dynamic Mechanical Analyzer after the melting process. Although this thesis does not highlight the induction heating, the self-healing from cracking with the induction heating principle was analyzed from the Sun et al.'s test to determine whether the asphalt mixture containing steel fiber or steel slag indicates a remarkable result.

Also, the recent research suggests that the electric energy (Q electric) heated the asphalt specimens (Q heat), then both of (Q melt & Q healing) was influenced by the heat energy (Q heat) as in (FIGURE 10). However, the same authors confirmed that measuring the micro-cracks of the asphalt mixture with this heating consistency was very challenging due to the uniformity of the temperature of the asphalt mixture. Therefore, the authors proposed that, after the melting process, another heating process should aid in the healing of healing cracks and keep melted snow and ice water from freezing on the pavement (Sun et al. 2018, 876). Finally, another promising line of research could be to find out the measure of the heating efficiency and measure of the micro-cracks with the MH mechanism. Additionally, the authors believe that self-healing performance with MH did not show promising results unless the second heating process would be applied after the de-icing process.

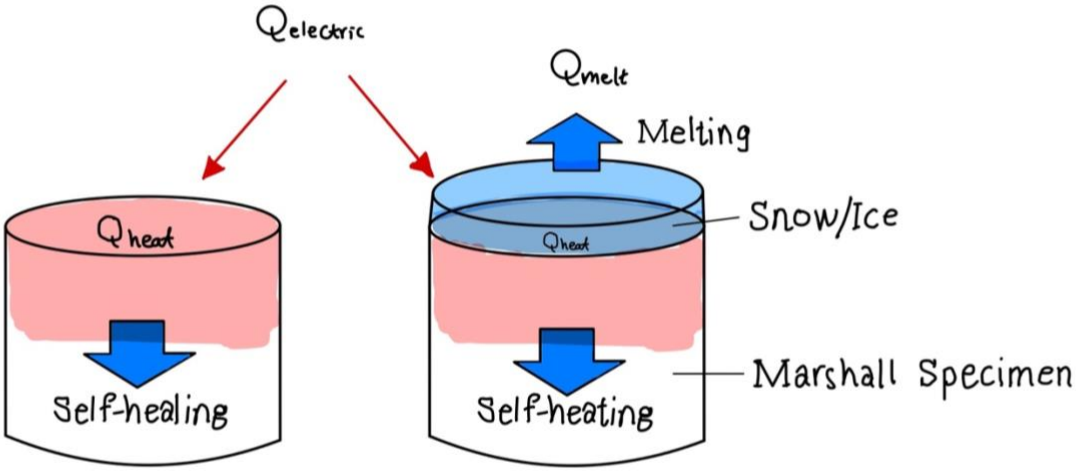

FIGURE 10. The schematic diagram of self-healing (Left) and ice melting test (Right)

4.1.3 Microwave heating efficiency

Generally, the MH rate of asphalt pavements is influenced by various factors as lowering the thickness of the specimen and height between pavement and the microwave radiating device leads to a higher heating rate. Moreover, the higher induced energy density and lower penetration depth of the radiated microwave results in a higher heating rate. (Gao et al. 2019, 1113.)

Sun et al. (2018, 878) analyzed the data in their experiment of the heating performance of steel-modified fiber and steel slag asphalt mixtures. The result revealed that after the 80s of MH, the average temperature of the steel-modified fiber asphalt specimen rose from -12.8 ºC to 20.00 ºC with the highest surface temperature of 35.9 ºC. On the other hand, steel slag asphalt mixtures showed the average temperature of MH heating from -11.2 ºC to 9.7 ºC with the highest surface temperature of 5.9 ºC. Consequently, MH of steel-modified fiber asphalt mixtures shows better performance mainly because the water could quickly be heated by the microwaves when the interface between ice and the asphalt mixture turns to free water due to its higher temperature range (see FIGURE 11). Since the average surface temperature of steel-modified fiber is higher than the one in the steel slag asphalt mixture, more free water is released in this respect. This melted water had further heated mainly due to microwave radiation enhancing the heating rate of the water. In contrast, the initial heating rate of the steel slag asphalt mixture is slower; thus, the overall heating rate decreases, causing less free water. (Sun et al. 2018, 878.) All in all, there seems to be some evidence to indicate that MH of water at the interface between ice and asphalt played an essential role in the ice melting process with MH.

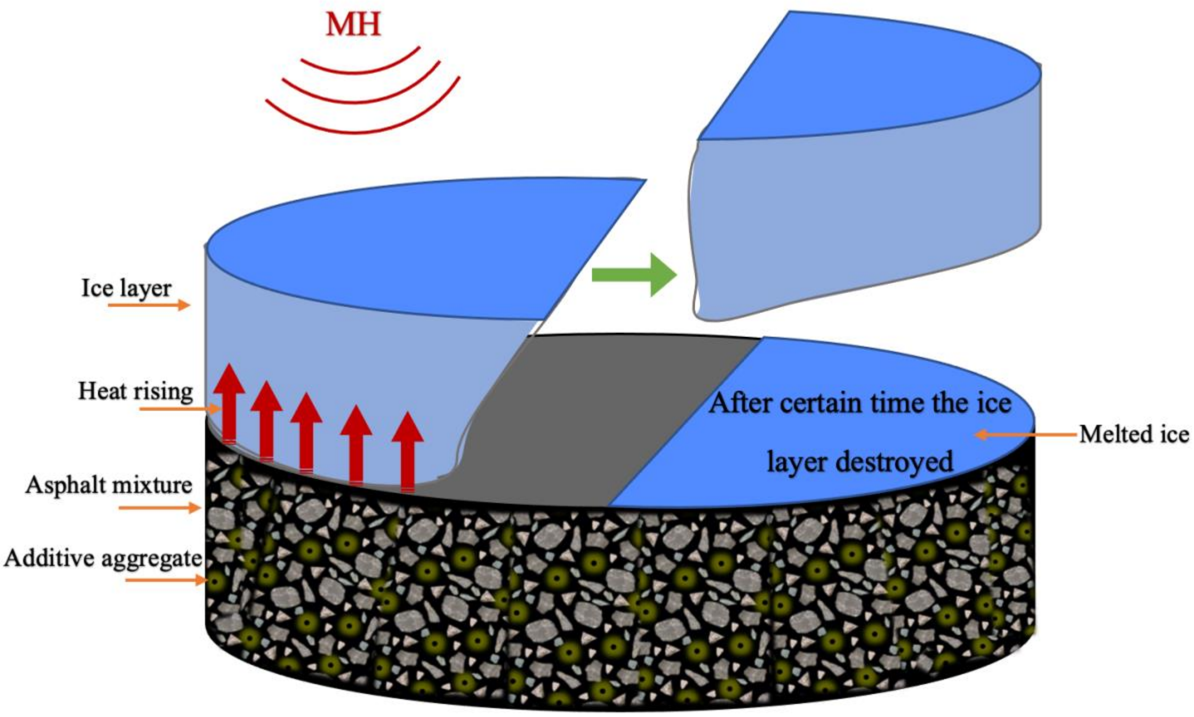

FIGURE 11. The effect of MH on ice layer on the top surface of asphalt pavement containing additive aggregates

The steel-modified fiber asphalt mixture shows the highest average melting velocity of 24.1 g/min; whereas, that steel slag is 18.5 g/min. That summarized the best MH performance of steel-modified fiber asphalt mixture over steel slag. The thickness of the ice has a travel effect on the ice melting process, (Sun et al. 2018, 880). However, the study addresses several further questions on the distance between the asphalt mixture and the heating equipment.

Since the water from melted ice was crucial in the de-icing process because it could be heated quickly by microwave radiation, snow's melting process shows a faster melting rate than the ice-melting process. With MH, the average melting velocity of snow for steel-modified fiber asphalt mixture and steel slag asphalt mixture was 53.9 g/min and 48.5 g/min respectively, with MH power at 800 W with the snow thickness of 15 mm, (Sun et al. 2018, 881-882). However, several questions regarding the exact volume of aggregate required for a certain thickness of snow, energy efficiency, and cost analysis on a large scale remain to be addressed.

Gao et al. (2019, 1117) conducted an experiment in MH performance for the asphalt mixture with different steel wool fiber specimens at an initial temperature of 18 ºC. The result showed that the surface temperature increased with the relative increase in radiation time regardless of steel wool content or type. More precisely, the addition of steel wool fiber in the asphalt mixture increased the surface temperature of the asphalt pavement. Technically speaking, 0.3% of steel wool content in the asphalt mixture reached 97.4 ºC with 180s of MH, whereas with 0% steel wool content it had only reached 24.8 ºC. Paradoxically, the surface temperature increased as the steel wool content increased, but it decreased nonetheless, after it got to a specific substance content. Granted this, one of the specimens with 0.9% reached 127.8 ºC, and exceeded 128.5 ºC with 1.0%; however, the surface temperature declined to 114 ºC in the one with 1.3% of steel wool content. Furthermore, García et al. (2014, 12) observed clustering in the asphalt mixture when the high content of steel wool had been applied. Consequently, justification for those remains in that a cluster will reflect electromagnetic waves, in other words, more cluster equals low heat.

Although the frequency was not mentioned in the research experiment, the authors highlighted the effect of time on the surface temperature. Given that, the authors pointed out that the rate of temperature rise decreases as the radiation time increases, even though more extended radiation will result in higher surface temperatures. However, the effect becomes less noticeable as the radiation time increases. (Gao et al. 2019, 1119.)

Gao et al. (2019, 1116) provided evidence that the integration of steel wool within the asphalt mixture showed an increase in air voids despite the fiber content and fiber type. Besides increasing aggregate volume in the specimen, decreasing the thickness of the asphalt specimen also resulted in higher air voids. García, Norambuena-Contreras, & Partl (2014, 12) confirmed that durability in the particles' mass declined when the high air voids got higher. Under these circumstances, Gao et al. (2019, 1116) draw their conclusion to not use more than 0.9% volume of fibers in the asphalt mixture, since clusters have a high surface area and act as a (sponge) in bitumen reducing its ability to catch the aggregates. Consequently, the amount of cluster increased when increasing the volume of steel fiber (Garcia et al. 2014, 12).

4.2 Magnetite as an aggregate

Various studies have been conducted on a laboratory scale to investigate the effect of magnetite aggregates in asphalt pavement for de-icing mechanisms. This section examines the various factors, including the effect on the rise in temperature, heat generation, packing density, particle size due to magnetite as a hyperactive compound in asphalt pavement, based on different scientific papers.

Furthermore, in this chapter, the magnetite will be analyzed from different perspectives based on the thesis's methodology, presented in (TABLE 1); additionally, the gaps/shortcomings revealed will be discussed in depth.

4.2.1 Microwave heating efficiency of magnetite due to particle size

Wang et al. (2016, 592) conducted two experiments for both magnetite and basalt as an additive aggregate in asphalt pavement for the 30s of MH. The result showed that the surface temperature of the asphalt specimen rose by 25.1 °C when the basalt was used. However, by substituting that with magnetite, the surface temperature rose significantly to 155.2 ºC. Remarkably, the MHE of magnetite additives was 5.17°C/s and consequently, of basalt additives 0.84°C/s, which revealed that the MHE of the magnetite additive is 6.15 times than that of the latter. However, Wang et al. (2016, 592) did not present the effect of particle size on the MHE. In another study by Guo et al. (2020, 8), the effect of particle size is addressed. The findings from that study showed that the increased particle size had a positive effect on MHE when MH was applied for 180s on the magnetite additives. The correlation between the MHE and particle size is divided into three subcategories concerning the filler: with a size of 1.15 mm in a positive correlation, 1.15 mm to 1.18 mm negatively correlated, and 1.8 mm to 13.2 mm positively correlated. Amongst the aggregates, particle sizes ranging from 4.75 to 9.5 mm, 9.5 mm to 13.2 mm, and 13.2 mm to 16 mm, showed the highest MHE. Besides these findings, the reason for the higher MHE due to particle size has not been clarified.

Moreover, the asphalt mixture with magnetite as an additive aggregate can reach strong penetration with microwaves at 2.45 GHz frequency, and 12.24 wavelength applied for a short period for optimum heating efficiency. Previous studies have almost exclusively focused on the size of additives and their effect on MH; however, the gap between the effect on MHE due to particle size and applied frequency needs to be covered in future studies to enrich the probability of implementing magnetite in the asphalt pavement for de-icing. Provided this, we assume the outcome will lead to lower energy consumption and a faster heating rate of the asphalt pavement. (Zheng, Zhang, Liu, Jia, Tang & Zhang 2020, 22-29.)

On the other hand, material properties, physical characteristics, and the electromagnetic field to which the particle is exposed determine the MH rate. For instance, the microwave absorbing rate differs from the bulk and powder stages of additives. Furthermore, the dielectric property of the material is directly proportional to the packing density as the rate of heating goes higher when the space between the pores gets lower by increasing the induced current density of the sample. Thus, if the gap between the powder is infinitely lowered, the rate of heating increases. (Zheng et al. 2020, 22-29.)

Moreover, the presence of the main component of magnetite, Fe_3O_4, was found to reduce MHE in two studies (Wang et al. 2016, 592; Guo et al. 2020, 8). At a high temperature, magnetite reacts with air to form Fe_2O_3 which has a low magnetic loss; where, the primary mechanism of MH below Curie points of 585 °C. Furthermore, the rate of MHE declines as particle size decreases due to increased exposure to air, resulting in a higher Fe_3O_4 to Fe_2O_3 conversion (Wang et al. 2016, 592; Guo et al. 2020, 8). These findings conclude that the bigger size of aggregates leads to higher heating efficiency; it should also be considered that the increase in particle size will lead to an increase in the space/gap between pores, therefore reducing heat transfer. These are circumstances needed to be taken into account when using aggregates in asphalt pavements.

4.2.2 Microwave De-icing time

The relation between magnetite layer thickness (MALT) and de-icing time was studied by Guo et al. (2020, 13). This research has provided evidence that reducing the MALT decreases de-icing time. It was observed that the magnetite content of 30%, 50%, and 70% showed a de-icing time of 93.8%, 89%, and 68.9% respectively, at an initial temperature of -5 °C. Moreover, at an initial temperature of -20 °C, the de-icing time was 94.4%, 75.9%, and 51.5% in a similar volume of magnetite content. After analyzing the heating efficiency, the heat transfer rate, and minimum de-icing time, the authors concluded the specimen with 30% magnetite content had the optimum design for microwave de-icing technology. (Guo et al. 2020, 13.)

In contrast, according to Wang et al. (2016, 595), microwave de-icing time (MDT) decreases (as magnetite content is increased up to 80%) then rises due to the lower microwave absorbing ability. The literature explains that MDT at -5°C, at magnetite content 0%, is 242s, whereas when at 80%, it drops to 28s. Similarly, under the same magnetite content in an asphalt specimen, MDT was 275s and 34s at -10 °C; 354s and 56s at -15 °C.

In summary, several authors have considered the effects of the MDT increases with a decrease in the surrounding temperature (Guo et al. 2020,13; Wang et al. 2019, 9; Wang et al. 2016, 595). Additionally, Wang et al. (2019, 9.) address that the MDT is 15-20% higher at -20 °C than at -5 °C. The authors include that ice thickness does not profoundly influence de-icing time, which is the opposite of what they obtained from their findings. However, they do point out that the result obtained might be due to experimental errors. Albeit many authors have conducted studies, this problem is still insufficiently explored.

4.2.3 Reflection loss

According to Wang et al.'s (2016, 593) study of reflection loss during MH in asphalt pavement with magnetite as an additive aggregate, they found that the reflectivity decreases while increasing magnetite content up to 80%, then gradually increases. Another study conducted by (Guan, Liu, Zhao, Wu, Liu & Yang 2019, 10-11) revealed that the height of asphalt pavement and magnetite content on asphalt pavement affects the microwaves reflection loss. The experimental research concluded that the small height of pavement results in lower reflection losses, thus optimizing the heating efficiency of asphalt pavement. Together, these studies indicate that the magnetite content, the height of pavement, and applied frequency on asphalt pavement leads to microwaves reflection loss. However, the frequency of the microwaves' absorbing ability of different additives may differ from each other, showing that different frequencies should be applied based on the aggregates and the height of asphalt pavements. Hence, optimal absorbance efficiency can be reached when a matching thickness of the magnetite layer is exposed to microwaves radiation at a matching wavelength. The gap existing in the literature between the matching thickness and frequency should be covered to ensure the application of microwave de-icing technology on a large scale.

4.2.4 Low temperature properties of aggregates

The Low-temperature properties of the asphalt mixture with magnetite were studied with a three-point bending test. (Guan et al. 2019, 8) researched to determine the maximum bending tensile strength, maximum tensile strength, and bending stiffness module. The result demonstrated that the addition of magnetite slightly enhances the bending stress of asphalt specimen at low temperatures. In addition, tensile strain at a low temperature increased with the addition of magnetite powder in asphalt specimens showing a favorable impact on deformation capacity. Moreover, the bending stiffness of the asphalt specimen increased by increasing the magnetite up to 20%, however, it decreased on further addition of the same compound. A similar result was obtained by Wang et al. (2016, 397), showing that increasing magnetite tailings in asphalt mixture decrease the splitting strength at -10 °C with different additive compositions.

This study leaves many compelling questions behind for further researched to fill the missing gaps. For example, the optimal percentage of magnetite needed to be used, the height of the pavement to resist lower temperature properties, the required frequency of microwave to be induced. Additionally, the effect on different tests remains to be verified for determining the maximum bending tensile strength, maximum tensile strength, and bending stiffness module.

4.2.5 Radiation depth

If the rate of microwave radiation time increases, the radiation depth in the asphalt pavement increases, and a lower radiation depth can be obtained by raising the applied frequency of the electromagnetic waves (Gao et al. 2018, 1114). A series of recent studies have indicated that increases in aggregate volume in asphalt pavement led to increased radiation depth. In contrast, the findings from the research conducted by (Guo et al. 2020, 10-11) showed similar radiation depth regardless of the volume of magnetite in the asphalt specimen. The authors believed that the result obtained was due to the higher thermal conductivity of the lower layer of specimens. Magnetite has a higher porosity than limestone, and in principle, thermal conductivity depends on the porosity in the asphalt mixture. Furthermore, this phenomenon creates a confusion as to determining the radiation depth, due to heat transfer from the upper surface to the lower. Lowering heat transfer from the surface layer to the deeper layer is necessary for an efficient de-icing mechanism. Although many authors have conducted studies, this problem is still insufficiently explored, which needs to be covered in future research to understand the behavior of the thermal conductivity of additives in asphalt mixture and radiation depth.

4.2.6 Water sensitivity of asphalt pavement

The water sensitivity of the asphalt specimen using limestone and magnetite aggregate was determined by (Guan et al. 2019, 9) with a tensile strength ratio (TSR) test. Limestone, on the one hand, showed an increasing ratio in the TSR test. According to the literature, the higher TSR was due to the rough, small size, and larger surface area of limestone than that of magnetite. These characteristics of limestone made it easier to absorb and stabilize the interface by increasing the area between asphalt and filler. Moreover, the higher content of calcite ($CaCO_3$) in limestone reacted with the acidic compounds of asphalt, improving the cohesion of the asphalt mixture; therefore, increasing the water sensitivity of the pavement. On the other hand, the smooth surface of magnetite particles used in the experiment made it harder to stabilize the interface leading to lower water sensitivity. Hence, the volume of magnetite used should be controlled to improve the water sensitivity. In another study Wang et al. (2016, 397-398.)

concluded that a similar phenomenon occurred in a decrease of water stability due to the increase of magnetite tailings as additives in the asphalt specimen. However, when hydronated lime (1.2%) was used with magnetite tailings in asphalt specimens, surprising increases in water sensitivity were obtained by an average of 10%. The value of TSR was above 80% in all the results, the minimum requirement based on Chinese road standard specification.

In addition, based on different test methods, the authors concluded that magnetite as aggregates does not result in toxicity, which helps to utilize the leftover magnetite content from ores in asphalt pavement. Thus, they can be used as a microwave-sensitive material for de-icing method. However, in addition to these findings, several questions regarding the properties such as segregation, uniaxial compression, fatigue, air void content and its effect, and dynamic modules of the asphalt mixture containing magnetite as an additive and its effect on low-temperature properties remained to be addressed.

5 POLICY OF WINTER ROAD MAINTENANCE IN FINLAND

In Finland, the Transport Infrastructure Agency and the Centers for Economic Development, Transportation, and the Environment keep the roads in proper working order. The winter road maintenance scheme follows the principles outlined in the winter maintenance plan. In 2018, the latest winter road maintenance plan was revised, and new contracts for the years 2019 to 2023 were authorized. (Finnish Transport Infrastructure Agency.)

According to winter road maintenance policy, snowplowing begins on the busiest highways and moves to pedestrian and biking paths. Antiskid treatment is applied to plowed snow, and snow thickness should not exceed a few centimeters. Once snowfalls stop, the law states that the snow must be cleared from major highways, walking, and cycling routes within three and four hours, respectively. Snow should be cleared from low-traffic roads within six hours, and the thickness should not exceed ten centimeters. (Finnish Transport Infrastructure Agency.)

In winter road repair, the anti-skid treatment on the icy road is dependent on the weather forecast. Various forms of chloride salts such as sodium chloride, potassium chloride, calcium chloride, and ammonium chloride are used for busy de-icing paths. In low-traffic asphalt pavements; however, gritting or roughening of the road surface is used. Anti-skid road maintenance occurs on the main routes, where treatment must be completed within two to three hours of the first occurrence of slipperiness. In pedestrian and bicycle paths, the level of slipperiness is supervised and defined as a minimum level of slipperiness. Similarly, snow from low-traffic roads must be cleared before six hours. However, anti-skid treatment may take longer than average in inclement weather. Furthermore, the new winter road maintenance policy came into practice from autumn 2019, aiming to reduce the maximum anti-skid treatment time of non-busy roads by one hour. In addition, the snow removal time for medium-traffic roads is also shortened, and the same policy is projected to be applied in the upcoming years. (Finnish Transport Infrastructure Agency.)

5.1 Winter road maintenance categories

The quality of service supplied for snow removal in the winter is determined by the traffic volume and road composition. Under a certain budget, it is impossible to maintain the good condition of every road within a limited time frame, therefore, roads are classified into various maintenance categories. (TABLE 3) depicts the different types of winter road maintenance divisions, along with their length (km), the proportion of heavy and light traffic, and the type of maintenance service offered (Finnish Transport Infrastructure Agency).

TABLE 3. Winter Road maintenance divisions

Category of road	**Length (km) based on the % of the total road**	**Light traffic (%)**	**Heavy traffic (%)**	**Maintenance technique**
Ise	1523 (2%)	31	28	• Salt is used for increasing the friction besides its function as de-icing • Maintenance is difficult in some weather conditions.
Is	7484 (10%)	37%	42%	• Chemical (mainly salt) is the main anti-slipping procedure used • Packed snow may exist however doesn’t influence the traffic safety
I	519 (1%)	2%	2%	• Slating is the main anti-slipping procedure used • Road is almost completely free of ice
Ib	13517 (17%)	18%	18%	• Salt is used in limited amounts in whatever conditions roads are slippery Ise, Is and I. • Good condition of road is mentioned except in very bad conditions
IC	1685 (2%)	2%	1%	• Salt is used only if the condition is devastating • Traction is not good and safety measures should be applied for safe driving
II	15113 (19%)	7%	5%	• Sand is used rather than salt to increase the friction • Sufficient traction for safe driving is mentioned
III	38111 (49%)	4%	4%	• Sand or roughening of road is done to increase the friction • Maintenance quality is similar as that of category II

5.2 Cost of removing snow in Finland

Currently, the overall cost of winter road maintenance of state roads in Finland per winter is around 99 million euros. This indicates that the maintenance cost per kilometer is almost 1270 €. Besides this, Finnish Transport Agency is facing challenges and unsatisfactory outcomes from maintenance category III. (Snow and Ice Databook 2018, 98.) By taking the current economy and challenges into consideration, the assumption is made that using microwave de-icing technology for removing ice/snow will mitigate the cost with satisfying responses from the people. However, this assumption needs to be verified as there is no actual implementation of this technology yet. Further studies will support verifying this statement.

5.3 Road Network and traffic

Roads contribute great importance in Finland as most of the large area is sparsely populated, and roadways account for 67% of freight transport. Out of 70,000 km of the public road, 50,745 km has been paved with asphalt. Winter maintenance is given a high priority to make the road usable throughout the country with a lower risk of traffic issues. However, destructive climate change is making winter maintenance more challenging, mostly in northern and eastern Finland. Anti-icing is given more priority in the southern and western parts of the country due to the coastal climate. However, in the eastern and northern parts, where the climate is continental, snow removal is the principal concern. (Snow and Ice Databook 2018, 92.)

5.4 Organization

The governmental organization Finnish Transport Agency (väylä) is the central body governing the management of public roads all over the country. However, the municipality is responsible for the maintenance of city roads, and the private road is the responsibility of landowners. Based on the quality standards and responsibility of the winter road maintenance, the service is ordered from contractors. It is the responsibility of contractors to take a decision and make a plan for choosing the suitable equipment and maintenance actions to be implemented. Certain requirements need to be fulfilled when using anti-icing materials by contractors. It is necessary to use only moistened salt and brine to improve the friction. Calcium chloride is used in a very small amount on roads covered with black ice. However, potassium formate is preferred more than sodium chlorite and used in an aquifer area as it is believed that it does not cause heavy corrosion and degrades before reaching groundwater. (Snow and Ice Databook 2018, 96.)

The regional implementation and development work related to the operation of winter maintenance is governed by regional centers for Economic Development, Transport, and the Environment (ELY centers). Policy, quality standards, and guidance are implemented by the Finnish Transport Agency. At the same time, competitive biddings and economical payment to the contractors are handled by regional ELY centers. The service of winter and summer maintenance is ordered by ELY center (clients) from contractors based on the price offered. Under the guidance of the Finnish Transport Agency, four ELY centers order the maintenance to different parts of the country. However, nine ELY centers are responsible for the traffic. There are altogether 79 regional contracts and are responsible for the maintenance of 450-2300 km of road. (Snow and Ice Databook 2018, 96.) The organizational structure of winter road maintenance in Finland is depicted in (FIGURE 12).

Currently, developing the friction meter to measure the friction of the road in winter is the concern of the road authorities, quality control consultants, and private winter maintenance contractors. All these authorities are currently developing new methods of friction measurement in the winter roads. However, a new approach to de-icing is needed for an efficient and environmentally friendly ice removal mechanism. Though the use of microwave de-icing technology for removing snow is in the early stage of development, it shows a promising future. Consequently, more research and funding from the government and different organizations need to be provided in this field.

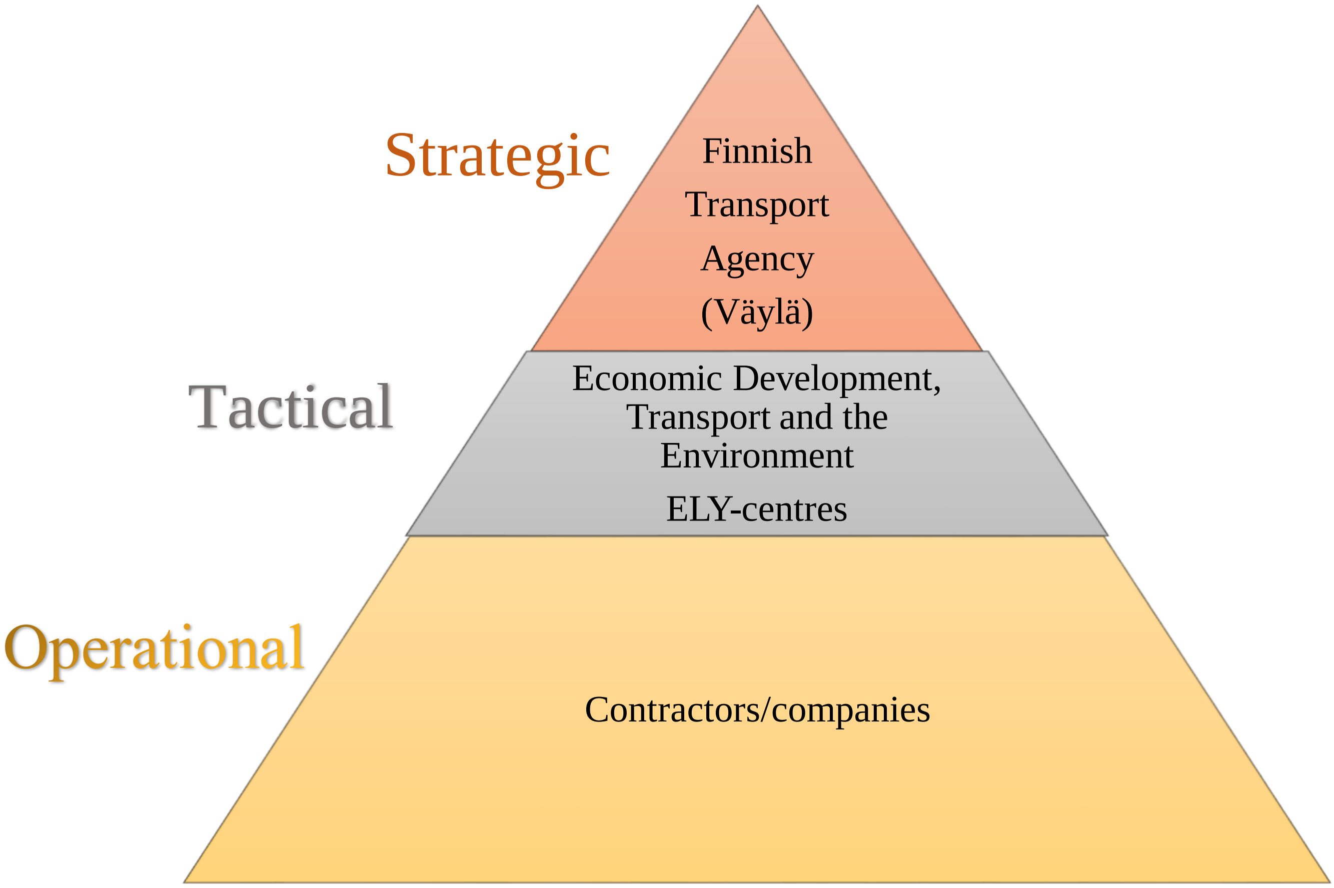

FIGURE 12. Organizational structure of winter road maintenance

6 FINDINGS/ EVALUATION

The findings from the literature review of steel fibers and magnetite, including their behavior under MH technology as well as their implication for Finnish road infrastructure, are discussed in depth in the following chapter.

6.1 MH applications for Steel fibers

According to Guo & Shi (2013, 1265), China's industrial solid waste from the iron and steel industry accounted for roughly 31% of the total annual accumulation of waste. That waste is estimated to be over one billion tons of steel slag, and the authors argue that less than 50% of these accumulations cannot be recycled (Gao et al. 2017, 429). Furthermore, Guo & Shi (2013, 1265) concluded that the reason behind the pollutions of soil, surface water, and underground water are triggered by the discarding of solid waste. However, using this steel waste as an aggregate has several benefits: it gives higher stuffiness to asphalt pavement, lower permanent deformation, better fatigue, aging, and better abrasion resistance (Gao et al. 2017, 429-430). Under those circumstances, the addition of steel to the asphalt mixture as the aggregate not only mitigates environmental issues but also enhances asphalt pavement durability.

Regardless of steel wool or steel slag, the ice-thawing efficiency decreases with the lower initial temperature. For instance, Gao et al. (2019, 1119) conducted a series of tests on an asphalt mixture containing steel wool. The finding of this experiment is that in 0.3% content, the ice-thawing time reaches 68s with -5 ºC and 92s with -10 ºC. That summarizes the initial temperature influence for the ice-thawing efficiency. By and large, the bottom surface of the ice/snow and the top surface of the asphalt concrete is the only interface set between both (See FIGURE 11); when this set is detached, the ice/snow can easily be removed by snowplows; hence less energy consumption will be required (Sun et al. 2018, 873). From the short review above, a key finding emerges that it is more efficient to remove ice when it is solid than to melt it because the water will be frozen again; thus, more energy will be needed to break the interface. Therefore, detaching the layer of ice/snow from the asphalt concrete is one of the main objectives of microwave heating to keep the process efficient.

Moreover, Sun et al. (2018, 873), in their experiment, examined the asphalt specimens on the self-healing test. The authors noted, "the moisture on crack surfaces could prevent the thermal healing of cracks."

With this in mind, the healing rate reached 24.1% for the asphalt mixture containing steel-modified fiber, and 16.4% for steel slag. The limitations are becoming clear, after analyzing the healing rate, and it is evident that the self-healing asphalt mixture shows poor healing performance. However, the authors argued that applying another heating process after the melting process should promote cracking on the self-healing asphalt mixture. Although no prominent data is showing the average melting velocity of steel wool, the asphalt mixture containing steel-modified fiber exhibited better performance over steel slag. Because the average surface temperature of steel-modified fiber is higher than the steel slag asphalt mixture, more free water is released. In this condition, free water efficiently absorbs the energy from the microwave, and since the heating efficiency of water is very high, a good melting performance of MH can be expected from steel-modified fiber as a result. (Sun et al. 2019, 873.)

Gao et al. (2019, 1117) pointed out that the surface temperature of asphalt pavement containing steel aggregates increases with the increased radiation time regardless of steel aggregates content and type. Similarly, the surface temperature increases with the increase of steel aggregate content; however, it decreases after it reaches a particular amount. Gao et al. (2017, 434) conducted the MH capacity of steel slags according to particle size. It is essential to determine the particle size to utilize its minimum content because the MH capacity of slags is highly related to its particle size. By increasing the particle size, the surface temperature increases. Again, these results would undoubtedly be strictly scrutinized, as there are some relatively reliable conclusions to the themes outlined in (TABLE 4) focusing on the answers to the questions posed by this thesis's methodology, as shown in (TABLE 1).

TABLE 4. Theme findings of Steel fibers corresponding to (TABLE 1)

Qualitative questions from Table 1	**Themes**
• To what extent the aggregates are suitable and how do these factors give optimal engineering properties in asphalt content for future substitution?	(1) Substitution of steel aggregates have a decisive impact on the environment.
• How does that influence the ice melting on an asphalt pavement? • Negative aspects of MH by the addition of aggregates and their effects. • How does that correspond to energy utilization efficiency?	(2) Lowering initial temperature equals lower ice-thawing efficiency

(Continues).

• To what extent the aggregates are suitable and how do these factors give optimal engineering properties in asphalt content for future substitution? • To find out the behavior of the mixture under microwave heating.	(3) Promoting self-healing asphalt pavement, a second MH should be employed to obtain a better result.
• To what extent the aggregates are suitable and how do these factors give optimal engineering properties in asphalt content for future substitution? • To find out the behavior of the mixture under microwave heating.	(4) Steel-modified fiber shows better MH and average melting velocity over steel slag.
• To find out the behavior of the mixture under microwave heating. • How does that influence the ice melting on an asphalt mixture?	(5) increasing the particle size, the surface temperature increases.
• To find out the behavior of the mixture under microwave heating.	(6) The heating uniformity of specimens declines as the steel aggregates content increases.

(TABLE 4) provided the most extensive set of significant groups of answers to the questions posed by this thesis's methodology, with the interest to promote our findings within the structural organization for road infrastructure of Finland (see FIGURE 12). It could conceivably be hypothesized that our approach certainly gives better results than the traditional method of de-icing asphalt pavement. It has already been known that sunlight and water with salt acting as catalysts accelerate the deterioration of asphalt pavement resulting in oxidizing the asphalt binder due to water penetration in asphalt pavement, (Speight 2016, 253). However, using steel aggregate in asphalt pavements will eliminate the use of traditional salt, and we assume that the use of the aggregate will have a lower environmental impact in contrast to the traditional method where the use of salt harms groundwater. Additionally, our findings (Theme one) conclude that the life span of asphalt pavement will be higher and with higher resistance to water and low temperature.

Speight (2016, 254) confirmed several factors that lead to poor performance of asphalt roadways, including aging of the asphalt binder, weakening of the adhesive bond due to mechanical stress, and the environmental factors that cause asphalt oxidation and moisture-related outcomes. Theme three, however, highlights that using asphalt pavement containing steel aggregates shows moderate self-healing. With this intention, MH is not only effective in de-icing snow/ice but also shows a promising outcome for healing the damage due to the factor mentioned in the literature. Not to mention that the authors recommended a second heating process after MH de-icing to have higher self-healing performance. Hence, it could conceivably be hypothesized that theme three covers this matter with a note of caution since this approach is unique so more studies should be conducted with further data gathered to analyze the self-healing feature.

As mentioned in the literature review, the outermost absorbed water layer is released when the aggregate surface is heated, resulting in a more favorable interaction between the binder and the aggregate, contributing to a more solid bonding association between them (Speight 2016, 277). With this in mind, Theme six mainly focuses on the heating uniformity of asphalt pavement, by which the increase in steel additive aggregate content, the heating uniformity deteriorates. On the other hand, when concerning the aggregates-asphalt composition, which is ~95% (w/w) aggregates and ~5% (w/w) asphalt (Speight 2016, 264), it was found that based on the reactivity of new aggregates with MH, it is essential to determine the additive aggregates optimal content. Theme 5 from our findings states that increasing the particle size of additive aggregates increases the surface temperature when subjected to MH. Another promising finding was of comparing the steel-modified fiber, which shows better MH and average melting velocity over steel slag.

Finally, regarding the limitations of Theme two, which states the initial temperature of the surrounding influence the MHE, it could be argued that more heating time is needed to effectively remove the snow/ice in harsh weather conditions. Another outcome of this finding is that further research on the optimal content of the additive aggregate on the pavement will lead to a higher heating rate despite lower initial temperature, leading to economical and labor-savings in the de-icing process. All things considered, the hierarchal organization for road infrastructure of Finland (see FIGURE 12) needs to fill the gaps of initial surrounding temperature, self-healing asphalt pavement on a large scale, decreasing the particle size and the heating uniformity of asphalt pavement within steel additive aggregates.

6.2 MH applications for Magnetite

Microwave efficiency enhances by increasing the size of magnetite particles. However, the properties of aggregates might influence the MHE to some degree (Guo et al. 2020,8). This result is supported by (Wang et al. 2016, 592), which demonstrates that the larger aggregate size lowers the conversion rate of Fe_3O_4 to Fe_2O_3. Lowering the upper layer of asphalt pavement with additive aggregates (magnetite) shortens the microwave de-icing time. Moreover, a longer de-icing time is required to achieve a specific temperature in an asphalt pavement with a lower initial temperature than the slightly higher initial temperature of the pavement, (Guo et al. 2020,13; Wang et al. 2019, 9; Wang et al. 2016, 595). The reflectivity of induced microwave radiation from the surface of asphalt pavement decreases as the aggregate volume increases due to higher magnetic properties in the pavement. However, the reflectivity increases when the magnetite content in asphalt pavement exceeds 80% (Wang et al. 2016,593.)

In addition, lower reflectivity loss is experienced by keeping the volume of aggregate constant and lowering the height of asphalt pavement (Guan et al. 2019, 10-11). Radiation depth can be influenced by various factors, as raising the frequency of applied microwave, and lowering the volume of aggregates used in asphalt pavement leads to lower radiation depth. However, enhancing the heating time increases the radiation depth of the specimen (Gao et al. 2018, 1114; Guo et al.2020, 10-11). The physical and the chemical properties of magnetite, such as surface roughness and its ability to bond with the acidic compounds of asphalt, lead to a lower water sensitivity in the asphalt pavement. Moreover, by increasing the magnetite content it also leads to a similar phenomenon regarding water sensitivity. (Wang et al. 2016, 397-398; Guan et al. 2019, 9). Although these results would undoubtedly be strictly scrutinized, there are some reliable conclusions to the themes outlined in (TABLE 5) focusing on the answers to the questions posed by this thesis's methodology, as shown in (TABLE 1).

TABLE 5. Theme findings of magnetite corresponding to (TABLE 1)

Qualitative questions from Table 1	Themes
• To find out the behavior of the mixture under microwave heating.	(1) MH enhances with increasing aggregate sizes in asphalt pavement.
• How does that influence the ice melting on an asphalt pavement? • How does that correspond to energy utilization efficiency	(2) De-icing time increases by increasing upper aggregate layer composition and lower initial surrounding temperature.

(Continues).

• How does that influence the ice melting on an asphalt pavement? • Negative aspects of MH by the addition of aggregates and their effects.	(3) Reflection losses increase with increasing height and decrease with increasing aggregate volume.
• To what extent the aggregates are suitable? • How do these factors give optimal engineering properties in asphalt content for future substitution?	(4) Radiation depth increases with increasing radiation time and volume of aggregate
• How does that influence the ice melting on an asphalt pavement? • How does that correspond to energy utilization efficiency?	(5) Increase in aggregates content lowers water sensitivity of asphalt pavement

(TABLE 5) provides an extensive set of significant groups of answers to the questions posed by this thesis's methodology. It has already been known that high temperature deteriorates the asphalt pavement; however, thick asphalt pavement has been shown to lower the deterioration process. On the other hand, according to our findings, this thesis can infer that MH on thick asphalt pavement with a higher composition of additive aggregates leads to an increase in radiation depth. When this technology will be implemented, there will further need to study the nature of MH in asphalt pavements with aggregates and radiation time for that of deterioration of the asphalt pavement. Furthermore, the probability of the pavement surface cracking due to heating cannot be ignored. However, the specific degree to which the pavement with aggregates may crack because of MH needs to be verified further. Nevertheless, the nature of the aggregates shows the self-healing property in the pavement which could eliminate this issue, presented in Chapter 4.1.2 of this thesis.

On the other hand, asphalt-aggregate interaction also plays a decisive role in asphalt life cycle, which in turn is influenced by heavy traffic and spilling of oil, weakening the pavement, and finally breaking the surface. Furthermore, freezing weather is a catalyst boosting the breaking of an asphalt pavement into pieces (Speight 2016, 254). In this situation, organizational structure of winter road maintenance in Finland should consider that the working load, particularly during harsh weather conditions, may lead to higher costs. Hence, these issues need to be addressed before implementing the aggregates and MH technology for de-icing.

The existing asphalt pavement has an overall poor performance due to the deterioration of its adhesive bond between the asphalt pavement and binders. Moreover, moisture and its effect on oxidization weaken the pavement further, together with damages caused by the increased mechanical load of heavy traffic (Speight 2016, 254). According to the findings of Guo et al., water sensitivity can be reduced by increasing the asphalt and additive aggregate layer thickness. However, implementing this approach on Finnish highways would lead to higher costs and may require a new plan for the Väylä, but this thesis's findings presume that this novel approach would in fact, reduce the adverse effect on pavements due to the new self-healing asphalt pavement during the MH de-icing process. The self-healing asphalt pavement not only overcomes the deterioration of the adhesive bonding, but it also goes beyond that by healing the cracks formed by the mechanical load of heavy traffic. Furthermore, according to our findings, aggregate composition on asphalt pavement affects the reflection loss and radiation depth. To sum up, implementing this method by replacing the existing de-icing methods is a national duty of the Finnish transportation infrastructure organization.

Scientific and technological frameworks should be considered while constructing a new pavement design that incorporates additional aggregates. More importantly, a new environmental road policy needs to be implemented by the governmental and Finnish Transport Agency väylä. The findings of this thesis emphasize that little is known about the MH in asphalt pavements with magnetite and steel aggregates. Nevertheless, this thesis critically evaluates the new sophisticated technology to replace the traditional way of de-icing the asphalt pavement. Several research papers were used to analyze the proposed alternative aggregates in asphalt pavements under various conditions. By comparing the results from the literature review, the data were derived based on the methodology of (TABLE 1). Consequently, in this Chapter all the data was investigated and the responses for the enquires in (TABLE 1) were justified. Additionally, the current snow removal process and strategy in Finland were scrutinized and the use of this technology is recommended as a remedy. (TABLE 6) shows the recommendation for using MH de-icing technology with aggregates.

TABLE 6. Future recommendation on different aspects of Finnish society due to various properties of additive aggregates for effective MH de-icing process

Additives on Asphalt pavement	Effect on de-icing process	Effect on structural organization of road maintenance	Economic Impact	Social Impact	Environmental Impact
Increase in particle size of aggregate	Higher efficiency	New plan implementation	Impacts are not yet known	Reduce need of new mining for rocks	Lower GHG emission
Increase in aggregate percentage	Deteriorate heating uniformity	Subjecting the issue to the R&D studies	Increase in cost	May risk workers' health	Reducing the aggregate resource
Lowering asphalt layer thickness	Shorter de-icing time	Reducing allocation of de-icing expenses	Lower cost	Less traffic issues	Expand life of petroleum resources
Initial surrounding temperature	Increase in de-icing time with decrease in surrounding temperature and vice versa	New strategies should be considered	Lower cost with increasing surrounding temperature and vice versa	Higher traffic issues with lower surrounding temperature and vice versa	Intensive performance in lower surrounding temperature and vice versa
Increase in reflection loss	Lower de-icing rate	Impacts and trade-offs unknown	High cost	Health issue if exposed for prolonged period	Might have negative environmental impact
Increase in radiation depth	Lowers efficiency	Impacts should be further studied	High cost	Unknown	Unknown
Self-healing asphalt pavement	No-impact	More research and studies from authorities needed	High cost	Higher operators demand (Human resource)	Reduce GHG emission

Based on the methodology of this thesis, (TABLE 6) presents the future recommendation of using magnetite and steel fibers as additive aggregates for higher MHE to Finnish road infrastructure. Various properties such as initial surrounding temperature, reflection losses, pavement height, and radiation depth with self-healing properties of new additive aggregates are analyzed based on economic, social, environmental, organizational impacts with de-icing process efficiency. Furthermore, the summary of (TABLE 6) is presented on (TABLE 7). This Table shows the findings by color code stating the specific factors leading to an efficient and in-efficient de-icing process, with the findings which need to be verified by further studies to determine the efficiency of the MH process.

TABLE 7. The summary of (TABLE 6)

Environmental impact after implementing the additive aggregates	Lower initial temperature of the surroundings	Self-healing of new asphalt pavement with MH technology	Steel-modified fiber over other steel aggregates	Increasing particle size	Increase in aggregate content	Water sensitivity after addition of aggregates
The description for the color code						
Efficient de-icing process		inefficient de-icing process		Should be verified		

With the intention of incorporating the new approach of this thesis, it nevertheless remains the responsibility of the organizational structure for the road infrastructure of Finland (as displayed in FIGURE 12) to manage the activities sustainably. More research should be carried out, and advanced methods should be examined. The sustainability concerning the new approach of this thesis should include environmental, social, and economic factors as discussed in (TABLE 6). This method should instead be taken solely as an innovation for new asphalt de-icing applications. Despite implementing the new additive aggregates in the asphalt mixture, several factors should be considered in the new aggregate interaction with asphalt and other performance-related properties, along with durability and functionality in the long run. Water sensitivity and moisture damage with certain types of aggregates, leading to lowering these impacts during MH is yet one more concern for the Finnish transport agency. The de-icing process needs to balance the use of higher and lower quality additive aggregates for more MHE, as well as the environmental, social, and economic impacts. Furthermore, the feasibility of implementing these aspects should be taken into account in accordance with their sustainability. Thus, the outcome can lead to better functionality for traffic improvement, construction processes, and environmental impacts.

The main challenges this new approach is facing a high energy consumption and sustainability related GHG emissions. However, making a solid assumption for new testing for this technology will give a fundamental understanding of these key aspect presented in (TABLE 6). Nevertheless, the findings of these tests provide evidence that both magnetite and steel additive aggregates showed better performance in MHE with low content in asphalt pavement a promising future for this approach regarding sustainability. Likewise, another beneficial factor of this approach is the opportunity of utilizing the waste material to create a suitable additive aggregate, which will give the same result as the one in this thesis. The data from the literature review supports this concept, as the Chinese industrial solid waste from the iron and steel industry accounted for about 31% annually (roughly 1 billion tons) (Guo & Shi 2013, 1265). Meanwhile, Yalcin (2021, 2) pointed out that Turkey's metallic waste accounts for 3 million tons of annual accumulation. As for Finland, according to Eit Raw Materials Academy, 76% of construction and demolition waste is from mining and quarrying waste.

Furthermore, the Official Statistics of Finland (OSF) provided data about the amount of residue from mining and quarrying waste being 96 million tones only in 2018. Additionally, according to the Nordic Council of Minister’s report in 2020, the statistical data showed the amount of construction and demolition waste in Finland was 1,250,000 tons of mineral waste and 170,000 tons of metal wastes. Likewise, Finland approximately exported 173 thousand euros and imported 826 thousand euros of ferrous waste and scrap during 2020 (Suomen vienti ja tuonti. Rauta-ja teräsromu, 2021).

In view of utilizing these materials for asphalt pavement construction as an additive aggregate, these wastes would tackle environmental and economic issues, besides their ability to be reactive material for MH. A recent study by Yalcin (2021, 12) was conducted on the effect of MH on asphalt mixtures containing additive aggregates from waste material. The study concluded that the asphalt mix with waste metals has lower air void and yielded higher bulk specific gravity than the mixture without additives. Also, the study provided evidence that air voids increase with the increase of waste metal content. Furthermore, the findings indicated that with MH the temperature of aggregate and bitumen around them shows a significant increase; hence, increased waste metal content increases asphalt pavement temperature. From this standpoint, industrial waste metals can be considered as an additive aggregate for new asphalt pavement concerning MH technology for de-icing.

At this stage, the finding of this thesis deems that one can strongly support this proposal to be verified from the road infrastructure of Finland. Therefore, international collaboration should be considered examining these proposals on a larger scale. Again, more data should be accumulated from various tests and their outcomes in order to make solid strategic planning and execution. Finally, this thesis proposes a general action plan for further advancement and implication of this proposed technology, as shown in (FIGURE 13).

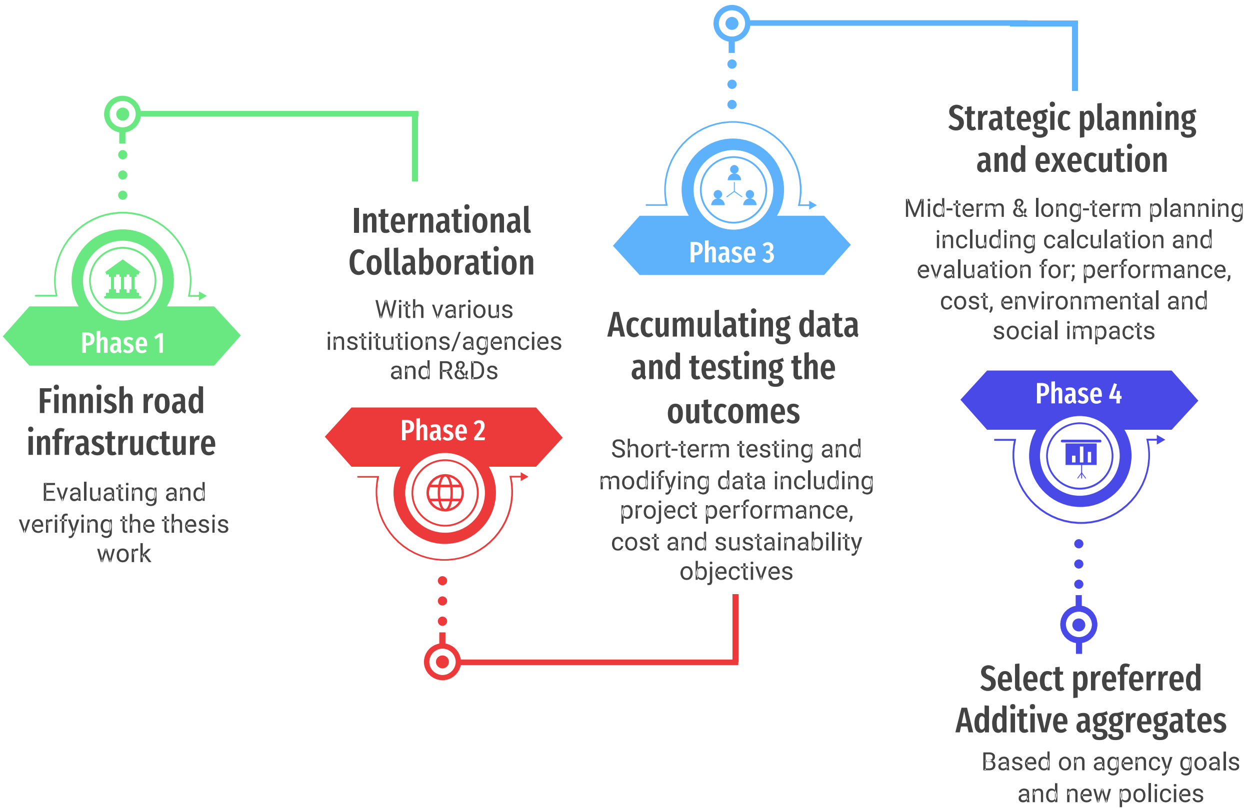

FIGURE 13. Future implication and framework for the Finnish road infrastructure

With this in mind, if väylä will adopt the proposal's concept as in (FIGURE 13), then they will need to develop new policy, quality standards, and guidance for ELY centres/municipalities. Furthermore, the ELY centres/municipalities will develop new plans for contractors and companies responsible for winter road maintenance (de-icing practices). Therefore, one can speculate the result will pay off well for the organizational structure, with a smoother plan and less environmental, social, and economic impacts. Nevertheless, it should be considered that on a larger scale MH influences the oxidation of the asphalt mixture in the long run. Thus, the results in this thesis need to be interpreted with caution. Overall, the methodology and evaluation highlighted a unique approach to utilize MH, and suggested additive aggregates giving a recommendation for the future of Finnish road infrastructure.

7 CONCLUSION

In this study, snow and ice melting processes with traditional and novel approaches were discussed. This thesis research aimed to examine the fundamental analysis of MH with different additive aggregates. The study's second aim was to investigate the behavior of additive aggregates under MH based on the thesis's criteria presented in (TABLE 1). Additionally, the MH principle was reviewed from different aspects and insight on prospects for economic possibilities. To this end, conclusions can be drawn that MH showed an exemplary efficiency for steel fibers and magnetite on a laboratory scale based on various tests. This finding, however, is limited by the lack of data from the current studies concerning large scale research which is needed to open a new opportunity for R&D. Following this, a proposal is made for future implications on MH for de-icing asphalt pavement. Additionally, this is the first study made with such depth to examine possible associations between the novel approach of a de-icing practice and proposing a framework of initial implementation for the Finnish road infrastructure.

To summarize, while the developed technologies for MH of de-icing asphalt pavement are still in the early stage, it nonetheless shows a bright future. However, it is both challenging and critical to implement such a novel approach with the current understanding of MH under different aggregates on a large scale. Consequently, the government's responsibility is to act and coordinate new legislation, to favor implementing this novel approach and move ahead of the traditional de-icing method due to the environmental, social, and economic benefits. With a focus on these factors, such an in-depth research should be considered and funded for further advancement of innovation.

REFERENCE

Ding, L., Wang, X., Cui, X., Zhang, M., and Chen, B., 2021. Development and performance research of new sensitive materials for microwave deicing pavement at different frequencies, 181, 103176.

Espo, J., 2021. Statistics Finland - Waste statistics 2018 [online]. Available from: https://www.stat.fi/til/jate/2018/jate_2018_2020-06-17_tie_001_en.html [Accessed 24 May 2021].

Fernández Díez, Y., Arenillas de la Puente, A., and Menéndez Díaz, J. Á., 2011. Microwave heating applied to pyrolysis. InTech.

Gao, J., Guo, H., Wang, X., Wang, P., Wei, Y., Wang, Z., Huang, Y., and Yang, B., 2019. Microwave deicing for asphalt mixture containing steel wool fibers, 206, 1110–1122.

Gao, J., Sha, A., Wang, Z., Tong, Z., and Liu, Z., 2017. Utilization of steel slag as aggregate in asphalt mixtures for microwave deicing, 152, 429–442.

García, A., Norambuena-Contreras, J., and Partl, M. N., 2014. A parametric study on the influence of steel wool fibers in dense asphalt concrete, 47 (9), 1559–1571.

García, Á., Schlangen, E., van de Ven, M., and Liu, Q., 2012. A simple model to define induction heating in asphalt mastic, 31, 38–46.

Guan, B., Liu, J., Zhao, H., Wu, J., Liu, J., and Yang, F., 2019. Investigation of the Microwave Absorption of Asphalt Mixtures Containing Magnetite Powder, 9 (12), 813.

Gulisano, F. and Gallego, J., 2021. Microwave heating of asphalt paving materials: Principles, current status and next steps, 278, 121993.

Guo, H., Wang, Z., Huo, J., Wang, X., Liu, Z., and Li, G., 2020. Microwave heating improvement of asphalt mixtures through optimizing layer thickness of magnetite and limestone aggregates, 273, 123090.

Guo, X. and Shi, H., 2013. Modification of steel slag powder by mineral admixture and chemical activators to utilize in cement-based materials, 46 (8), 1265–1273.

Jahanbakhsh, H., Karimi, M. M., Jahangiri, B., and Nejad, F. M., 2018. Induction heating and healing of carbon black modified asphalt concrete under microwave radiation, 174, 656–666.

Jin, S., Guo, C., Lu, Y., Zhang, R., Wang, Z., and Jin, M., 2017. Comparison of microwave and conventional heating methods in carbonization of polyacrylonitrile-based stabilized fibers at different temperature measured by an in-situ process temperature control ring, 140, 32–41.

Li, B., Sun, Y., Liu, Q., Fang, H., Wu, S., Tang, J., and Ye, Q., 2017. Ice melting properties of steel slag asphalt concrete with microwave heating. In: . Presented at the IOP Conference Series: Materials Science and Engineering, IOP Publishing, 012041.

Liu, Z., Yang, X., Wang, Y., and Luo, S., 2019. Engineering properties and microwave heating induced ice-melting performance of asphalt mixture with activated carbon powder filler, 197, 50–62.
Ma, T., Geng, L., Ding, X., Zhang, D., and Huang, X., 2016. Experimental study of deicing asphalt mixture with anti-icing additives, 127, 653–662.

Marcos-Meson, V., Michel, A., Solgaard, A., Fischer, G., Edvardsen, C., and Skovhus, T. L., 2018. Corrosion resistance of steel fibre reinforced concrete - A literature review. [online], 103, 1–20.

Meredith, R. J., 1998. Engineers’ handbook of industrial microwave heating. Iet.
Snow and Ice databook 2018. PIARC.

Speight, J. G., 2016. Asphalt materials science and technology. Springer.

Struková, Z. and Sičáková, A., 2017. Construction and Demolition Waste Management.

Sun, T. and Chen, L., 2017. Temperature field of asphalt mixture based on microwave heating, 51 (1), 59–70.

Sun, T., 2013. Thermoelectric coupling model for asphalt mixtures based on microwave heating, 43 (4), 353–363.

Sun, Y., Wu, S., Liu, Q., Hu, J., Yuan, Y., and Ye, Q., 2018. Snow and ice melting properties of self-healing asphalt mixtures with induction heating and microwave heating, 129, 871–883.

Suomen vienti ja tuonti. Rauta-ja teräsromu (SITC 282) 2019/Q4 - 2020/Q4 [online]. Available from: https://karirast.com/ulkomaankauppa/282_SitcQ.html [Accessed 24 May 2021].

Wang, H., Zhang, Y., Zhang, Y., Feng, S., Lu, G., and Cao, L., 2019. Laboratory and numerical investigation of microwave heating properties of asphalt mixture, 12 (1), 146.

Wang, H., Zhao, J., and Chen, Z., 2008. Experimental investigation of ice and snow melting process on pavement utilizing geothermal tail water, 49 (6), 1538–1546.

Winter maintenance [online]. Available from: https://vayla.fi/en/maintenance/road-network/winter-maintenance [Accessed 9 May 2021].

YU, W., LI, S., FENG, W., and YI, X., 2011. Snow and Ice Melting Techniques of Pavement: State of the Art and Development Tendency [J], 4.

Zheng, Y., Zhang, J., Liu, Y., Jia, S., Tang, R., and Zhang, D., 2020. Dehydrogenation and spheroidization of titanium hydride powder based on fluidization principle, 2 (1), 22–29.

Zu Castell-Rüdenhausen, M., Wahlström, M., Fruergaard Astrup, T., and Oberender, A., 2021. Strategies and methods for implementing CE in construction activities in the Nordic countries: policy brief. Nordic Council of Ministers.