Minnesota Taconite as a Microwave-Absorbing Road Aggregate Material for Deicing and Pothole Patching Applications

Final Report

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16. Abstract (Limit: 200 words)

This report presents modeling of temperature profiles for application of microwaves to pothole patching and roadway deicing. Values of key parameters are estimated and presented for asphalt-aggregate composites containing varying magnetite content (compacted and with voids), ice, and water. The key parameters are: microwave absorption coefficient at 2.45 GHz, density, heat capacity, and thermal conductivity. This reports summarizes the work we were able to complete, including a large number of equations characterizing key parameters and an extensive list of references. The natural magnetite in taconite is an outstanding microwave absorber. Consequently, when a truck-mounted microwave generator is driven over an ice-covered roadway constructed with crushed taconite as the aggregate, the microwaves should pass through the ice and be absorbed as heat at the road-ice interface, allowing the ice to be easily detached and scraped away. This energy-efficient process is the only non-chemical method of deicing practical for many miles of roadway. Adoption of this deicing method could lead to a significant demand for taconite aggregate. The same microwave equipment used for deicing could be used year-round for pothole patching applications, with the microwave energy used to generate just the required amount of hot mix on-site for permanent repairs.

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Executive Summary

This report presents modeling of temperature profiles for application of microwaves to pothole patching and roadway deicing. From previous work and a literature survey, values of key parameters for asphalt-aggregate composite with varying magnetite content (compacted and with voids), ice, and water are estimated and presented. The parameters are microwave absorption coefficient at 2.45 GHz, density, heat capacity, and thermal conductivity. This report summarizes the work we were able to complete, including a large number of equations characterizing key parameters and an extensive list of references (see References and Appendix A).

There are limitations associated with an explicit numerical solution for mathematically modeling microwave deicing. Therefore, a more complex implicit method would be preferable. Unfortunately, implicit methods are complex and require substantial computer programming and debugging efforts, efforts that were beyond the resources available to this project.

Nonetheless, we have found that the natural magnetite in taconite is an outstanding microwave absorber. Consequently, when a truck-mounted microwave generator is driven over an ice-covered roadway constructed with crushed taconite as the aggregate, the microwaves will pass through the ice and be absorbed as heat at the road-ice interface, allowing the ice to be easily detached and scraped away. This energy efficient process is the only non-chemical method of deicing practical for many miles of roadway.

Adoption of this deicing method could lead to a significant demand for taconite aggregate. The use of large tonnages of chemicals for deicing of roads has many adverse effects, including accelerated corrosion of both vehicles and of the road and bridge infrastructure, damage to vegetation, and pollution of lakes, streams, and ground water by run-off. Because present-day non-chemical methods of deicing, such as buried electric heating cables, are expensive to install, operate, and maintain, they can only be used for short segments of roadway, such as bridges.

Other applications that make use of the unique microwave-absorption properties of taconite aggregate would allow use of the same microwave equipment year-round. Currently in cities like Duluth pothole repair in winter is a very inefficient process. A temporary repair is made by the "throw-and-go" method. Later, when the weather warms sufficiently for plants to produce hot-mix asphalt, crews must go back to produce a permanent repair. By use of a granulated patching compound containing taconite and a microwave power supply, only the required amount of hot mix could be prepared on-site and used to produce a permanent repair the first time under any weather conditions.

Based on this report and previous bench-scale research by the authors, it is recommended that future work take advantage of these findings and apply them to a scaled-up and practical testing program against which additional numeric modeling can be compared. Building on the information captured in this report, we hope to be able to move on efficiently in the future with regard to these testing and modeling efforts.

Chapter 1
Introduction

Background

Dr. David M. Hopstock conceived the idea to test magnetite-bearing taconite aggregate and microwave technology for two potential road-use applications: 1) all-season hot-mix pothole patching and curing and 2) chemical-free deicing of surfaces paved with asphalt concrete, including highways, bridge decks, pedestrian walkways, and airport runways.

In 2002, seed money was provided by the NRRI to Dr. Hopstock to conduct a preliminary bench-scale assessment of his ideas, using a conventional microwave oven. His test results (Hopstock, 2003) showed that natural magnetite in taconite is an outstanding microwave absorber. Consequently, when a truck-mounted microwave generator is driven over an ice-covered roadway constructed with crushed taconite as the aggregate, the microwaves should pass through the ice and be absorbed as heat at the road-ice interface, allowing the ice to be easily detached and scraped away. This energy-efficient process is the only non-chemical method of deicing practical for many miles of roadway. Adoption of this deicing method could lead to a significant demand for taconite aggregate. The same microwave equipment used for deicing could be used year-round for pothole patching applications, with the microwave energy used to generate just the required amount of hot mix on-site for permanent repairs.

An earlier study (Wouri, 1993) was brought to our attention by Mr. Edward Fleege, Research Fellow, and Board member of NATSRL. That study, supported by the Strategic Highway Research Program (SHRP), was entitled *Ice-Pavement Bond Disbonding — Surface Modification and Disbonding*. It summarizes work performed at Michigan Technological University (MTU) in 1989 to 1990, before the project was terminated prematurely when it was determined that none of the approaches, save one, was sufficiently developed to be put into practice during the life of the SHRP program. The project included physical pavement modifications to facilitate ice disbonding by traffic action or other external energy. An investigation of microwave disbonding was conducted relative to external energy application. The preliminary results suggested that the use of microwave radiation to disbond ice appeared feasible, but attainment of realistic highway speeds was difficult and required further study.

Significantly, the researchers investigated different materials to assess their microwave absorbing potential, and found coal and ferrites to be excellent microwave absorbers. The practicality of using coal as an aggregate component in asphalt mixes is dubious, given its lack of strength. However, taconite, which contains the naturally occurring ferrite mineral magnetite, is known to have excellent aggregate properties and is already used as aggregate in asphalt concrete. The MTU study was terminated before a reasonable evaluation could be performed on pavement mixes that incorporated these materials. Dr. Hopstock's NRRI-supported 2002 research and the current research project demonstrated – at the bench scale and mathematically – that simulated pavement mixes incorporating taconite aggregate could achieve effective ice disbonding at a rate that could allow deicing at reasonable speeds.

The following chart (Fig. 1.1), based on the microwave heating of natural minerals performed by McGill and Walkiewicz (1987), helps to illustrate the concept of using magnetite-bearing aggregate. Note the arrows; they show the types of minerals commonly found in granitic aggregates, i.e., quartz, and feldspar (albite and orthoclase), and the analogue of limestone and/or dolomite, i.e., marble. All have poor microwave absorbing characteristics, which confirms that for the microwave deicing technology to be effective, typical pavement mixes need to be supplemented with aggregates that contain good microwave absorbing minerals.

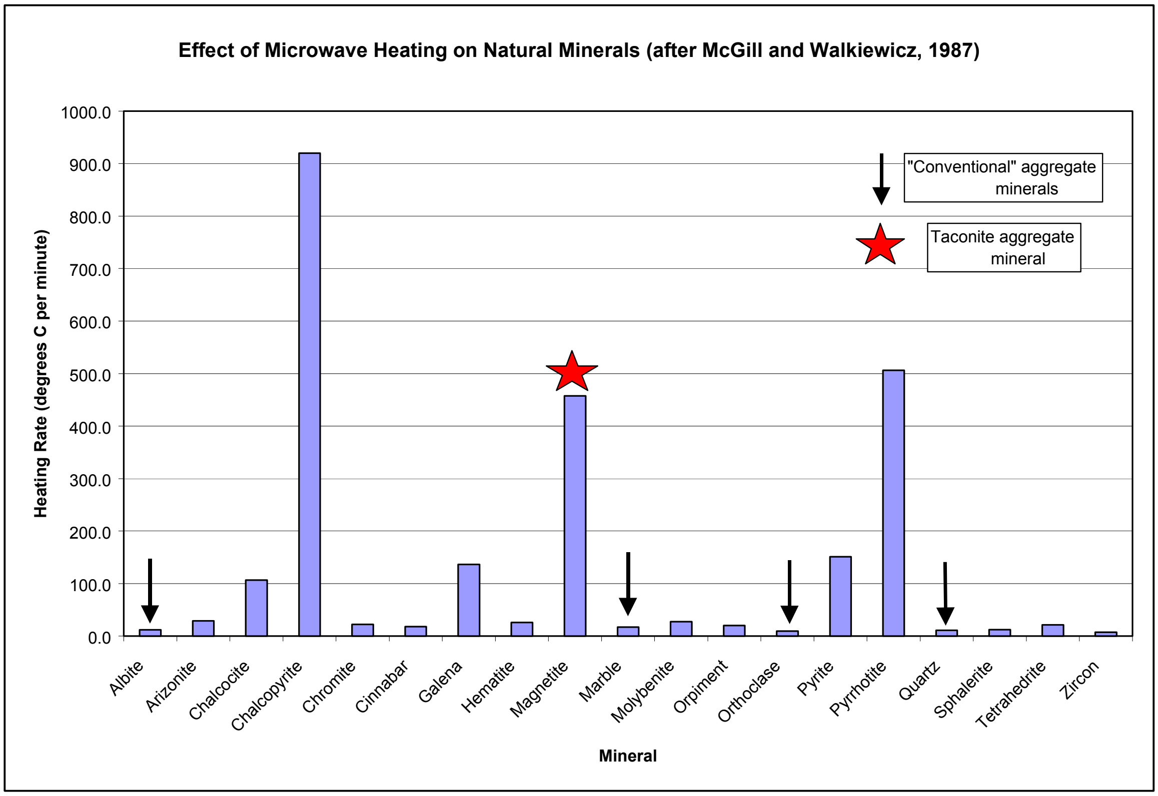

Figure 1.1 Comparison of microwave heating on various minerals (after McGill and Walkiewicz, 1987).

The chart shows that chalcopyrite, pyrrhotite, and magnetite have the highest microwave heating potential. However, chalcopyrite and pyrrhotite are sulfur-bearing (and therefore physically and chemically undesirable for inclusion in pavements), and are not usually found in rocks at concentrations that would attain comparable heating. For example, these minerals are typically present in sulfide ores at concentrations of 0.5 to 5 percent. Compare that to the 20 to 25 percent magnetite concentration typically found in Mesabi Range taconite ore, and the 5 to 15 percent content found in various low-grade taconite mining byproducts like cobber rejects. In other words, if one assumes an aggregate's microwave heating rate is proportional to its mineral concentration, aggregate made from typical crude taconite ore or processing byproducts would be easily superior to any of the other aggregates.

Project Objectives

We have proposed the use of Minnesota taconite as an aggregate material with unusual microwave absorbing properties. Asphalt concrete made with taconite aggregate can be used in a number of unique applications, such as all-season pothole patching and non-chemical deicing of roadways. The objective of this project was to conduct a modeling study to determine temperature profiles as a function of time for the pothole patching and roadway deicing applications.

The first part of the project required surveying the literature (Appendix A) and previous work to estimate values of key parameters for ice and water and for asphalt concrete with varying compaction densities, made with taconite aggregate of varying magnetite content. The parameters of interest are microwave absorption coefficient at 2.45 GHz, density, heat capacity, and thermal conductivity. To facilitate modeling efforts, in cases where this information was available over a range in temperatures and/or from sources of varying reliability, statistical analysis was used to find "best" values of the parameters and to convert from tabular to mathematical functional form.

For several reasons, we were not able to carry the modeling calculations as far as we had originally anticipated:

> (1) Time was taken out to prepare a written summary and PowerPoint presentation on the status of the project, including some of the results given in this report, for the University of Minnesota Mining Symposium in Duluth on April 13, 2004. Our presentation was summarized in the Spring 2004 issue of NATSRL's *Northland Transporter* (Hopstock and Zanko, 2004).
>
> (2) As our primary references and extended references of Appendix A show, the required information on the physical and thermal parameters is widely scattered and poorly correlated. It took a more extensive effort than anticipated to bring it all together in a useful format. We did complete development of a unique spreadsheet that enables prediction of all the required parameters for asphalt concrete made with taconite aggregate.
>
> (3) The original plan envisaged finite-difference thermal modeling by means of explicit step-by-step formulas in a simple Excel spreadsheet. For reasons explained below, it turned out that this method would not be applicable to the application of most interest for modeling purposes — pavement deicing — and that more sophisticated computer programming would be required.

After it became apparent that a more sophisticated computer modeling effort would be required, we assisted Professors Zhuangyi Liu and Harlan Stech of the Department of Mathematics and Statistics of UMD in preparing a proposal to NATSRL entitled *Models of Microwave Heating and Heat Transfer Arising in the Use of Taconite-asphalt Paving Materials*. Unfortunately, this proposal was not funded, and we have been unable to proceed further in mathematical modeling efforts.

This report summarizes the work we were able to complete, including a large number of equations characterizing key parameters and an extensive list of references (see References and Appendix A). Building on the information captured in this report, we hope to be able to move on efficiently in the future with testing and modeling efforts.

Chapter 2
Modeling

Formulation of the Equations Governing Microwave Heating

As a reasonable first approximation, the use of microwaves either for deicing of asphalt concrete or for heating of a patching compound for pothole repair can be modeled as a one-dimensional problem. The microwave energy is assumed to enter the roadway from the normal (*z*-) direction as a transverse electromagnetic (TEM) wave at a uniform power density (W/m^2), where W=watts. Lateral transfer of thermal energy is assumed to be negligible. For each incremental thin slab of material (such as roadway, ice, or patching compound) one can set up a heat balance on a per unit time and unit volume basis:

$$\{Thermal\_energy\_stored\} = \{Microwave\_energy\_absorbed\} + \{Net\_heat\_input\_by\_conduction\} \quad (1)$$

The thermal energy stored (W/m^3) is given simply by

$$\{Thermal\_energy\_stored\} = \rho C_p \frac{\partial T}{\partial t} \quad (2)$$

where ρ is the material density (kg/m^3), C_p is the heat capacity on a mass basis (J/kg/°C), T is the temperature (°C), and t is time in seconds.

The thermal energy generated by absorption of microwaves is given by

$$\{Microwave\_energy\_absorbed\} = 2\alpha P_{in} \quad (3)$$

where α is the microwave absorption coefficient (also known as the attenuation constant) of the material (m^{-1}), and P_{in} is the power density of the microwave energy entering that incremental slab (W/m^2). The reciprocal of the absorption coefficient, $1/\alpha$, is known as the penetration depth or attenuation constant. Within the penetration depth 86.5% of the incident energy is absorbed. The factor of 2 enters because the absorption coefficient α is generally defined in terms of the amplitude of the TEM wave, but the power density carried by the wave depends upon the square of the amplitude. (This discussion follows the notation given by Von Hippel (1954a,b). Some writers, such as Lindroth et al. (1995), use the notation "α" for what we label "2α." Their definition of the attenuation distance is one-half of our definition.)

From Fourier's law of thermal conduction, in the one-dimensional case the net heat input by conduction is given by

$$\{Net\_heat\_input\_by\_conduction\} = \kappa \frac{\partial^2 T}{\partial t^2} \quad (4)$$

where κ is the thermal conductivity (W/m/°C). Thus equation (1) can be rewritten

$$\rho C_p \frac{\partial T}{\partial t} = 2\alpha P_{in} + \kappa \frac{\partial^2 T}{\partial t^2} \quad (5)$$

To model the microwave heating processes of interest, we need to solve equation (5) subject to the appropriate boundary conditions. At the interface between asphalt concrete and ice, for example, the heat flux must be equal on either side of the boundary, where the heat flux is given by

$$\{Heat\_flux\} = -\kappa \frac{\partial T}{\partial z} \quad (6)$$

At the top surface of the ice, a reasonable boundary condition may be to fix the ice temperature at the ambient air temperature. For the heating of a patching compound, the appropriate boundary condition at the top of the patching layer may be a convection heat-transfer term. (See, for example, Holman (1976), pp. 106, 126.)

In the most general case, the key parameters C_p, α, and κ (and ρ, to a lesser extent) are all temperature-dependent. In most cases a computer-based solution by a finite difference approximation is required to solve equation (5). Allowing for temperature dependence of the parameters increases the complexity of the programming involved only to a moderate degree.

Before the governing equations can be solved, it is necessary to estimate values for the parameters characterizing the material properties of all the materials involved. The primary material of interest is asphalt concrete in which taconite is used as the aggregate. The asphalt concrete has three principal components — the taconite aggregate, the bitumen (or asphalt) binder itself, and air present as voids. (It will be assumed that the voids are closed, not allowing water to penetrate into the asphalt concrete, and therefore the water or ice content is negligible.) The taconite aggregate in turn will be considered to be made up of two components, magnetite and gangue (non-metallic accessory minerals). Although there are in fact several gangue minerals, we will lump them into a composite gangue material, typical of Minnesota Iron Range taconite ore. In the case of the deicing application, we will also need to estimate material parameters for ice and water.

In the following sections each of the material properties will be considered in turn, and equations giving these properties as a function of temperature will be developed.

Microwave Absorption Coefficient

For a TEM microwave passing through a dielectric material in the *z*-direction, the power per unit area *P* of the microwave radiation is attenuated according to the equation (Thuéry, 1992, p. 47)

$$\frac{\partial P}{\partial z} = -2\alpha P \quad (7)$$

where α is the microwave absorption coefficient (m^{-1}). For constant α this equation can be solved to give

$$P(z) = P_o e^{-2\alpha z} \tag{8}$$

where P_o is the power per unit area initially entering the material. In the case of constant α, $P(z)$ from equation (8) can be substituted for P_{in} in equation (5). If the dielectric and magnetic properties of the material are known at the frequency of interest, the absorption coefficient can be calculated. The complex relative dielectric permittivity ε^* and complex relative magnetic permeability μ^* can be represented by the equations

$$\varepsilon^* = \varepsilon' - i\,\varepsilon''$$

(9)

$$\mu^* = \mu' - i\,\mu''$$

The dielectric and magnetic loss tangents corresponding to the electric and magnetic phase angles δ_e and δ_m are given by

$$\tan\,\delta_e = \varepsilon''/\varepsilon'$$

(10)

$$\tan\,\delta_m = \mu''/\mu'$$

If these quantities are known, the absorption coefficient can be calculated from (Von Hippel, 1954b, p. 294)

$$\alpha = \frac{2\pi f}{c}\sqrt{\varepsilon'\,\mu'\,\frac{1-\tan\delta_e\,\tan\delta_m}{2}\left\{\sqrt{1+\tan^2(\delta_e+\delta_m)}-1\right\}} \tag{11}$$

where f is the frequency (s^{-1}), and c is the speed of light (2.9979×10^8 m/s). For nonmagnetic materials, for which $\mu' = 1$ and $\mu'' = 0$, a simpler expression can be written:

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\varepsilon'}{2}\left\{\sqrt{1+\tan^2\delta_e}-1\right\}} \tag{12}$$

Ice. For ice from conductivity water at -12°C, at the standard industrial microwave frequency of 2.45 GHz, the dielectric constant ε' is 3.20 and the dielectric loss tangent, $\tan\,\delta_e$, is 0.0009 (Von Hippel, 1954b, p. 301). By equation (12) the microwave absorption coefficient is 0.041 m^{-1}, corresponding to a penetration depth of 24 meters. Thus, for ice-covered roads, microwave absorption by a clean ice layer is negligible. Snow, either freshly fallen or hard-packed, similarly has very low microwave absorption.

Water. There is excellent data available on the dielectric properties of conductivity water over a wide range in temperature and frequency (Von Hippel, 1954b, p. 361). Results for a frequency of 2.45 GHz (dielectric properties assumed to be essentially identical to the tabulated results at 3.00 GHz) are given in Table 2.1. According to these numbers, the strength of the microwave absorption α decreases by more than a factor of eight as water is heated from 0 to 100°C.

Table 2.1. Dielectric and microwave absorption properties of water at 2.45 GHz

Temp. (°C)	ε'	tan δ_e	α (m^{-1})	α^{-1} (mm)
1.5	80.5	0.310	70.6	14.2
5	80.2	0.275	62.7	16.0
15	78.8	0.205	46.5	21.5
25	76.7	0.157	35.2	28.4
35	74.0	0.127	28.0	35.7
45	70.7	0.106	22.9	43.8
55	67.5	0.0890	18.8	53.3
65	64.0	0.0765	15.7	63.7
75	60.5	0.0660	13.2	75.9
85	56.5	0.0547	10.6	94.8
95	52.0	0.0470	8.7	115

Asphalt concrete. Of the three components of the asphalt concrete, only the taconite aggregate contributes significantly to microwave absorption. Bitumen has a very low loss tangent of about 0.001 (Von Hippel, 1954b, p. 356). Equipment was not available for determining the complex dielectric permittivity and complex magnetic permeability of specimens containing taconite aggregate. As an alternative, it was possible to compare the microwave absorption of taconite to that of a well-characterized material — water — and thus to estimate the microwave absorption coefficient α for composites containing taconite.

Microwave energy absorption by samples of taconite of varying particle size and varying magnetite content in a plaster-of-Paris matrix was determined by Hopstock (2003). It was found that, over the range of conditions studied, the microwave absorption rate depended only upon the mass (or volume) of magnetite in the specimen. In a 1000-watt microwave oven at 25°C the rate of energy absorption by the specimens was 34.25 watts per gram of magnetite in the specimen. On a volumetric basis, this corresponded to 178.1 watts per cm^3 of magnetite. For beakers of water of the same volume as the plaster-of-Paris specimens, the microwave absorption rate at 25°C was 7.32 W/cm^3. Thus a given volume of magnetite is $178.1 \div 7.32 = 24.3$ times more effective than water in absorbing microwave energy. From Table 2.1 the microwave absorption coefficient for water at 25°C is 35.2 m^{-1}. If magnetite is 24.3 times more absorptive than water, then we can estimate its microwave absorption coefficient as 35.2 × 24.3 = 855 m^{-1}. The microwave absorption coefficient for the asphalt concrete is found by multiplying this number by the volume fraction of magnetite in the asphalt, which in turn is equal to the volume fraction of aggregate in the asphalt concrete multiplied by the volume fraction of magnetite in the aggregate.

Density

Knowledge of the densities of the various materials is required to solve equation (5) and also to be able to convert from mass fractions to volume fractions in order to calculate other properties.

Ice and water. The density of ice is 0.917 g/cm^3, nearly independent of temperature. From 0 to 12°C the density of water is 1.000 g/cm^3. If precise values at higher temperatures are required, Weast (1980, p. F-5) can be consulted.

Taconite aggregate. The density of magnetite is 5.20 g/cm^3. Hopstock (2003) found that the average density of the gangue minerals in the taconite sample tested was 2.74 g/cm^3. Given these values, the density of a taconite aggregate particle ρ_p can be calculated from

$$\rho_p = \frac{1}{0.3653 - 0.1730 w_m} \qquad (13)$$

where w_m is the weight fraction of magnetite in the taconite.

Bitumen. The density of the bitumen used to produce asphalt concrete can be expected to be approximately 1.02 g/cm^3.

Asphalt concrete. Since the mass of the air in the void spaces is negligible, the density of the asphalt concrete can be calculated from the densities given above and the volume fractions of aggregate and bitumen in the compacted asphalt.

Heat Capacity

Ice. Data on the heat capacity of ice can be found in Weast (1980, p. D-175), which in turn is based on data obtained in 1915 by Dickinson-Osborne. Between -40°C and 0°C the data can be fit to the linear equation

$$C_p = 2.117 + 0.00789T \qquad (14)$$

where C_p is the heat capacity (J/g/°C) and T is the temperature (°C).

Water. Precise data on the heat capacity of water from 0 to 100°C is given by Weast (1980, p. D-174). This data is fit very accurately by the equation

$$C_p = 4.2849 + 0.002352T - 0.02995\sqrt{T+5} \qquad (15)$$

In the transition from ice to water, in addition to the heat capacities of each phase we must also be concerned with the (very large) latent heat of fusion, 333.55 J/g (Dean, 1992, p. 6.115). For modeling purposes, this is difficult to deal with, because it corresponds to a semi-infinite heat capacity at 0°C. To make the problem more tractable for modeling purposes, it is reasonable to assume that melting takes place over the finite temperature interval from 0.0 to 0.1°C. The total enthalpy change will be the heat of fusion plus the enthalpy contribution from the heat capacity of water (0.42 J/g), or 333.97 J/g. The effective heat capacity over that 0.1°C temperature interval is thus 3339.7 J/g/°C. Thus, as long as we understand that melting is not complete until the temperature reaches 0.1°C, we can apply a piecewise approximation to the heat capacity.

Taconite aggregate. The heat capacity of magnetite is given by the equation (Kelley, 1960)

$$C_p = 0.6334 + 0.871 \times 10^{-3} T \qquad (16)$$

Comparison with the experimental data for magmatic and metamorphic rocks of Vosteen and Schellschmidt (2003) and the data of Hopstock (2003) indicates that the heat capacity of the gangue minerals in taconite is reasonably represented by the equation of Kelley (1960) for quartz:

$$C_p = 0.9372 + 0.571 \times 10^{-3} - \frac{18{,}800}{(T + 273.15)^2} \qquad (17)$$

The heat capacity of the aggregate is then estimated by a weighted average of expressions (16) and (17), with the weight fractions of magnetite and gangue as the weighting factors.

Bitumen. There is very limited and scattered data on the heat capacity of bitumen. It is reasonable to expect the heat capacity of bitumen to be similar to the heat capacity of liquid alkanes C_nH_{2n+2} in the limit as *n* becomes large. From the data of Weast (1980, p. D-176) an estimated value at 25°C is 2.2 J/g/°C. Since the temperature coefficient is apparently quite low, this value can be used at all temperatures.

Asphalt concrete. Since the contribution from the air-filled voids is negligible, the heat capacity of asphalt concrete is the weighted average of the heat capacity of the aggregate and that of the bitumen.

Thermal Conductivity

Ice. Data on the thermal conductivity of ice is available from the U.S. Coast Guard (1999). For temperatures between -50 and 0°C the data closely fit the linear equation

$$\kappa = 2.2212 - 0.01058T \qquad (18)$$

where κ is the thermal conductivity (W/m/°C) and T is the temperature (°C).

Water. Data on the thermal conductivity of water as a function of temperature is available from a number of sources (Weast, 1980, p. E-11; U.S. Coast Guard, 1999; Holman, 1976). An excellent fit for temperatures T from 0 to 100°C is given by the equation

$$\kappa = 0.5621 + 0.00193T - 7.3\times10^{-6}T^2 \tag{19}$$

Taconite aggregate. Data on the thermal conductivity of rocks and minerals are given by Clauser and Huenges (1995) and Vosteen and Schellschmidt (2003). For rock types similar to taconite, a good fit to the thermal conductivity data for temperatures T from 0 to 200°C is given by the equation

$$\kappa = 0.70 + \frac{770}{T + 350} \tag{20}$$

Bitumen. A reasonable estimate for the thermal conductivity of bitumen at 25°C is 0.17 W/m/°C. In the absence of data on temperature dependence, this estimate can be used at all temperatures.

Air. Reasonably consistent data on the thermal conductivity of still air is available from a number of sources (Weast, 1980, p. E-2; Dean, 1992, p. 5.142; Holman, 1976; Kreith, 1973). Data from -40°C to 100°C can be correlated well by the equation

$$\kappa = 0.02407 + 71.6\times10^{-6}T \tag{21}$$

Asphalt concrete. Asphalt concrete is a composite of three components: taconite aggregate, bitumen, and air, each of a different thermal conductivity. Calculating the effective thermal conductivity κ_{eff} of a fairly randomly ordered mixture of the three components is a common problem in applied physics. For linear composite systems, the same mathematical equations apply to thermal conductivity, electrical conductivity, dielectric permittivity, and magnetic permeability. Obtaining an exact mathematical solution depends upon knowing the exact microstructure of the media. Under certain assumptions, such as a random, isotropic media, even if no exact solution can be obtained, upper and lower bounds can be placed on the effective conductivity (Burridge et al., 1982). In the absence of further knowledge, our best estimate may be some sort of average of the upper and lower bounds. An excellent equation for this purpose for a two-component system, attributed to Landau and Lifshitz by Thuéry (1992), is

$$\kappa_{eff}^{1/3} = \upsilon_1\kappa_1^{1/3} + \upsilon_2\kappa_2^{1/3} \tag{22}$$

where υ_1 and υ_2 are the volume fractions of the two components. An obvious extension to our three-component system is

$$\kappa_{eff}^{1/3} = \upsilon_t\kappa_t^{1/3} + \upsilon_b\kappa_b^{1/3} + \upsilon_a\kappa_a^{1/3} \tag{23}$$

where the subscripts t, b, and a stand for taconite, bitumen, and air, respectively.

To compare with the results of equation (23), there is a limited amount of thermal conductivity data on asphalt concrete, obtained by uncalibrated slab cooling and thermal probe methods, available (Allen, 1995; Chadbourn et al., 1998). (Allen and Chadbourn are the same person.)

Sample Calculations for Asphalt Concrete With Taconite Aggregate

Because of the complexity of the calculations involved, an Excel spreadsheet was set up to calculate the physical and thermal properties of asphalt concrete made with taconite aggregate. As an aid to individuals who may wish to repeat this work, a sample calculation is given.

***Input Parameters*:**

Wt. fraction of magnetite in aggregate =	15.00%
Wt. fraction of bitumen in asphalt concrete =	6.00%
Void fraction in asphalt concrete =	8.00%
Temperature (°C) =	75.0

***Calculated Results*:**

Density of aggregate (g/cm^3) =	2.947
Vol. fract. bitumen in no-void asphalt concrete =	15.57%
Vol. fract. bitumen in asphalt concrete =	14.32%
Vol. fract. aggregate in asphalt concrete =	77.68%
Vol. fract. magnetite in aggregate =	8.50%
Vol. fract. magnetite in asphalt concrete =	6.60%
Density of asphalt (g/cm^3) =	2.435
Heat capacity of magnetite (J/g/°C) =	0.6987
Heat capacity of gangue (J/g/°C) =	0.8249
Heat capacity of aggregate (J/g/°C) =	0.8060
Heat capacity of asphalt concrete (J/g/°C) =	0.8896

Thermal conductivity of aggregate (W/m/°C) =	2.51
Thermal conductivity of bitumen (W/m/°C) =	0.17
Thermal conductivity of air (W/m/°C) =	0.0294
Thermal conductivity of asphalt concrete (W/m/°C) =	1.560
Thermal diffusivity of asphalt concrete (mm^2/s) =	0.720
Microwave absorption coeff. of asphalt concrete (m^{-1}) =	56.5
Microwave penetration depth (mm) =	17.7

Because taconite aggregate does not differ greatly in thermal properties from conventional aggregates, such as crushed granite and river gravel, it makes sense to compare the calculated results with measured values from Chadbourn et al. (1998) for a Superpave (SMA) hot-mix design asphalt concrete with the same bitumen content and void fraction. We estimate the heat capacity as 0.89 J/g/°C, in very good agreement with the Chadbourn's preferred value of 0.92 J/g/°C. Our calculated value of thermal conductivity, 1.56 W/m/°C, is in reasonable agreement with Chadbourn's measured value of 1.3 W/m/°C. In accordance with Chadbourn's results, our calculations show the thermal conductivity decreasing as the void fraction increases and increasing as the temperature decreases. We conclude that the Excel spreadsheet that has been developed gives reliable values for modeling the thermal behavior of asphalt concrete with taconite aggregate.

Practical Aspects of Computer Modeling

Solving equation (5) is most conveniently done by converting the partial differential equation to a finite difference approximation and solving. (In the one-dimensional case the finite difference and finite element methods are essentially identical.) The method is explained in many heat transfer textbooks, such as Kreith (1973) and Holman (1976), and in numerical analysis textbooks, such as Forsythe and Wasow (1960), Smith (1978), and Anderson et al. (1984). Specific application of numerical methods to microwave heating is illustrated by Watters et al. (1988), Liu and Marchant (1999, 2002), and Wu (2002). Thermal modeling of a conductive concrete bridge deck by the finite difference method is described in detail by Yehia (1999). A finite difference method for computing cooling during compaction of freshly laid hot-mix asphalt was described by Allen (1995) and Chadbourn (1998).

If we temporarily leave out the microwave energy source term, equation (5) becomes

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} \tag{24}$$

This can be rewritten

$$\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial z^2} \tag{25}$$

where D is the thermal diffusivity (units of m^2/s) , defined by

$$D = \frac{\kappa}{\rho C_p} \tag{26}$$

The simplest and most easily programmed method of solving equation (26) uses a forward difference approximation for the time derivative and a central difference approximation for the second distance derivative. This leads to a simple, explicit step-by-step solution method. The only problem with this solution method is that, for the solution method to be stable, the time increment Δt used in the calculation must meet the criterion

$$\Delta t \le \frac{(\Delta z)^2}{2D} \tag{27}$$

where Δz is the distance increment. This leads to a practical problem in modeling microwave deicing, because a realistic model requires very small distance increments within the ice layer. As reported by Wuori (1993, p.59), for disbonding of ice, melting of an ice layer of thickness on the order of 2 to 10 microns is sufficient. From the parameters given above, the thermal diffusivity for ice at 0°C is 1.144×10^{-6} m^2/s. For the minimum reasonable distance increment of 10 microns within the ice layer, by equation (27) for the explicit method the time interval cannot exceed 44 microseconds. Because of the quadratic dependence, the problem becomes much worse as the distance increment is decreased. If the distance increment is reduced to 1 micron, the time increment must be reduced by a factor of 100 to 0.44 microseconds. Since the time of exposure to microwaves in a realistic deicing application is on the order of 0.1 second or greater, an excessive number of time intervals would be required.

Because of this practical problem with the explicit numerical solution, a more complex implicit method would be preferable. Implicit methods, such as the well-known Crank-Nicolson method, typically require solving large sets of simultaneous linear equations and thus require substantial computer programming and debugging efforts.

Chapter 3
Conclusions

This report has presented a range of important parameters and equations relevant to the microwave energy absorption characteristics of magnetite-bearing aggregate (taconite) for use in deicing and pothole repair applications. The report also includes a review and summary of related literature.

As the report showed, there are limitations associated with an explicit numerical solution for mathematically modeling microwave deicing, and that a more complex implicit method would be preferable. Unfortunately, implicit methods are complex and require substantial computer programming and debugging efforts, efforts that were beyond the resources available to this project.

However, there comes a point where numeric modeling needs to give way to scaled-up laboratory and field testing of equipment and mix formulations, against which actual instrumented measurements can be made. This report and previous bench-scale research by the authors has shown that magnetite-bearing taconite aggregate is indeed an excellent microwave absorber. Therefore, we recommend that future work take advantage of these findings and apply them to such a scaled-up and practical testing program.

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Appendix A
Extended Literature Review

Probably the most widely cited guide on pothole repair is the "Pothole Primer," by Eaton et al. (1989). This publication explains why cheap repair methods, such as "throw-and-go" may actually be the most costly in the long run. A shorter "Pothole Primer" is available online (Santucci, 1999). Information on bonding of road aggregate to asphalt, test procedures, and further references are given by Santucci (2002).

In one of the earliest studies of the application of microwaves to road repair, Sawyer et al. (1973) used a 1.2-kW microwave system to perform melt curing of polymer concrete as a quick-patch technique for winter road maintenance.

Extensive commercial-scale work on application of microwaves to pothole patching and continuous strip repair of asphalt highways was done by the Microdry company in the early 1980s (Thuery, 1992; Lindroth, 2002). The equipment was capable of recycling old, broken-up asphalt concrete into a fresh, long-lasting road surface. In the truck-mounted demonstration system, a 100-kW microwave generator at 2.45 GHz was powered by a 180-kW diesel generator. The microwave energy was supplemented by hot air from the diesel exhaust.

In the state of Minnesota Lindroth et al. (1995) developed a smaller, but similar truck-mounted system for field testing of microwave thawing of frozen soils. A 6-kW, 2.45-GHz microwave generator and portable generator were mounted on the bed of a pickup truck and connected by flexible waveguide to a rectangular antenna stabilized 6.5 inches above the ground by a spring-loaded support frame. The antenna was shielded to provide for the safety of the operators by minimizing emitted microwave energy.

More recently Terry L. White and Timothy S. Bigelow of the Oak Ridge (TN) National Laboratory demonstrated a robot-like machine that uses microwaves to repair potholes and cracks (ORNL, 1997). It works by heating both the area to be fixed and the asphalt used to fill the hole in order to form a seamless bond. The repair is much more durable than that produced by simply compacting hot asphalt into a hole. The ORNL device was tested on standard asphalt patching compounds.

A Polish company, Marbet-Wil, Ltd., has developed the "Sul-Fix-Mix" process for pothole repair (Marbet-Wil, 2003). It is based upon a sulfur polymer called "Sulcem" that is produced from waste sulfur removed from natural gas. Road aggregate particles are covered with a layer of Sulcem powder, the mixture is used to fill a pothole, and the filling is compacted with a vibrating roller. Microwave radiation is then applied to form a strong, durable homogeneous composition permanently bonded to the road surface.

It has long been recognized that magnetite is a highly efficient absorber of microwave energy. Walkiewicz et al. (1995) proposed the use of microwave energy at the standard microwave oven frequency of 2.45 GHz to induce thermal stress cracking in taconite ores in order to decrease grinding energy requirements. Osborne and Hutcheson (1989) proposed an improved asphalt composite in which a microwave absorptive material is dispersed homogeneously throughout the asphalt matrix. Applying microwave energy enhances removal, reconditioning, and reforming of the asphalt composite during patching or repair operations. They showed that incorporating 2.0 percent magnetite by weight in the asphalt reduced the time required for the asphalt to reach its melt temperature of 250 °F from 240 seconds to 45 seconds when heated in a standard 2.45 GHz microwave oven. Further increase in magnetite content to 5.0 percent had little effect.

Howard W. Long (1995) also noted that pothole repairs by the use of applied microwave energy could be done more rapidly and effectively with a patching compound with enhanced microwave absorption. In addition, he recognized that paving with such a compound would enhance deicing of roads. Instead of using magnetite as the microwave absorber, Long tested a pavement formulation that was made microwave absorbing by the addition of 10 to 40 percent anthracite coal. A small test section of pavement was covered with 2 inches of water and frozen to below 0 °F. Long found that, when microwave energy was directed through the ice, the ice rapidly disbonded from the pavement, leaving a dry pavement section. Because ice is a relatively poor microwave absorber, the microwave energy was selectively absorbed at the pavement-ice interface, and little of the ice was melted before it was possible to remove it.

There is extensive literature on the performance of rubber-modified asphalt concrete (dry process). A brief summary, with references, is given by the Turner-Franklin Highway Research Center (2002). Two brief reports on the performance of asphalt-rubber in field testing in Minnesota and Florida were given by Turgeon (1989) and Choubane et al. (1998). A very extensive report was prepared by Roberts et al. (1989).

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