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An evaluation of electrically conductive asphalt mixtures for electrically heated flexible pavement systems

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AN EVALUATION OF ELECTRICALLY CONDUCTIVE ASPHALT MIXTURES FOR ELECTRICALLY HEATED FLEXIBLE PAVEMENT SYSTEMS

by

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Abstract

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The goal of this study is to develop Electrically Conductive Asphalt (ECA) mixtures with optimized electrical and mechanical properties for use in electrically heated asphalt pavements for anti-icing applications. Laboratory experiments were carried out to design ECA mixtures at varying dosages, using three graphite grades of different particle sizes, one virgin aggregate type, two binder grades, and one carbon fiber. The impact of graphite dosage and particle size on the volumetric properties and electrical resistivity of asphalt mixtures was assessed. Different factors with potential impact on the electrical properties were investigated, including the graphite particle size and dosage, the air voids level, the addition of carbon fiber, and binder PG used. Laboratory testing was conducted to evaluate the rutting, cracking, and durability of graphite modified mixtures using the Asphalt Pavement Analyzer, Hamburg Wheel Tracking Device , Semi-Circular Bend, Indirect Tension Cracking Test, and Cantabro loss tests. The results revealed that graphite improves the electrical conductivity of asphalt mixtures when introduced at dosages of 10 to 15% or higher by volume of binder. Graphite-modified mixtures prepared with larger graphite particle sizes, lower air voids, and carbon fibers' addition exhibited improved electrical conductivity than their equivalents. Furthermore, graphite modified mixes had better rutting resistance but higher susceptibility to breakdown and cracking than the unmodified control mix.

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Chapter 1

Introduction

1.1 Background

Statistics indicate that about 21% of all roadway accidents are directly related to weather conditions. Twenty-nine percent of these weather-related vehicle crashes occur on snowy, slushy, or icy pavements (Federal Highway Administration , 2020). This percentage alone represents thousands of personal injuries and fatalities and millions of dollars in property damage annually (Eisenberg and Warner, 2005). Furthermore, icy pavement surface conditions adversely affect aviation economic performance by causing flight delays or cancellations. Winter contaminants, such as snow, slush, or ice, also contribute to aircraft incidents; thus, most transport aircraft are not allowed to operate on runways covered by more than half an inch of snow or slush (U.S Department of Transportation Federal Aviation Administration [FAA], 2011). Snow and ice accumulation on paved surfaces is a seasonal problem that remains an uphill struggle for both state highway agencies and airports in all affected regions.

Several strategies have been traditionally employed to remove accumulated ice and snow from paved roadway and runway surfaces. Two of the most commonly used snow and ice removal methods are chemical melting and mechanical snow plowing, both of which have many detrimental effects on pavements (Yu et al. 2014). For example, deicing salts cause physical deterioration of pavements by decreasing the indirect tensile strength and modulus of mixtures and degrading the physical properties of asphalt binders (Hassan et al. 2002). Chemical melting agents also affect the environment by increasing the salinity of groundwater streams (Novotny et al. 2008) and causing plant damage (Czerniawska-Kusza et al. 2004). Moreover, chemical deicers have a corrosive effect which damages vehicles (Fay and Shi 2011) and transportation infrastructure such as reinforced or prestressed concrete structures and steel bridges(Shi et al. 2009). Mechanical snow removal has been proven to cause scraping and abrasion of the pavement surfaces (Nixon et al., 1996 Nixon et al., 1996 Ma et al. 2018) and affect the skid resistance of the pavement (Bandara, 2020). In airports, chemicals applied to runways impact the aircraft braking performance and require long removal time to clear priority areas, whereas mechanical snow removal damages the embedded lighting fixtures on runways (FAA, 2011). These challenges require innovations in pavement technology to reduce the negative impacts on transportation safety and reliability as well as the environment.

In recent years, an innovative, proactive solution to mitigate snow/ice accumulation has gained increased interest, which is the use of Electrically Conductive Asphalt (ECA) mixtures for electrically heated pavement systems (Arabzadeh et al. 2019; Hasan et al. 2021). The concept is to pass an electric current through the pavement structure; thus, generating heat in the pavement, preventing the accumulation of the ice/snow on paved surfaces. The electrically conductive mixture is prepared by incorporating sufficient amounts of conductive additives into the mixture; once these additives are dispersed into the mixture, they enable the conduction of electricity by creating a conductive path that allows for the charge flow

(Wu et al. 2013). The concept's ultimate purpose is to generate sufficient heat in the material through electrical resistance and deliver an adequate portion of it to the pavement surface, preventing snow/ice accumulation.

An electrically heated asphalt pavement system involves an electrically conductive asphalt layer as the heating element, a power supply, electrical wiring, a control system, and electrodes to transfer electric current into the pavement structure (Arabzadeh et al. 2019). While the electrical and control system components are commercially available, the design and development of an ECA mixture that meets the design requirement and achieves the necessary electrical conductivity without compromising the mechanical performance can be challenging.

Several studies have been conducted to develop and investigate the properties of ECA mixtures for snow and ice melting applications. Researchers have introduced electrically conductive additives in different types, forms, and dosages into conductive mixtures. Wu et al. (2005) studied the content at which different conductive additives should be incorporated into the mixtures. The researchers concluded that the conductive additive content introduced into asphalt mixtures should range between two values, the percolation threshold and the optimum additive content. Wu et al. (2005) defined the percolation threshold as the critical content of fillers at which the mixtures become electrically conductive, and that is characterized by a sudden improvement in the electrical conductivity. Table 1 presents the percolation thresholds for different conductive additives found by Huang et al. (2009)

and Vo and Park (2017). As shown in Table 1, the percolation threshold of one conductive additive may differ from one study to another, depending on the physical characteristics of the additive introduced. The optimal additive content was defined as the dosage at which the further increase in content does not remarkably enhance mixtures' electrical conductivity (Vo and Park 2017). Table 2 presents some examples of optimum additive contents.

Table 1

Percolation Threshold for Different Conductive Additives

Study	**Dosage (%) by Volume of inder**	**Conductive Additive**
Huang et al. (2009)	0.20%	Steel fibers
	1.03%	Carbon fibers
	9.20%	Graphite
Vo and Park (2017)	3%	Carbon fibers
	15%	Graphite
	10% + 1%	Graphite + Carbon Fibers

Table 2

Examples of Conductive Additive Contents Required Achieve Certain Resistivity Levels

Study	Dosage by volume of binder	Conductive Additive	Electrical Resistivity Level
Huang et al. 2009	1.32%	Steel fibers	100 Ω-m
	8.00%	Carbon fibers	
	28.00%	Graphite	
Zhang et al 2010	18% +3%	Graphite + Carbon Fiber (Aggregates are steel slag)	10 Ω-m

As shown in Table 2, electrical conductivity is characterized in terms of volume electrical resistivity in Ω-m. That is a material property that is the inverse of electrical conductivity. For an asphalt mixture to be as conducive as possible, its electrical resistivity should be as low as possible. Studies in literature achieved a high conductivity with an electrical resistivity as low as 100 Ω-m (Shao-peng et al. 2002; Huang et al., 2009; Liu and Wu 2011), and in some cases, with an electrical resistivity value even below 10 Ω-m (Pan et al. 2015) compared to an electrical resistivity level that ranges from 108 and 1012 Ω-m for conventional asphalt concrete (Pan et al. 2015). Nevertheless, the level of desired electrical resistivity differs from one project to another. The required resistivity varies with the geometry of the pavement, the spacing between electrodes, the voltage difference between the electrodes that are usually placed in alternating order of positively and negatively charged electrodes, and finally, the targeted power dissipation level by surface area.

To maintain a snow-free paved surface, Minsk (1968) designed small-scale slabs (to achieve a 215.3 Watt/ m2 power dissipation per unit surface area level, using a 30 volts power. Zhuang et al. (2016) reported a power dissipation level of 200 Watt/m2 for ice/snow removal applications. Arabzadeh et al. (2019) conducted a snow melting experiment on a (380 mm X 210 mm) slab with a thickness of 75 mm and three electrodes embedded in the conductive asphalt mixture with a diameter of 25 mm each and spaced 152.5 mm apart. The slab successfully melted a 190-mm-thick layer of snow in 2 hours when connected to a power supply of 40 volts.

It is essential to bear in mind that conductive asphalt concrete is a posistor material, a material that its resistance increases with temperature. Arabzadeh et al. (2019) performed a field test and reported a decrease in resistivity due to low ambient temperature at the beginning of the test. Conversely, the heat generated within the slab increases the material's volume resistivity, leading to a reduction in the electric current flow. According to Arabzadeh et al. (2019), conductive asphalt concrete's posistor behavior results in highly efficient energy consumption of electrically heated pavements as the material reacts to heat loss with an increase in electric current, which enhances the heat generation process.

The conductive additives commonly used in literature come in fibrous and powder forms. Previous studies indicated that fibrous additives help better enhance asphalt mixtures' electrical conductivity than powdery additives due to their high aspect ratio (Wu et al. 2005 and Huang et al. 2009). However, fibers have a relatively high cost and a tendency to clump and gather in bundles causing a non-uniform dispersion within asphalt mixtures (Wu et al. 2013; Vo and Park 2017). Notani et al.

(2019) and Gureri and Gürgöze (2017) found that fibers of shorter length help better improve the conductivity due to more uniform distribution within asphalt mixtures. Researchers have also investigated the dosage of different conductive additives that must be incorporated into the mixture to bring the electrical conductivity to the required level. Powder additives must be introduced in much higher quantities (up to 25% by volume of binder) than fibrous additives that were generally introduced in dosages less than 5% (by volume of binder).

Limited earlier investigations studied the impact of conductive additives on the mechanical properties of asphalt mixtures. Liu and Wu (2011) reported that although graphite's addition improves the electrical properties of asphalt mixtures, it does not enhance the mixtures' mechanical strength. Liu and Wu (2011) suggested optimizing the graphite content to ensure acceptable electrical and mechanical properties. Finally, the literature suggested that the combination function of fibrous and powdery additives had appreciable advantages over single filler regarding the electrical conductivity, mechanical performance, and the overall cost of asphalt mixtures (Liu and Wu 2011; Wu et al. 2013; Vo and Park 2017).

1.2 Problem Statement

The previously presented studies highlighted that conductive asphalt mixtures' electrical properties are dependent on the type, form, and dosage of electrically conductive additives. These studies provided a proof of concept that the use of electrically conductive asphalt mixtures can be effectively used for snow and ice melting applications. However, many gaps in the available literature have been identified as follows:

- Limited research exists focusing on the impact of conductive additive dosage on the volumetric properties of asphalt mixtures. For many of the studies, no separate mix designs were performed for the mixtures containing conductive additives. Only adjustments to the gradation were made to reduce the fine aggregate portion from the control mix. (Huang et al. 2009; Yang et al. 2013; Vo and Park 2017).

- Limited studies focused on how various raw materials, like binder and aggregates, affect conductive asphalt mixtures' electrical properties. Most of the studies designed conductive asphalt mixtures using the same nominal maximum aggregate size of 19 mm (Lui and Wu 2011; Wu et al. 2013; Bai et al. 2015; Vo and Park 2017), whereas other studies used another coarse nominal aggregate size of 12.5 mm (Huang et al. 2009). Furthermore, no studies investigated the effect of different binder grades on the electrical properties of asphalt mixtures. The majority of studies utilized one binder grade for all samples (Shao-peng et al. 2002; Lui and Wu 2011; and Wu 2013). A neat binder of PG64-22 was used in most cases (Huang et al. 2009; Bai et al. 2015; Vo and Park 2017).

- While some studies focused on the length of carbon fibers used as conductive additives (Gureri and Gürgöze 2017; Alnotani et al. 2019), and others investigated the different types of graphite introduced (Shao-peng et al. 2002), no attention has been given to particle size on the volumetric and electrical properties of ECA mixtures when additives additives are introduced in the powder form. When graphite was used as a conductive filler, not only did the reported studies use one particle size of graphite, but they were also conducted using the same particle size average of 150 μm (Wu et al. 2005; Lui and Wu et al. 2011; Yang et al 2013 ; Wu et al. 2013, Bai et al. 2015 ; Vo and Park 2017).

- Most of the studies prepared conductive asphalt mixtures at the same air void level, with no studies considering the effect of different air-void levels on the mixtures' electrical conductivity.

- Lack of studies focusing on the electrical resistivity testing of electrically conductive asphalt mixtures.

Therefore, additional research should be conducted to address these gaps in the current state of knowledge presented.

1.3 Research Hypothesis

This study was conducted to investigate the hypothesis that a mix-design approach can be followed to successfully develop a cost-effective conductive asphalt mixture that balances electrical resistivity with laboratory performance (rutting, durability, and cracking) .

1.4 Significance of the Study

This study is conducted to fill the research gap and design ECA mixtures using graphite of different particle sizes and varying dosages. The conductive mixtures are designed as a High-Performance Thin Overlay (HPTO) mix, meeting the New Jersey Department of Transportation (NJDOT) requirements using a nominal aggregate size of

4.75 mm, broadening with that the aggregate gradation ranges typically used in literature. The study involves designing and testing large sets of asphalt mixtures of various properties, all in accordance with the Superpave mix design and performance test specifications.

The study evaluates the effect of graphite dosage and particle size on the volumetric properties of ECA mixtures. The study considers the impact of graphite dosage and particle size, binder grade, and air voids levels on asphalt mixtures' electrical conductivity. Additionally, the study provides a comparison between the electrical conductivity of mixtures prepared using graphite and those prepared using a combination of graphite and carbon fibers. The investigation of these various parameters comes in an attempt to expand the understanding of how different properties can be controlled to obtain optimized electrical properties of ECA mixtures at the lowest cost possible. Finally, the study assesses the effect of graphite as conductive filler on asphalt mixtures' laboratory mechanical performance, including rutting, durability, and cracking performance. This will help to broaden the knowledge of the mechanical strength of electrically conductive asphalt mixtures.

As the next phase of this study, the designed mixture with the most improved electrical conductivity will be utilized in a full-scale construction of an electrically heated flexible pavement to provide an evaluation of the system's efficiency in ice/ snow accumulation mitigation. The flexible pavement section will then be tested on the accelerated pavement testing facility to widen the understanding of the actual (in-field) performance of electrically heated flexible pavements. The full-scale construction will also bring an insight into the practicality, operational costs, feasibility, sustainability, and reliability of electrically heated pavement systems as an alternative deicing technique. If the experimental laboratory plan were successful, the following benefits would be offered to the Department of Defense (DoD):

- A dosage -particle size- electrical resistivity model that helps predict the required graphite dosage and particle size to achieve the desired resistivity; and
- An insight into the electrical properties, power requirements, and the cost of producing electrically conductive asphalt mixtures, a multifunctional material that can be possibly utilized in many innovative applications including self-healing, damage self-sensing, energy harvesting, and cathodic protection of concrete bridge decks;

If the constructed electrically heated flexible pavement were found to be effective for the prevention of ice/snow accumulation, the following benefits would be offered to the Department of Defense (DoD):

- Snow free airfield pavements,
- A solution for ice/snow accumulation problem in winter storm conditions,
- Economic benefit by reducing flight cancelation and delay caused by winter storm conditions,
- Environmental benefit: an alternative strategy for mitigating the impacts of deicing salts contaminants,
- Enhanced safety for aircraft and equipment operators
- Increased aviation capacity during winter storm conditions,
- Reduced snow removal times required to clear priority areas; and

- An insight into the cost, heating capability, and power requirements of electrically heated flexible pavements.

1.5 Research Objective

This study presents a laboratory experiment to assess the laboratory electrical and mechanical performance of electrically conductive asphalt mixtures.

This phase of the study aims to evaluate the electrical conductivity of ECA mixes prepared with graphite and carbon fibers. The study involves evaluating the laboratory mechanical performance of these asphalt mixtures containing conductive additives (i.e., graphite). Besides, this study examines the impact of graphite particle size, binder PG grade, and sample air voids on ECA mixes' electrical conductivity and performance. The objectives to achieve the goal are as follows:

- Design control (with no additives) and graphite modified asphalt mixtures at initial dosages ranging from 10% to 20% (by volume of binder) using three different graphite particle sizes, all according to the Superpave volumetric mix design procedures.
- Develop an efficient resistivity-testing set-up and evaluate the electrical resistivity of the control (unmodified) and the electrically conductive samples that meet the design requirements.
- Optimize the dosage of each graphite size with the lowest possible electrical resistivity.
- Evaluate the electrical conductivity of modified asphalt mixtures prepared at two different air void levels, binder grades, with or without 1% of carbon fibers for three different graphite particle sizes at the optimum dosage: and,

- Evaluate the mechanical performance of the control and modified mixtures at optimal graphite dosage.

1.6 Research Approach

The research approach developed to meet the overall goal of this study consisted of the following tasks:

1.6.1 Task 1: Conduct a Comprehensive Literature Review

This task is performed by reviewing studies related to conductive asphalt mixtures to gain an insight into the conductive additives that are typically incorporated in mixtures, along with the advantages and disadvantages of each conductive additive form. Additionally, the literature provided the typical dosages at which additives are usually introduced as a starting point for determining each additives' percolation threshold. Previous studies also presented different mixing techniques used for introducing the conductive material into the asphalt mixtures. Finally, the literature shed light on the electrical resistivity values typically achieved among various studies and the voltage difference commonly applied, and the typical power dissipation values achieved.

1.6.2 Task 2: Material Selection and Procurement

This process includes selecting conductive material, calculating the estimated material quantities needed, procurement of raw materials, and the procurement of a resistivity-testing device.

1.6.3 Task 3: Design a Conductive Asphalt Mixtures

Develop an experimental program to design electrically conductive mixtures at initial dosages ranging from 10% to 20% by volume of binder to determine the percolation threshold and the optimum graphite dosage for three different particle sizes of graphite.

1.6.4 Task 4: Electrical Resistivity Testing and Dosage Optimization

In this task, electrical resistivity tests are employed to determine the optimum dosage of each graphite particle size; this is an iterative process that includes a repeated cycle of mix design and resistivity testing. Figure 1 demonstrates the iterative process; if the increase of 5% by volume of the binder of conductive additive results in a significant electrical resistivity improvement and next dosage of conductive additives will be designed until the improvement in electrical resistivity is insignificant.

1.6.5 Task 5: Prepare Conductive Asphalt Mixtures at Optimized Graphite Dosage

This task is done for three graphite particle sizes at the optimum dosage of each, at 3.5% and 7% air voids, using a neat and modified binder, with or without carbon fibers.

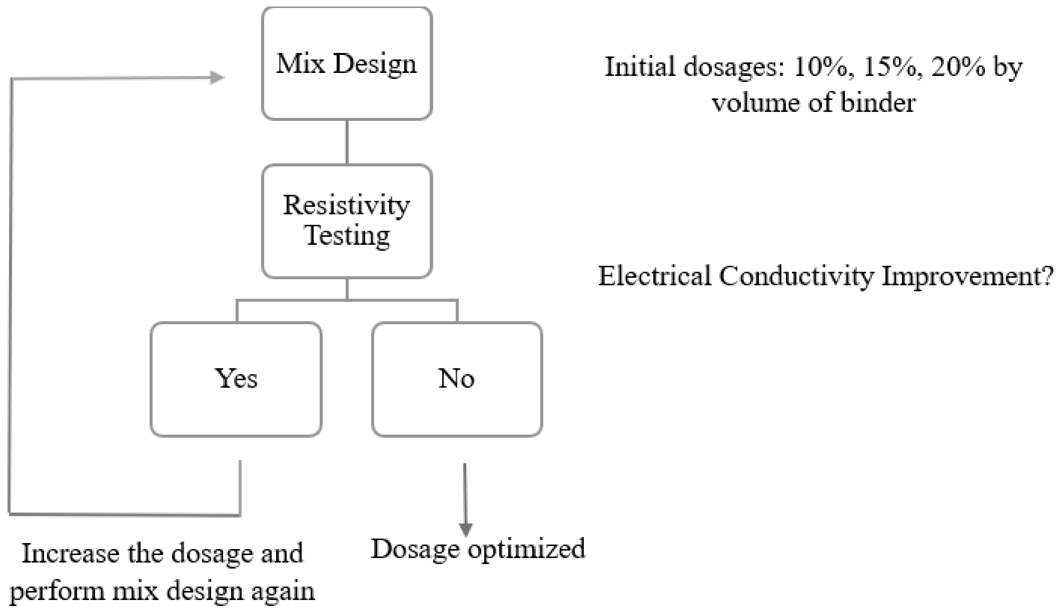
1.6.6 Task 6: Laboratory Performance Testing

Laboratory tests are performed at optimized dosages for three-graphite particle sizes; the tests include:

- Dry Rutting Resistance Using the Asphalt Pavement Analyzer (APA)
- Wet Rutting Resistance Using the Hamburg Wheel Tracking Device (HWTD)
- Durability Using the Cantabro Loss Test
- Cracking Resistance Using the Semi-Circular Bend (SCB)
- Cracking Resistance Using the Indirect Tension Asphalt Cracking Test (IDEAL-CT)
-

Figure 1

Electrical Resistivity Testing and Dosage Optimization (Iterative Process)



1.6.7 Task 7: Recommendations for Future Research

This task included reporting the results with recommendations that can aid and enhance future research or implementation of electrically heated pavement systems.

Chapter 2

Literature Review

2.1 Electrically Conductive Asphalt Mixtures

An Electrically Conductive Asphalt (ECA) mixture is an asphalt mixture incorporated with a sufficient amount of electrically conductive constituents (Wu et al. 2005). Once these constituents are dispersed into an asphalt mixture, they enable the conduction of electricity by creating a conductive network that, in turn, allows electrical current to pass through (Park and Vo 2017). Minsk first introduced the concept of ECA mixtures in 1968 as a technique for heating the pavement for deicing applications. Minsk (1968) performed laboratory and field tests to validate that asphalt mixtures can potentially conduct electricity. Minsk prepared laboratory samples by replacing a portion of the mineral aggregates with a more conductive material such as graphite and aluminum chips. Exploratory tests led to the rejection of aluminum as a conductive filler, whereas graphite was used to prepare conductive samples (with a low resistivity of one 2.54 ohm - cm). Minsk used the graphite-modified mixture to construct an outdoor test section that could keep a snow-free surface during the winter; however, the test section failed to meet the design requirements due to the contractor's unfamiliarity with the conductive mix.

An Electrically Conductive Asphalt Concrete (ECAC) is a multifunctional material that can be possibly utilized in many innovative applications. (ECA) composites can be a promising structural material with many potential non-structural functions including self-healing, damage self-sensing, energy harvesting, cathodic protection of concrete bridge decks and deicing. Liu et al. (2011) and Garcia et al. (2011) demonstrated the ability of ECA mixtures to promote (accelerate) self – healing by raising the temperature of the pavement using heat induction. Both studies proposed a non-contact electric heating technique using electromagnetic fields. Liu and Wu (2009) investigated the piezo-resistivity effect of ECAC, which refers to change in electrical conductivity with applied mechanical stress; the researchers examined asphalt mixtures modified with carbon fiber and graphite and concluded that applied stress or strain considerably affect the resistance of ECA mixes, which indicates a microstructural change in the material. Hence, the piezo-resistivity mechanism can be utilized for damage monitoring and self-sensing applications in pavements. Guo, and Lu (2017) designed an energy harvesting pavement system that collects the dissipated vehicle kinetic energy to generate electric energy. The ability of certain materials to generate an electric charge in response to applied mechanical stress is known as the Piezoelectric Effect. Guo and Lu (2017) designed a pavement system that consists of two conductive asphalt layers and one piezoelectric material layer as a piezoelectric energy harvester. Fromm (1976) suggested that ECA mixtures could potentially prevent the corrosion of the concrete bridge deck's rebars by applying cathodic protection to the deck. Fromm (1976) described that spreading the ECA mix over the bridge deck can distribute the protective power. Resistance probes were buried in the decks and indicated that ECA provided protection against corrosion.

This study will focus on the use of ECA mixtures in electrically - heated pavement systems for deicing and anti-icing applications. The basic concept is to heat the pavement electrically by converting electric energy to heat. This system involves embedding electrodes into the pavement structure to transfer electric current through a conductive layer (Malakooti et al. 2020). This system is an emerging technique for regions that require deicing, high impact areas of applications would be critical paved areas such as airports, and roadways with persistent reliability requirements. These pavements do not only remove snow from the surface (deicing), but they also can prevent its accumulation in the first place (anti-icing) by passively heating in winter storm conditions to just above the freezing point of water.

Intending to utilize the broad- spectrum of ECA mixture's applications, an excellent conductivity of the mixture must be achieved. That refers to asphalt mixtures with easiness of electric current flow with easy heat release and stable conductive performance in the long run (Pan et al., 2015).

Studies in literature achieved a high conductivity with an electrical resistivity as low as 100 Ω-m (Shao-peng et al. 2002; Huang et al., 2009; Liu and Wu 2011), and in some cases, with an electrical resistivity value even below 10 Ω-m (Pan et al. 2015). The quantification of electrical conductivity in terms of electrical resistivity is explained in the section 2.3. With that being said, the pavement self-deicing system's challenge is to construct a conductive asphalt mixture with both excellent conductivity and acceptable mechanical properties.

2.2 ECA Mixture Components and Mixing Methods

For an asphalt mixture to be electrically conductive, a portion of its non-conductive material (aggregates) is usually substituted with one or more conductive additives. These additives are incorporated in one of the two methods, the wet or dry mixing method. When the wet mixing method is used, the conductive additive is introduced into the mixture after the binder (the wet component of the mixture) is mixed with the aggregates. When the dry mixing method is used, the conductive additives are blended directly with the aggregates (the dry component of the mixture), before being mixed with the binder. For example, Bai et al. (2015) reported that for dry mixing, the conductive fillers were added to the heated aggregates before mixing with the binder, while the wet mixing method involved using a high-speed shear mixer and a hot plate. The asphalt was heated to 180∘C, and the conductive fillers were then added and stirred from 500 to 3500 rpm for 30 minutes. It can clearly be seen from this example from the literature that the wet mixing method requires a great deal of time and energy compared to the simple dry mixing method.

Table 3 presents a summary of the components of ECA mixtures prepared in previous studies. Table 3 lists the Nominal Maximum Aggregate Size(NMAS) of aggregates used in each of the studies, the binder grade used, the target air voids for the mixes prepared, the conductive additive introduced, and the dosage at which each additive was introduced and finally, the Optimum Asphalt Content (AC%) required to meet the air voids requirements. As can be seen from Table 3, aggregates gradations with a 12.5 mm or 19 mm NMAS were common among previous studies, with all studies using one type of binder for all mixtures. The target air voids were 4% in all presented studies, and the dosage varied with the additive introduced in each mix. It is important to note that in some studies, Lui and Wu (2011), for example, the optimum binder content was adjusted for each conductive additive and dosage. In other studies, Vo and Park

(2017), for example, no binder content adjustments were reported, even though both the conductive additives and the dosages varied.

It is noteworthy that the dosage of the conductive additives introduced into the mixture was reported in terms of a volume fraction of the asphalt binder used in most of the studies presented in Table 3 and the literature. Nonetheless, in some cases, the dosage was reported as a percentage of the total mix weight. Table 4 presents the few studies that introduced conductive additives by total mixture weight. It can be seen from Tables 3 and 4 that carbon fiber, for example, was introduced in much lower percentages in the case of total weight fraction compared to volume fraction.

Table 3

Summary of Materials and Dosages used in Previous Studies to Prepare ECA Mixtures

Study	Aggregates NMAS	Binder Grade	Target Air Void	Dosage *	Conductive Additive	Optimum AC%
Lui and Wu (2011)	19 mm	AH-70 (60 – 70 mm penetration)	4%	0%	-	4.2%
				15%	Graphite	4.8%
				22%	Graphite	5.2%
				2%	Carbon Fiber	4.3%
				15% + 2 %	Graphite + Carbon Fiber	4.9%
				22 %+ 2%	Graphite + Carbon Fiber	5.3%
Wu et al. (2013)	19 mm	A styrene–butadiene–styrene (SBS) modified asphalt (72 mm penetration)	4%	18%+2.5%+2.2%	Graphite + Steel Fibers + Carbon Fiber	8.7%
Vo and Park (2017)	12.5 mm	PG64-22 (65 mm penetration)	4%	5%, 10%, 15% , and 20%	Graphite	5.3%
				1%, 2%, 3%, and 4%	Carbon Fiber	
Alnotani et al. (2019)	12.5 mm	PG 58-28	4%	1%**	Carbon Fiber	6.3%

* Dosages are generally represented in terms of volume of the binder.

** Dosage is represented in terms of the total volume of the mix.

Table 4

Examples of Conductive Additives Introduced by Total Mix Weight

Study	Conductive Material	Dosage (By Total Weight of Mix)
Shao-peng et al. (2002)	Graphite Particles (crystalline and micro-crystalline)	0% to 20 %
Garcia et al (2011)	Steel Wool (fibers)	7.50%
Gürer and Gürgöze2 (2017)	Carbon Fiber	0.1%, 0.2%, 0.3%,0.4%,0.5%

2.3 Electrical Properties of Conductive Asphalt Mixtures

Asphalt mixtures' electrical properties are generally characterized in terms of electrical conductivity and its inverse, electrical resistivity. The electrical conductivity of an asphalt mixture represents the material's ability to conduct electric current. In contrast, electrical resistivity (the inverse of conductivity) quantifies the material's resistance to the passage of electric current regardless of its shape or size. Equations 1 shows the relationship between a material's resistivity and conductivity.

$$Conductivity\ \left(\frac{1}{\Omega \cdot m}\right) = \frac{1}{Resistivity\ (\Omega \cdot m)} \qquad (1)$$

$$Resistivity\ (\Omega \cdot m) = \frac{Resistance\ (\Omega) \times Cross\ Sectional\ Area\ (m^2)}{Specimen\ Height\ (m)} \qquad (2)$$

Equation 2 represents the relationship between resistivity and resistance of a material. It can be inferred from the equation that resistivity is an intrinsic[1] property of

[1] An intrinsic property is a property of a substance independent of the amount of the substance present. Such properties are inherent qualities of the type and form of matter, mainly dependent on chemical composition and structure such as density and specific gravity.

the material that describes how many conducting particles are present per one unit of cross-sectional area and for each unit of length, how many electrons they carry, and how fast they move in an electric field. Electrical resistivity is independent of the geometry of the material.

Resistance is a property in electrical circuits that governs the relationship between voltage difference and current. The German physicist Georg Simon Ohm discovered this relationship in 1827, introducing Ohm's law, which states that:" the amount of steady current through a material is directly proportional to the voltage across the material, for a fixed temperature." Equation (3) represents Ohm's law formula:

$$\text{Resistance } (\Omega) = \frac{Voltage\ (volt)}{Current\ (Amp)} \qquad (3)$$

Concerning the electrical resistivity of the conductive asphalt mixtures, Ohm’s law was used in the literature for determining the desirable (design) resistance once the voltage difference and the amount of current are obtained. Thus, the resistivity can be calculated using the length and the cross-sectional area of the material. Minsk (1968) could obtain the necessary resistivity using equations (2) and (3); based on the design requirements of 20 Watts/square foot power dissipation per unit surface area and a conductive layer thickness of 1/2-in, for a 30-volt potential drop between electrodes that are spaced 5 ft. apart.

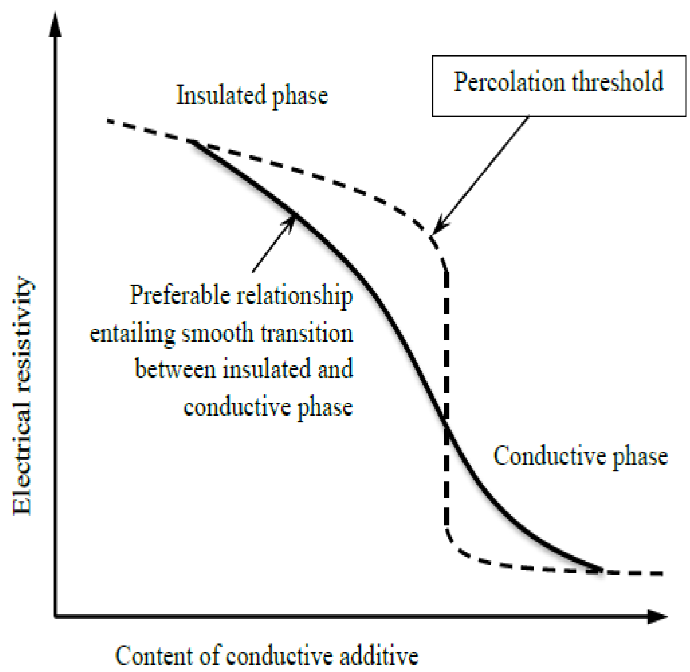
Resistive heating (also Joule Heating and Ohmic Heating) is the process by which the passage of an electric current through a conductor produces heat. The concept was first introduced in 1840 by James Prescott Joule, who suggested that the heat generated is caused by the collisions between charge carriers (electrons) and the conductor (the conductive asphalt mixture in our case). The electrically conductive pavement system can be described as a single - one loop- electric circuit in which the voltage difference pushes the charge to move between the electrodes, creating an electric field that accelerates the electron flow in its direction, giving them kinetic energy. As the charged particles collide with the conductor, they become scattered, meaning that their motion direction is random and not aligned with the electric field, which creates thermal motion, in which the electrical field energy is converted to thermal energy. This thermal energy is dispersed along the conductive path through the pavement, functions as a heating element, and deices the surface.

2.4 Percolation Threshold and Optimal Additive Content

As can be inferred from Equation (1), for an asphalt mixture to be conductive, its electrical resistivity must be low enough to allow electrons to pass through easily. This is achieved by incorporating a sufficient amount of conductive additives that can establish a three-dimensional conductive network, according to Wu et al. (2005). The conductive additive content at which the asphalt mixture transitions from the non-conductive to the conductive phase is referred to as the percolation threshold and is characterized by a sudden drop in electrical resistivity. Figure 2 below illustrates the sudden jump in electrical resistivity at the percolation threshold on the electrical resistivity transition curve. Wu et al. (2005) also pointed that at a level of saturation, the increase in conductive additive content does not significantly improve the electrical conductivity of the mixture. This specific content is referred to as the optimal content. Thus, additives' ideal content should not exceed this point to minimize the effect on the asphalt mixtures' mechanical properties.

Figure 2

Percolation Threshold (Baranikumar, 2013)



Several studies investigated the optimal dosage at which conductive additives must be incorporated into the mixture. Starting from 1968, Minsk prepared laboratory ECA mixtures at two graphite levels of 20% and 25%. Minsk (1968) reported that the graphite content was increased to meet the mixture's electrical requirements (of approximately 2.54 ohm - cm). While each conductive additive has its specific percolation threshold and optimal dosage that changes with the physical characteristics of the additive, the overall trend of the electrical resistivity being reduced with the increase of content, with a sudden drop in resistivity at the percolation threshold and the reduced rate of change in resistivity at the optimal dosage was common in different studies for different additive.

For instance, Huang et al. (2009) examined the impact of three different conductive additives, namely micron-scale steel fibers, carbon fibers, and graphite. Although the conductivity values varied significantly for each additive type, the three types of values appeared to follow the same pattern of a sudden improvement in conductivity after the percolation threshold was reached. This percolation threshold is 0.2%, 1.03%, and 9.20% by volume content of binder for steel fibers, carbon fibers, and graphite, respectively. To bring the electrical conductivity to the same level of 100 Ω .m, an optimum dosage of 1.32%, 8.0%, and 28.0% was needed for the aforementioned additives, respectively.

2.5 Conductive Additives

Conductive additives can be classified based on the type of material and the form of particles being used. The asphalt mixture's conductivity was found to vary significantly with the use of each type and form. In this section, the characteristics of these additives, the advantages and disadvantages of different additive forms, and the factors that make these additives compatible with the asphalt mixture are discussed in detail.

2.5.1 Conductive Additives Forms

Carbon, graphite, steel, and aluminum were the primary materials used as conductive additives in previous studies. These come into different shapes and sizes (forms) as follows:

- Powder form: small particles that usually replace the fine aggregates in the mixture. Some examples of powdery conductive fillers are graphite, carbon black, and steel shavings. Most of the studies on literature (Wu et al. 2005; Huang et al. 2009; Liu and Wu 2011; Wu et al. 2013; Yang et al. 2013; Bai et al. 2015; Vo and Park 2017) used graphite with an average particle size average of 150 μm. Wu et al. (2005) used Acetylene Carbon Black with a 42 nm particle size.

- Fibrous form: researchers have commonly used fibrous additives. Some of the fibrous conductive additives are carbon fibers, steel fiber, steel wool, ad carbon Nanofiber. These additives have a high length to thickness ratio (aspect ratio). For instance, Wu et al. (2005) and Vo and Park (2017) reported using carbon fibers that are ten μm in diameter with an average length of 5 mm, whereas other researchers such as Gureri and Gürgöze (2017) and Notani et al. (2019) used fibers of different average lengths to study how the length affects the properties of ECA mixtures.

- Solid particles form: rarely used as a substitute for the coarse and fine aggregate according to their diameters. Examples of these are steel slag and carbon particles. Chen et al. 2012 and Ahmedzade and Sengoz (2009) prepared ECA mixtures using steel slag as the whole aggregates in the mixture, which demonstrated electrical conductivity improvement compared to natural aggregates.

Many researchers have investigated the effect of the conductive additives form in the electrical conductivity of asphalt mixtures. Huang et al. (2009) and Wu et al. (2013) reported that the use of fibrous conductive additives resulted in asphalt mixtures with higher electrical conductivity than powder additivities. Wu et al. (2005) reported optimum contents of 15%, 16%, and 6% when carbon black, graphite, and carbon fiber were used, respectively. The form of additives also plays a crucial role in the mechanical performance of ECA mixtures. Huang et al (2009) produced ECA mixes using micron-scale steel fiber, carbon fiber, and graphite. Huang reported that both steel and carbon fibers improved the laboratory performance of the mixtures, whereas graphite, because of its high content requirement, significantly altered the performance of the mixtures and particularly deteriorated the cracking resistance.

Garcia et al. (2009) investigated the conductivity of asphalt mortar modified with conductive fillers, fibers, and a combination of both. The conductive filler used was graphite, and the fiber-type additive was steel wool. Garcia et al. (2009) concluded that the percolation threshold happened by introducing much fewer fibers than fillers. The study revealed that the percolation threshold is a function of the sand-bitumen ratio, as well as the volume of fiber content. Garcia et al. (2009) also reported an optimum fiber content above which it is hard to make the "mixture and the electrical resistivity increases exponentially." In the case of conductive fillers or the combination, it was reported that once the maximum conductivity is reached, it remains constant, even when more fillers are added.

Chen et al. (2012) prepared ECA mixtures using steel slag as the whole aggregates in the mixture while mixed with graphite and carbon fiber as conductive fillers. Chen et al. (2012) evaluated the electrical properties of steel slag ECA mixtures compared to a control ECA mix (using basalt aggregates) by varying the graphite content from 10% to 24% by volume of binder in mixtures. At the maximum graphite content introduced (24% of binder volume), steel slag mixtures showed an electrical resistivity of 7.38. Ω-m compared to 6210 Ω-m for basalt asphalt mixtures. Chen et al. (2012) explained that utilizing steel slag as aggregates in the mixture improves the electrical properties by creating complex conductive paths through conductive steel slag aggregates and graphite powder compared to those created by graphite only.

2.5.2 Advantages and Disadvantages of Powder and Fiber Conductive Additives

Previous studies have shown that the conductive additive form is one of the main factors affecting the electrical properties of asphalt mixtures. Conductive additives in the form of powder have to be added in much higher quantities than those in the fiber form to produce conductive mixtures (Garcia et al., 2009). Most of the studies introduced graphite in percentages between 5% and 20%, in 5% increments (Bai et al. 2015, Vo and Park), while carbon fibers were introduced in percentages less than 5% and in 1% increments (Vo and Park 2017), as a fraction of the binder volume.

Wu et al. (2005) explained that fibers led to mixes with higher electrical conductivity due to the high aspect ratio that allows them to provide a bridging effect. Because of their high length to thickness ratio, fibers tend to tie (intermingle) together, which allows for a smoother flow of the current throughout the asphalt mixture. On the other hand, Wu et al. (2005) concluded that the use of excessive fiber contents (carbon in their study) leads to clumping when producing mixtures and ultimately results in non-uniform dispersion of fibers within asphalt mixtures. Vo and Park (2017) also reported similar observations.

While the previously mentioned studies (Wu et al. 2005; Vo and Park 2017) used one constant average length of carbon fibers, other studies used fibers with multiple average lengths to study the impact of fiber length on mixes' conductivity. Alnotani et al. (2019) and Gureri and Gürgöze (2017) used carbon fibers with average lengths of (3, 6, 12) mm and (5, 10, 15) mm, respectively. Both studies found that asphalt mixes' electrical conduct is inversely related to the length of fibers because shorter fibers (lengths of 3 and 5 mm) had more uniform distribution within mixtures than longer ones. Fibers with a higher length to thickness ratio (aspect ratio) are more likely to flocculate together during mixing, causing clumping of fibers.

To ensure adequate distribution of fibers, Vo et al. (2017) suggested a solution referred to as sonication, a technique that involves subjecting fibers to shear stress to induce a tensile force and disperse fiber bundles using an Ultrasonic bath to develop dispersion. This proceeds by immersing the carbon fibers in the bath for 360 minutes then drying them in a UV reactor for 60 minutes until the fibers become loose and incoherent. Using these sonicated fibers showed a significant improvement of 5% in the asphalt mixtures' thermal conductivity properties.

Another disadvantage of fibrous additives is the sudden drop in electrical resistivity at the percolation threshold. The transition from non-conductive to conductive phase is preferred to smooth. The percolation threshold is predominant when fiber additives are used; powdery additives can mitigate this phenomenon. Although a larger quantity is required, the use of powder additives ensures easy mixing and uniform dispersion.

Table 5 presents a comparison between the carbon fibers and graphite as reported in the literature, summarizing the advantages and disadvantages of additives in fibers and powder forms.

Table 5

Comparison between Carbon Fibers and Graphite as Conductive Additives in ECA Mixtures

Parameter / Additive	Carbon Fiber	Graphite Powder
Size *	Diameter: 10 μm Length : 5 mm	Diameter:150 μm
Distribution	clumping during mixing	relatively uniform distribution
Percolation threshold	the percolation threshold is prevalent	mitigated (less prevalent)
Quantity **	Less quantities	larger quantities

* Size as reported by Wu et al. 2005 and Vo and Park 2017

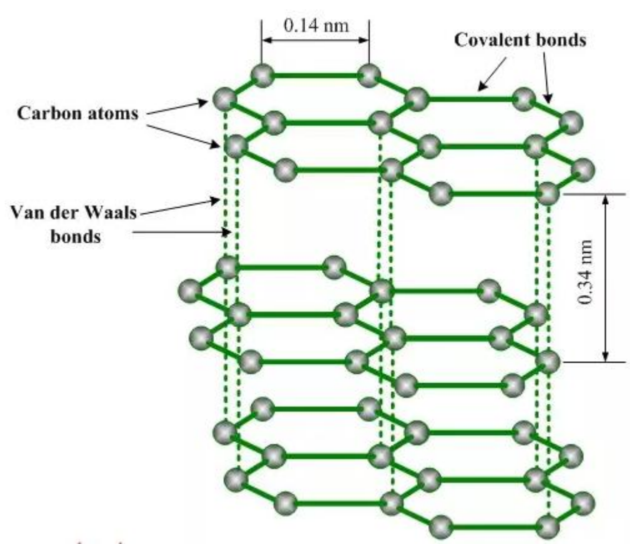
** Quantity needed to reduce the electrical resistivity to the same level.

2.5.3 Compatibility of Graphite and Carbon Fiber with Asphalt Mixtures

Many conductive materials were investigated for their suitability, with ECA mixes with graphite, carbon, and steel being the most compatible candidates for incorporation into the paving mix. Moreover, the high melting point of each of these materials (3600°C, 3675°C, and 1370 °C for graphite, carbon, and steel, respectively) makes it resistant to the high mixing temperatures of asphalt mixes. These conductive additives, according to Minsk (1971), are relatively similar to the typical constituents of asphalt mixtures, which results in a minimized effect on pavement performance.

Graphite is a naturally occurring form of crystalline carbon with a layered structure consisting of rings of six carbon atoms arranged in widely spaced horizontal sheets. Graphite, therefore, crystallizes in the hexagonal system. Its structure is the main reason for most of its characteristics. Figure C illustrates graphite structure; as can be seen from the figure, each carbon atom in graphite is connected to three other carbon atoms through covalent bonds. Therefore, out of the four valence electrons in a carbon atom, only three are used for bonding, and the fourth is relatively free to move from one carbon atom to the other. These free electrons give graphite its high electrical conductivity and lubrication property as wells.

Figure 3
Graphite Structure (Kopeliovich, 2013)



The covalent bonds within each graphite layer are strong, but the Van der Waals forces holding the layers together are weak, which causes the layers to slip over each other easily. This results in the graphite having a slippery surface, which makes obtaining it in powder form easy. Due to its internal structure, graphite has an extremely high melting point of 3600°C, since many strong covalent bonds have to be broken to allow the carbon atoms to move freely. Because of its high melting temperature, graphite can withstand the mixing temperature of asphalt mixes. Moreover, pure graphite has a relatively low specific gravity of 2.1 g/cm3, which is relatively similar to the constituent material of asphalt mixtures, which in turn results in a limited effect on the pavement performance. These characteristics together make graphite a suitable candidate for incorporation into asphalt mixtures.

Similar to graphite, carbon fibers have a high melting point of about 3675°C, which gives it high resistance to the high mixing temperatures used for mixing (Abtahi et al. 2010). Carbon fibers have a specific gravity of 1.8 g/cm^3, a value that falls within the range of specific gravities of asphalt mixture raw materials. (Binder about 1.03 g/cm^3 and construction aggregates about 2.5 to 3 g/cm^3). Unlike graphite and carbon fiber, steel slag has a higher specific gravity (3.2 - 3.6 g/cm^3) and a high absorptivity that goes up to 3 %. Finally, the major factor that makes all these conductive fillers the best alternatives to replace aggregate to produce conductive asphalt mixtures is their low electrical resistivity. For instance, graphite has an electrical resistivity that ranges from (3 – 60) $\times 10^{-5}$ (at 20 °C temperature), which can actively enhance the electrical conductivity of asphalt mixture when introduced in sufficient amounts.

2.6 Graphite Types

Shao-peng et al. (2002) produced asphalt mixtures using both crystallized (flake) and microcrystalline (amorphous[2]) graphite. The study concluded that flake-type graphite is more effective than microcrystalline graphite in reducing the electrical resistivity of ECA mixtures. Additionally, Park et al. (2014) reported that, among four other types of modified asphalt mastics, asphalt mastics modified with flake-type graphite displayed the lowest resistivity, whereas those modified with amorphous graphite showed no conductivity, even at a high content of 40%. Park et al. 2014 suggested that the difference in conductivity between the distinct types of graphite is attributable to their different particle shapes. These conclusions demonstrate the significance of selecting the proper type of graphite to impart conductivity.

2.7 Performance of Conductive Asphalt Mixtures

2.7.1 Electrical Performance

The electrical resistivity is generally measured using one of the two methods, the two probe-method and the four-probe method, with the difference being the number of electrodes used for passing the electric current through the asphalt mixture. While the two-probe method includes two electrodes covering the upper and lower surfaces of the specimen, the four-probe method includes embedding two other electrodes into the asphalt mixture. Due to the difficulty of embedding electrodes into the compacted laboratory samples, most researchers used the two-probe method for testing cylindrical

[2] Although it is a crystalline material, it is generally and inappropriately termed amorphous. Carbon Black is a genuine amorphous material, which does not have a long-range order in its atomic structure (Park 2014)

samples (Huang et al. 2009; Vo and Park 2017; Notani et al. 2019), whereas the four-probe method was rarely used when compacting in the field (Wu et al. 2013).

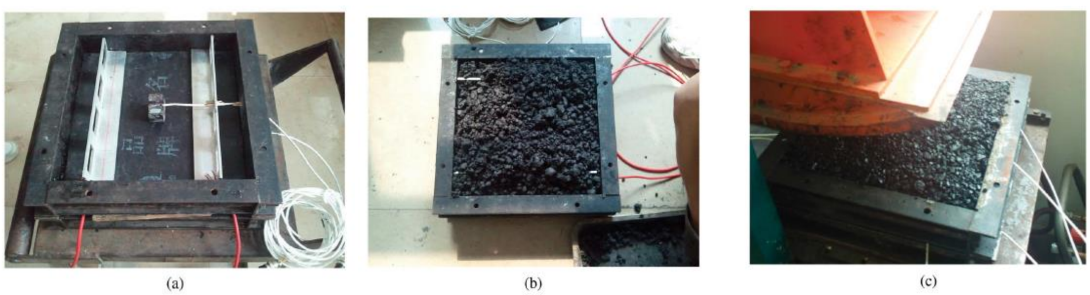
For measuring the electrical resistivity of asphalt mixtures, a multimeter must be used to measure the resistance. Many studies used the Keithley multimeter, which measures the resistance by measuring the voltage difference between the electrode and the passed current (Huang et al. 2009; Wu et al. 2013). The current passed through the mixture can be either a direct current (DC) (Wu et al. 2013) or an alternating current (AC). Knowing the sample's geometry and using Equation (1) mentioned above, the electrical resistivity can be calculated.

Researchers have used different techniques to ensure complete contact between electrodes and the specimen when measuring compacted samples' electrical resistivity. For instance, Huang et al. (2009) painted the specimen's contact areas with highly conductive silver paint. A conductive copper tape was then glued on the top of the silver paint to ensure these areas' conductivity. Another reported method is the use of graphite powder to fill the gaps between surfaces and for an accurate reading of the resistance (Wu et al. 2005).

To simulate a bridge deck structure, Wu et al. (2013) compacted two asphalt layers on top of a cement concrete layer to build a small-scale conductive asphalt slab. An insulating material was placed on top of the cement concrete layer, the conductive layer was then placed with a pair of aluminum electrodes being embedded into the conductive mixture before compaction, thermal sensors were also embedded within the slab, and finally, a conventional asphalt mixture was placed and compacted on top of the conductive layer. Figure 4 shows the preparation process of the asphalt concrete slab with the electrodes being embedded into the slab. Wu et al. (2013) used the four-probe method to test the conductive mixture's electrical resistivity. Two outer electrodes were placed to pass the current through the mixture, while the embedded electrodes were used to measure the voltage difference. The electrical contact was silver paint in conjunction with copper wires.

Figure 4

Preparation Process of Asphalt Concrete Slab: (a) Mold with Thermal Sensors and Electrode; (b) Packing of Mixture; (c) Compaction, (Wu et al. 2013)



2.7.2 Mechanical Performance

The incorporation of conductive material into an asphalt mixture, in substantial quantities, will inevitably affect the mechanical performance of asphalt mixtures. Studies about conductive asphalt concrete mainly focused on the additive contents as well as the electrical and thermal properties of ECA mixtures (Shao-peng et al. 2002; Wu et al. 2005; Bai et al. 2015; Vo and Park 2017; Alnotani et al. 2019). Limited studies investigated the effect of conductive additives on the mechanical performance of these mixes.

Researchers have generally used two approaches to study the CAC's mechanical properties. These are investigating the properties of the modified asphalt mortar used in the ECA mixes and evaluating the laboratory performance of such mixtures. The properties of asphalt binder and mortar prominently contribute to the mechanical performance of the conductive asphalt mixtures; hence, researchers focused on studying the rheological properties of asphalt mortar mostly using the softening point test (Rodgers et al. 2009) penetrability tests (Rodgers et al. 2009), viscosity test, and Dynamic Shear Rheometer test (Huang et al. 2009). While the performance of asphalt mixtures was typically evaluated, employing some laboratory tests like Marshall Stability, Freeze-Thawing, Asphalt Pavement Analyzer (Huang et al. 2009), Flow Number (Huang et al. 2009), Dynamic Modulus (Huang et al. 2009), Creep Stiffness, Indirect Tensile Strength (Huang et al. 2009), and Four-Point Bending Tests.

2.7.2.1 Impact of Conductive Additives on Binder/Mastic Properties. Huang et al. (2009) used the Dynamic Shear Rheometer (DSR) test to examine the viscoelastic behavior of asphalt binders containing different amounts of steel fiber, carbon fiber, and graphite, all compared to the properties of the standard unmodified binder. The test was performed at high temperatures of 58, 64, and 72°C and low temperatures of 0, - 6, and −12°C. The three different additives affected the asphalt binder at high temperatures, similarly, showing an increase in stiffness as the additive content was increased, which consequently resulted in higher complex shear modulus (G*), with higher values at lower temperatures. Moreover, there was a certain additive threshold, after which the increase in additive content increased the G* at a higher rate. These threshold points were reported as 0.6%, 5%, and 18% (by volume of binder) for steel fibers, carbon fibers, and graphite, respectively. Whereas at low testing temperatures, the increase of additive content increased the complex shear modulus gradually. The binder's rutting parameter $G^*/ \sin \Delta$ was also evaluated to characterize the binder's resistance to rutting. Steel and carbon fibers showed higher values than the control, whereas graphite showed a similar value to the control. A higher $G^*/\sin \Delta$ value represents a stiffened binder, which leads to a conclusion that modifying asphalt binder with steel and carbon fibers causes its stiffening, while on the contrary, graphite has no stiffening effect on binders.

Rodgers et al. (2009) modified binder with carbon black, pulverized fuel ash, and iron powder in percentages of 14, 27, 36, 41, and 57 by the volume of binder, in an effort to find the optimal content of additives. Rheological properties were examined by conducting softening point and penetrability tests in addition to the electrical performance tests. Rodgers et al. 2009 concluded that the addition of all three types of additives showed similar effects on bitumen rheology, as the softening point increased and the penetrability decreased, with carbon black exhibiting the most significant effect. Results suggested that pulverized fuel is not as useful as a conductive modifier because the conductivity was not always improved by adding more of the modifier. Carbon black and iron powder were found to be effective, with the latter being better for practical application for asphalt mixes. The conductivity improved linearly with the addition of carbon black with no percolation threshold, contradicting the results of Cui et al. (2007), which suggested that the electrical resistivity decreases at different rates of change with the inclusion of carbon black. Iron powder reduced the electrical resistivity in a polynomial relationship with a maximum substitution of 36 % being suggested. Rodgers et al. (2009) recommended that further research should be done to examine the effect of these modifiers on pavement performance.

2.7.2.2 Impact of Conductive Additives on Asphalt Mixtures Properties. The primary goal of studying the conductive and mechanical performance of ECAC is to design an electrically conductive mix without compromising the material's structural properties. Literature reviews indicated that different conductive additives impact the permanent deformation and fatigue resistance of asphalt mixtures differently.

Huang et al. (2009) modified asphalt mixtures using three different additive types, including micron-steel fiber, carbon fibers, and graphite powder. On the mechanical performance of these mixtures, Huang et al. (2009) reported that the inclusion of steel and carbon fibers did not have a significant effect on the indirect tensile strength and the fracture energy of the mixes, while introducing graphite into the mixture showed a compromised cracking resistance compared to the control mix. While on the contrary, the dynamic modulus of the samples was degraded by adding steel and carbon fibers, whereas the addition of graphite slightly enhanced it. According to the Flow Number test results, all three additives showed an improvement in the rutting property, with the graphite showing the most significant effect. In conclusion, Huang et al. (2009) explained that graphite significantly altered the samples' performance due to its introduction in large quantities.

Liu and Wu (2011) investigated the impact of introducing graphite and carbon fiber in different quantities on the mechanical and electrical properties of asphalt mixtures. The researchers introduced graphite and carbon fibers in dosages ranging between 0-22% and 0-2% by binder volume, respectively. The mechanical performance was evaluated for ECA mixtures modified with graphite, carbon fibers, and a combination of both. The Indirect Tensile test was utilized to examine the effect of incorporating theses conductive constituents. The inclusion of graphite at a percentage of 22% (by volume of binder) decreased the Marshall Stability and residual stability but slightly increased the mixtures' dynamic rutting stability. When modifying mixtures with 2% of carbon fibers (by volume of binder), all the Marshal Stability, residual stability, and dynamic rutting stability were improved. When a combination of graphite and carbon fiber was introduced into the mixtures, mechanical and electrical properties were maximally improved. Liu and Wu (2011) concluded that although graphite's addition improves conductive properties, it does not enhance the mechanical strength of asphalt mixtures. Liu and Wu (2011) suggested optimizing the graphite content to ensure low electrical resistivity without compromising the mechanical performance of the mixture.

Liu and Wu (2011) also studied the effect of the conductive component content on the resilient modulus of asphalt mixtures. Graphite was introduced at different dosages of 10%, 30%, and 45% by volume of binder, and it decreased the resilient modulus noticeably; while the 10% of graphite did not affect the resilient modulus, the 30% and 45% decreased it to 90% and 70% of the control's value. Nevertheless, when modifying the samples through a combination of graphite and carbon fibers, the resilient modulus was improved considerably even with low carbon fibers quantities of 1% and 2% by volume of binder.

Regarding the performance of steel slag ECA mixtures, Chen et al. (2012) substituted traditional basalt aggregates with steel slag and investigated its effect on the mixture's mechanical performance. The water-saturated Marshall Stability test, Indirect

Tensile Splitting Strength test, Dynamic Creep test, and Indirect Tensile Fatigue test were employed to evaluate the moisture susceptibility, high-temperature performance, and fatigue performance of the ECA mixtures. Results demonstrated that steel slag ECA mixtures have worse moisture susceptibility performance than basalt asphalt mixtures, but still above the requirements. Steel slag mixtures showed an improved temperature performance compared to basalt mixtures. Concerning the fatigue performance, steel slag mixtures performed better than basalt mixtures only when the applied stress was less than 0.77 MPa, which indicated that the fatigue performance of steel slag mixtures needs to be improved, especially when subjected to heavy-duty traffic. Finally, Chen et al. (2012) recommended that future research focus on improving steel slag asphalt mixtures' performance.

Ahmedzade and Sengoz (2009) prepared asphalt mixture specimens using steel slag and limestone and to evaluate the use of steel slag aggregates in hot mix asphalt concrete. The study investigated mixtures' mechanical properties using the Marshall Stability, Indirect Tensile Stiffness Modulus, Creep Stiffness, And Indirect Tensile Strength tests. Marshal stability results showed that steel slag mixtures improved stability and decreased flow values, indicating high stiffness and permanent deformation resistance. Indirect tensile stiffness modulus results revealed that steel slag mixtures have higher stiffness modulus than limestone mixtures. The ITS results of steel slag mixtures were higher than the control mix, which indicates that steel slag improves the cohesive strength of the mixture.

Alfalah et al. (2020) studied the impact of reinforcing asphalt mixtures with different fiber types, including carbon fibers. In his study, carbon fibers were incorporated in a percentage of 0.16% by total mixture weight. The laboratory tests used were the Complex Dynamic Modulus, Cantabro durability, Asphalt Pavement Analyzer (APA), Flow Number, and Indirect Tensile Strength. Results indicated that the mixtures modified with carbon fibers had higher Dynamic Modulus |E*| value compared to the unmodified control mix at low frequencies, which indicates that carbon fibers can potentially enhance the rutting performance of asphalt mixtures. Regarding the Cantabro durability test, the reinforced mixture exhibited a lower percentage loss, which points out improved mixture durability. The APA results show that the carbon-modified mixtures maintained the rutting performance with a slight (insignificant) improvement compared to the control mix. Flow Number results suggested that the control mix has a better rutting performance than the carbon-based mix, contradicting both the Dynamic Modulus and the APA results. Finally, the ITS and CT index results suggested that carbon fibers (and other fibers used in the study) do not impact the strength or cracking performance of asphalt mixtures.

2.7.3 Heating Capability of Electrically Conductive Asphalt Mixtures

Conductive additives improve not only the electrical performance but also the thermal properties of asphalt mixtures (Bai et al., 2015). Many studies investigated the effect of conductive additives on the thermal conductivity of ECA mixtures. Thermal conductivity refers to the material's ability to transfer heat through the asphalt mixture (Vo and Park, 2017). Vo and Park (2017) investigated the heating efficiency of ECA mixtures modified with graphite and carbon fibers for deicing applications. The thermal conductivity and the asphalt mixtures' thermal capacity were measured using a Heavy-

Duty Thermal Constant Analyzer designed with a hot disc probe that matches the compacted specimens' diameter. The probe was utilized to produce a heat pulse that generates a dynamic temperature field within the samples. The probe works as a heat source and a temperature sensor that measures the change in temperature with time. The thermal conductivity values were then found based on the temperature difference.

The dispersion of conductive material within the asphalt mixture body was also inspected using microstructural imaging. A Scanning Electron Microscope (SEM) imagining technique was employed to provide high-resolution images of the ECA mixtures' surfaces, which helped better understand the conductive paths formed and the conductive additives distribution into the mixture as well as the thermo-conduction mechanism of ECA mixtures. Carbon fibers were found to exhibit a long-range connecting effect (bridging effect) among graphite conductive clusters and gather in bundles, especially when introduced in excessive amounts. Figure 5 shows the preparation of SEM samples.

Figure 5

SEM Sample Preparation (Vo and Park , 2017)

Vo and Park (2017) also applied two actual test models to evaluate the heating capabilities of conductive asphalt mixes compared to the control unmodified mix. Two layers were compacted into each box, each of 50 mm thickness. The conductive mixture was a combination of 20% of graphite powder and 1% of carbon fibers (by volume of binder). The conductive mix was placed as the upper layer of one of the boxes. A heating coil was used to cover the upper and lower boxes' surfaces. A constant heating temperature of 60°C was controlled through a power source connected to the boxes. Figure 6 below represents the two model boxes covered with a 10 cm snow layer, at the beginning of the test and after 15 minutes. A snow-free condition was reached after 25 minutes for the conductive mixture box, while the five extra minutes were needed for the control mix to reach the same situation.

Figure 6

Actual Test Results at (a) the Beginning of the Test (b) 15 Minutes after Beginning the Test (Vo and Park 2017)

(a) (b)

Vo and Park 2017 reported an increase in thermal conductivity as the amounts of graphite, whether combined with carbon fiber or not, increased. Mixes with carbon fibers showed a decrease in thermal conductivity when added in contents higher than 1%. This was explained by fibers' tendency to gather into bundles (clumping) and the increase of air voids in the asphalt mixture. As a result, Vo and Park (2017) used 1% carbon fibers for mixes prepared in combination with graphite (powder form). Vo and Park (2017) concluded that graphite and carbon fibers enhance ECA mixtures' snow-melting ability, and their combination is more efficient than when used alone. According to the actual test, the electrically conductive mixture can improve snow-melting effectiveness by shortening the melting time and increasing the surface temperature.

Bai et al. (2015) also studied ECA mixtures' thermal properties to investigate its suitability for the deicing and solar harvesting pavement systems. Graphite and carbon black were used as conductive fillers for modifying the mixtures. A limited percentage of carbon fiber (0.5%) by volume of the binder was introduced with the graphite mixes, prepared at a percentage of 5%, 10%, 15%, and 20% (by volume of binder content). Two mixing methods, wet and dry were used. The thermal conductivity of the samples was measured using a surface probe type of QuickLine-30. The probe operates by applying a dynamic measurement method. The heat flow capacity is determined based on the temperature difference between before and after the applied heat. Bai et al. 2015 reported using graphite powders to ensure full contact between the probe and the surface specimen. The thermal conductivity was calculated using the equation (4) as follows:

$$\mathrm{K}=\frac{Q}{4\pi\ (\mathrm{T2}-\mathrm{T1})}\ln\left(\frac{t2}{t1}\right) \qquad (4)$$

Where k is thermal conductivity ($\mathrm{Wm^{-1}\ K^{-1}}$), Q is heater power (W), T_1 and T_2 are initial and final measured temperature (K), and t_1 and t_2 are initial and final time (sec).

The results showed that asphalt mixtures' thermal conductivity increases as the graphite or carbon black content increases. The wet mixing was reported to exhibit better thermal property compared to the dry mixing due to better dispersion of conductive fillers within the mixtures. Moreover, graphite better improved the thermal conductivity of asphalt mixtures compared to carbon black due to its widespread distribution within the mixture compared to carbon black, which gathered in clusters. Therefore, graphite was chosen along with 0.5 % of carbon fibers as the best conductive mixture.

Vo et al. (2016) prepared ECA mixtures by modifying conventional asphalt mixtures with milled carbon fiber, chopped carbon fiber, and graphite powder to study their effect on the mixture's thermal properties. The conduction performance was simulated using a two-dimensional finite element model based on modified asphalt mixtures measured thermal properties. Moreover, magnification was used to analyze the microstructure of ECA mixtures.

Vo et al. 2016 concluded that graphite and carbon fibers improve asphalt mixtures' thermal properties, with the combination performing better than when a single filler is used. The two-dimensional simulation presented the heat conduction related to each conductive filler. The microstructural analysis showed that graphite particles are better distributed throughout the asphalt mixture, whereas carbon fiber provides a long-range bridging effect that can connect conductive areas and chains to form better conductive paths. Hence, the combination of fibers and powders can potentially better improve the thermal conductivity of ECA mixtures.

Pan et al. (2017) proposed conductive asphalt mixtures with high thermal conductivity to improve the efficiency of solar energy collection and snow melting pavement systems. The study aimed at providing an insight into the material selection for preparing ECA mixes. The evolution of the thermal properties of asphalt mixes under the effect of different environmental parameters was examined. A thermal constant analyzer was employed to measure the thermal properties of asphalt mixtures. Results demonstrated that type of conductive fillers and aggregates substantially impact the thermal properties of asphalt mixtures, whereas the binder showed no effect. Pan et al. 2016 also reported that mixes' thermal properties change when subjected to different environmental factors like temperature and moisture conditions. Therefore, these parameters should be taken into consideration when determining the actual thermal properties of ECA mixtures. It was also concluded that aging did not affect the thermal properties, while freezing-thawing cycles substantially affect the thermal properties due to the volume expansion and bonding degradation of ECA mixtures.

2.8 Electrically Conductive Asphalt Mixtures for Electrically Heated Pavements

The literature review shed light on previous research focusing on the design and performance of ECA for deicing applications. However, designing a mixture with good electrical and mechanical properties is just one step towards constructing an electrically heated asphalt pavement. To this date, no previous studies exist presenting a full-scale construction of an electrically heated asphalt pavement.

Previous laboratory studies reported electrical resistivity in a wide range considering (generally) mixtures with resistivity values around 100 Ω.m and below as conductive (Huang et al., 2009). However, no specific borderline could be set to determine if a mixture is conductive enough or not because the acceptable resistivity range varies with the pavement's geometry, the thickness of the conductive layer, the spacing between embedded electrodes, the required power dissipation level, and the applied voltage potential.

Minsk (1968), the first to introduce the concept of ECA mixtures as a pavement heating technique, conducted field tests to demonstrate that asphalt mixtures can potentially conduct electricity and mitigate snow accumulation. Minsk (1968) used the conductive mixture to construct small-scale test sections (6ft by 8ft and 6ft by 6ft). In his study, Minsk provided the following equations, explaining the trade-off between different elements of a heated pavement.

$$P/A_s = \frac{P}{W*L} \tag{5}$$

Where P/A_s is the power dissipated per unit surface area,

P is the power in Watt,

L is the conductive path's length, which is the electrode spacing in this case (m or ft.),

W is the pavement width (m or ft.).

$$P = \frac{V^2}{R} \tag{6}$$

Where V is the applied potential difference (Volts)

R the electrical resistance in Ω

$$R = \frac{\rho * L}{T*W} \tag{7}$$

Where ρ is the resistivity (Ω.m or Ω.ft)

T is the thickness of the conductive layer.

Using equations (5), (6), and (7), the required level of resistivity can be determined specifically depending on each project. However, it is essential to bear in mind that conductive asphalt concrete is a posistor material whose resistance increases with temperature. Arabzadeh et al. (2019) performed a field test in which he reported a decrease in resistivity due to low ambient temperature at the beginning of the test. Conversely, the heat generated within the slab increases the volume resistivity of the material leading to a reduction in the electric current flow. According to Arabzadeh et al. (2019), conductive asphalt concrete's resistor behavior results in highly efficient energy consumption of electrically heated pavements as the material reacts to heat loss with an increase in electric current, which enhances the heat generation process.

2.9 Summary of Literature Review

The following is a summary of the findings from the literature review:

-Electrically Conductive Asphalt (ECA) mixture is an asphalt mixture that comprises conductive additives among its constituents. This innovative structural material has many potential non-structural applications, including the use of Electrically Heated Flexible Pavements for preventing snow/ice accumulation in winter storm conditions (anti-icing).

- For an ECA mixture to be utilized for anti-icing applications, the material must exhibit a conductivity level of at least 100 Ω-m without compromising the mechanical performance. While the electrical performance of asphalt mixtures is quantified in terms of the material's electrical resistivity (easiness of current flow, its mechanical performance is typically characterized in terms of permanent deformation, cracking, durability, and moisture damage.

- Electrical resistivity is an intrinsic property that describes the material's resistance to electric current passage independent of its geometry. For an ECA mixture to have high conductivity, its electrical resistivity must low enough to allow for the current passage throughout the material.

- For electrical resistivity to be significantly reduced, a sufficient amount of conductive additives must be incorporated in the mixture to create a conductive network that enables the current to flow through the mixture. This content is referred to as the percolation threshold, and it is specific for each type and physical characteristics of the additive introduced.

- Generally, as the dosage of additives in the mixture increases, the electrical resistivity decreases. However, the rate of reduction becomes insignificant after a certain dosage called the optimal dosage. Thus, each additive should be introduced in a specific content to achieve optimized electrical conductivity, minimum effect on the mechanical properties, and minimum possible cost.

- Additives in literature have different forms, such as powder, fiber, and solid particles. Those were mostly introduced as the volume fraction of the binder content and rarely as a percentage of the mix's total weight.

- Although additives in fibrous form were reported to improve the electrical resistivity even when introduced in much smaller quantities than the powder additives, due to their bridging effect, still, fibers were reported by many studies to clump and gather in bundles leaving the mixture with an inconsistent electrical resistivity and increased level of air voids. Furthermore, conductive fibers are relatively expensive. On the contrary, additives in the powder are reported to be uniformly distributed over the asphalt mixture, with more consistent electrical resistivity and a reasonable price.

- Generally, the conductive additives that were reported to successfully improve asphalt mixtures' electrical conductivity without compromising the mechanical property have physical characteristics that make them compatible with the asphalt mixtures, such as the melting point and specific gravity of the material. This led to graphite and carbon fiber being the most commonly used conductive additives in literature. Among different types of graphite used, flake -type was found to be the most effective in improving the electrical conductivity of asphalt mixtures.

- Most researchers used the two-probe method to test the electrical resistivity of asphalt mixtures samples, a method that involves a multimeter, electrodes, and electrical contact to ensure full contact between the electrodes and the sample surface.

- Researchers have investigated the effect of conductive additives on both the properties of binder independently and the overall mixture. As for the impact of conductive additives on binder properties, it was found that these additives increase the stiffness and softening point of the binder and decrease its penetrability. Literature showed that different conductive additives alter the properties of asphalt mixtures variously, with graphite having the most significant effect due to its introduction in larger quantities than fibers.

- Many studies investigated the effect of conductive additives on the thermal conductivity of ECA mixtures, that is, the material's ability to transfer heat through the asphalt mixture. Literature suggested that the addition of graphite and carbon fiber improves the heating performance of the asphalt mixture. However, when introducing carbon fiber in contents higher than 1%, the thermal conductivity decreases due to an increase in the air voids of the asphalt mixture.

However, many pieces in the previous research have not yet been explored. This study intends to fill these gaps in the literature, focusing on the mix design aspect of the ECA mixtures as well as the effect of graphite dosage on the volumetric properties of the asphalt mixture. This study designs conductive asphalt overlay mixes with 4.75 mm Nominal Maximum Aggregate Size, a size smaller than the aggregate sizes used in literature (12.5 and 19 mm). This study analyzes the different factors that may affect ECA mixtures' electrical conductivity and were never examined before, such as the mixture's binder grade and air void level. While different studies considered the effect of carbon fiber's length on the ECA mixture properties, none of the studies varied the size of graphite powder used or investigated how particle size may affect the mix design, binder content, the percolation threshold, the optimum dosage that should be introduced and the mechanical performance of ECA mixtures.

Chapter 3

Materials and Experimental Methods

Similar to conventional asphalt concrete, Electrically Conductive Asphalt Concrete (ECAC) also consists of bitumen, aggregates, and fillers, with aggregates providing a skeletal structure that needs to be covered, while the filler combined with bitumen forms a binding mastic that fills the voids created by aggregates and binds them together. A typical asphalt mixture acts as an insulator, owing to its non-conductive constituents. For an asphalt mixture to be electrically conductive, a certain amount of electrically conductive additives should be incorporated into it. In this study, the raw materials were one virgin aggregates and two different binder grades. The conductive additives were selected to be three natural flake-type graphite grades varying in particle size and one carbon fiber. This chapter presents a detailed description of the properties of materials as well as the reasons for selecting these materials.

3.1 Raw Materials

All asphalt mixtures were prepared as High-Performance Thin Overlay (HPTO) mix, a specialty overlay mix typically used in New Jersey (NJ). All mixes, including the unmodified control and the ECA mixtures, were designed to satisfy the New Jersey Department of Transportation (NJDOT) requirements for the HPTO mix presented in Table 6. All mixtures were prepared using a gneiss-type virgin aggregate of 4.75 mm Nominal Maximum Aggregate Size (NMAS). The aggregate gradation for all mixtures and the gradation limits are presented in Figure 7. Table A1 in the Appendix presents the control points of the aggregate gradation required in the Job Mix Formula, and Table A2 in the Appendix presents the optimum aggregate gradation used in this study.

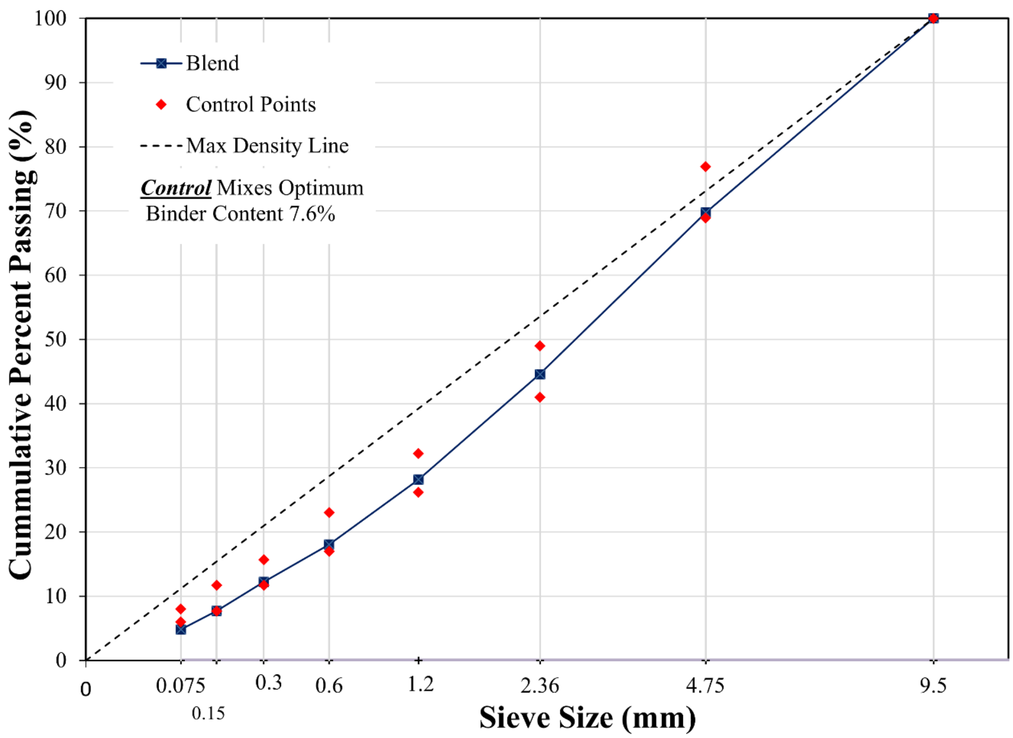
Table 6

New Jersey Department of Transportation (NJDOT) requirements for HPTO mix (New Jersey Department of Transportation, 2007)

Criteria	Requirement
Air Voids	3.5 ± 0.5%
Min voids in mineral	18%
Dust to binder ratio	0.6 to 1.2
Nominal Maximum	4.75 mm
Minimum Binder	7.4%

Figure 7

Gradation of Aggregates Used to Produce All Control and Modified Asphalt Mixtures



The control mix was prepared at 7.6% binder content by total mixture weight. Most of the asphalt mixtures were prepared using a polymer-modified binder PG76-22. Neat binder of PG64-22 was also used for a specific mixture set to assess the impact of different binder grades on the electrical resistivity of electrically conductive asphalt mixtures.

3.2 Conductive Materials

The selection of the conductive additives that were to be incorporated into the asphalt mixture was a challenging task that required many preliminary trials before producing electrically conductive mixtures with an acceptable range of electrical resistivity. By comparing the advantages and disadvantages of each form of conductive additives reported in the literature, graphite was selected as the primary conductive additive in this study instead of carbon fiber due to its reasonable price as well as the easiness of distribution in the mixture compared to carbon fibers.

3.2.1 Preliminary Trials for Selection of Graphite

As for the preliminary experiments, the first patch of mixes prepared was produced using two different graphite types: flake and amorphous graphite. The properties of the two types of graphite used in the preliminary study are presented in Table A3 in the Appendix. These were introduced in the mixtures in different dosages, alone and in combination. However, the prepared mixtures were all non-conductive, and even modifying the binder separately with the graphite using the wet mixing method resulted in no conductivity. Figure 8 shows modifying the binder with graphite using the wet mixing method and electrical resistivity testing of modified binder beams.

Figure 8

Preliminary Trials: (a) Modifying the Binder with Graphite (b) Preparing Binder Beams (c) Testing for Electrical Resistivity

(a) (b) (c)

When comparing the characteristics of graphite used for this study with those used in literature, it was noticed that most of the studies used one particle size of graphite, and that is an average diameter of 150µm. To determine if the particle size of graphite was the issue causing the samples to be non-conductive, some graphite was sieved, and the largest particles were separated and used to modify the binder alone; the results showed that particle size affects the conductivity of the asphalt mixtures. Hence, three flake-type graphite of varying sizes were selected to study in-depth the effect of graphite size on the electrical resistivity and the volumetric properties of conductive asphalt mixtures.

3.2.2 Selected Conductive Additives

Table 7 presents the properties of the selected conductive additives, including graphite and carbon fibers. As shown from Table 7, each graphite used did not have a specific particle size but a gradation. According to each graphite gradation, a substitution process was used to replace the portion of aggregates with graphite, correspondingly. Table 7 shows that Graphite A, B, and C change particle size from smallest, medium, to largest, respectively. A more precise idea about the difference in size can be obtained by comparing the percentage of particles retained on #200 mesh; those are 73.2%, 94.36%, and 100% for A, B, and C, respectively. Another critical factor when studying the physical properties of graphite grades is the specific gravity. When conductive additives are introduced into the mixture, they are introduced in terms of the binder's volume. The specific gravity of each graphite was used to convert to mass calculations. Although the specific gravities of the three graphite grades are close in value (2.30. 2.28, and 2.26) for (A, B, and C) respectively, this slight difference leads to differences in the mass of material introduced into the mixture.

Table 7 also shows the properties of the carbon fibers used in a specific mix set to assess the effect of introducing carbon fiber on ECA mixtures' electrical resistivity. The length of the carbon fiber (as indicated in Chapter 2) is a critical factor affecting the conductivity and the air void level of asphalt mixtures. While the graphite is introduced in powder form and has an aspect ratio of 1 (length = thickness), the carbon fiber used has a high aspect ratio of about 882. This high aspect ratio provides the mixture with a bridging effect that significantly enhances the conductive path, leading to higher electrical conductivity. However, by comparing the prices of the four conductive additives presented below, it can be seen that graphite price ranges from \$1.23 to \$1.58 per pound, whereas the carbon fiber costs 19.5 \$/lb. This price difference led to the selection of graphite as the primary additive in the designed ECA mixtures. The secondary reason was the easiness of distribution; because of its lower aspect ratio, graphite can be uniformly distributed throughout the mixture even using the simplest mixing methods.

Table 7

Properties of Electrically Conductive Additives Selected to Produce Modified Asphalt Mixtures

Mesh Size/Property	Graphite A	Graphite B	Graphite C
% +300 Mesh (600 µm)	-	-	12.48
% +40 Mesh (425 µm)	-	-	32.04
% +50 Mesh (300 µm)	0.67	-	36.54
% +60 Mesh (250 µm)	-	30.01	7.13
%+80 Mesh (180 µm)	-	-	5.05
%+100 Mesh (150 µm)	34.68	55.55	6.76
%+200 Mesh (75 µm)	37.85	8.8	-
%+325 Mesh (44 µm)	6.64	1.6	-
%-325 Mesh (<44 µm)	20.16	4.03	-
% Ret. Above 200 Mesh	73.2%	94.36	100%
%Carbon	91.63	95.03	93.23
Specific Gravity	2.30	2.28	2.26
Resistivity (Ω . cm)	0.1082	0.0581	0.1114
Surface Area(m^2/g)	3.15	1.80	2.50
Price ($/lb) >20,000 lb	1.23	1.36	1.58
Carbon Fiber Properties			
Length (mm)	6.35		
Diameter (microns)	7.2		
Electrical Resistivity	0.0016		
Specific Gravity (g/cm3)	1.82		
Young’s Modulus (GPa)	228		
%Carbon	99.08		
Surface Area(m^2/g)	0.54		
Price ($/lb) >10,000 lbs.	19.5		

* Calculated as summation of sizes retained on Mesh No. 200 and larger

3.3 Experimental Program

Experiments in this study was classified into two categories: mix preparation and performance testing. The ECA mixtures were prepared using different graphite sizes, dosages, air void levels, binder grades, with and without carbon fibers. These samples' performance testing included many properties starting with the electrical resistivity to various mechanical properties of asphalt mixtures such as rutting, cracking, and durability, ending with the heating capability of such mixtures. The experimental laboratory plan for mix preparation and the testing program will be discussed in detail in this chapter.

3.3.1 Sample Preparation

All specimens in this study were prepared in accordance with Superpave design procedures and following the New Jersey Department of Transportation (NJDOT) requirements for HPTO mix. As for the control mixes, the aggregates were at first sieved for size separation and blended again according to design size distribution presented in (Chapter 3). The aggregates were preheated for four hours in the oven at 170 C, and the binder was preheated for two hours at a similar temperature before mixing. The constituents were mixed using a rotational mixer for 60 seconds or until the aggregates are fully covered with the binder. Mixtures were then conditioned in an oven at a compaction temperature of 160 C for two hours before being compacted to simulate short-term aging during plant production. The specimens were compacted using in the Superpave Gyratory Compactor (SGC) in a cylindrical mold that is 150 mm in diameter. Specimens were compacted either to 50 Gyrations or to a specific height depending on the mixture set.

To produce ECA mixtures, the same procedure was followed, with the difference being the introduction of the conductive element into the mixture. In its three different particle sizes, Graphite was introduced into the mixtures in increments of 5%, with a total percentage ranging from 10% (by binder volume) to the optimum content of each Graphite. On the other hand, Carbon Fibers were introduced at a dosage of 1% by volume of binder. All additions and substitutions are reported as volume fractions of the binder to ensure consistency in case of binder content change. When Graphite was introduced into the mixture, a dry mixing method was employed; Graphite was blended with the aggregates before the wet element (binder) is introduced. When Carbon Fibers were introduced, they were added during the mixing process to ensure maximum distribution throughout the mixture. The addition of Graphite was offset by an equivalent reduction of aggregates. This substitution process was employed to maintain the same aggregate skeleton structure. Carbon fiber additions were of such low quantity that no substitution was necessary.

Table 8 below presents a sample blend sheet with sample calculation of the constituents' weight of an ECA mixture to elaborate more on graphite and aggregates' substitution process. Table 9 represents the default inputs imported into Table 8 when a specific binder PG and Graphite grade were selected. The cells highlighted in yellow are the user input values for each mix, and the cells highlighted in the green present the final blend weights after substitution. In this example, the mix was selected to be modified using 30% Graphite C and 1% Carbon Fiber for a binder of PG 76-22 and a total mix weight of 5000 with an optimum binder content of 8.1%. Using the equations presented in the table and the default values from Table 9, the blend weights were prepared for each specific mix. It is noteworthy that these calculations are specific for this mix and change with changing any of the dosage, binder grade, binder content, graphite size, the inclusion of carbon fiber, and the total mix weight.

Table 8

Sample Calculation for an Aggregate Blend Sheet Showing the Substitution Process

Mix Identifiers			
Binder Grade	PG 76-22	Date:	05/21/2020
Graphite Grade (Size)	Graphite C	Graphite SG:	2.26
Graphite Dosage (%)	30.0%	Binder SG:	1.045
Binder Content (%)	8.10%	Target Wt.	5000
Mix G_{mm}	2.423	Fiber Dos. (%)	1%
Blend Calculations			
Total Mix Wt. (g)	5000	(User Input)	
Binder Wt. (g)	405	(Binder Content x Total Mix Weight)	
Agg. Wt. (g)	4595	(Total Mix Weight - Binder Wt.)	
Binder Vol. (cm^3)	387.6	(Binder Wt./ Binder SG)	
Graphite Vol. (cm^3)	116.3	(Graphite Dosage x Binder Vol.)	
Graphite Wt. (g)	262.8	(Graphite Vol. x Graphite SG)	
Carbon Fiber Vol (cm^3)	3.9	(Fiber Dos. x Binder Vol.)	
Carbon Fiber Wt. (g)	7.1	(Carbon Fiber Vol x Carbon Fiber SG)	
Calculated Weights (g)			
Sieve	**Control**	**Graphite**	**Mod. Control**
No. 4	1390.7	0.0	1390.7
No. 8	1155.9	0.0	1155.9
No. 16	754.0	0.0	754.0
No. 30	465.6	32.8	432.8
No. 50	266.5	180.2	86.3
No. 100	209.3	49.8	159.5
No. 200	132.3	0.0	132.3
pan	220.7	0.0	220.7

Table 9

Material Properties and Size Distribution Used as Inputs for Substitution Process of Graphite into the ECA Mixtures

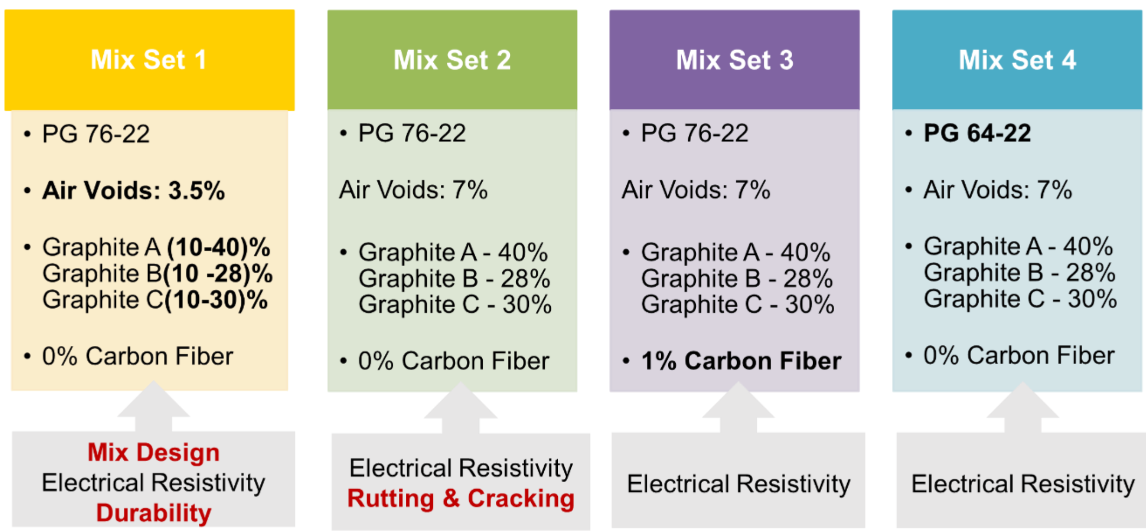
Material Properties				
Binder Grade	**Binder SG**	**Additive**	**Graphite SG**	
PG 76-22	1.045	Graphite A	2.3	
PG 64-22	1.03	Graphite B	2.28	
		Graphite C	2.26	
		Carbon Fiber	1.82	
Gradation				
Sieve Size	**Control**	**Graphite A**	**Graphite B**	**Graphite C**
No. 4	0.303			
No. 8	0.252			
No. 16	0.164			
No. 30	0.101			0.125
No. 50	0.058			0.686
No. 100	0.046	0.354	0.856	0.189
No. 200	0.029	0.379	0.088	
Pan	0.048	0.268	0.056	
Total	1.000	1.000	1.000	1.000

3.3.2 Properties of Different Mix Sets Prepared

To achieve the objectives of this study, four Mix Sets were prepared with combinations of various properties. Figure 9 below describes the different Mix Sets produced, with the colored boxes representing the properties of each group and the grey boxes representing the property assessed using each mix set:

Figure 9

Properties of Different Mix Sets Produced



Mix Set No. 1: This set represents the mixtures prepared to evaluate the impact of Graphite particle size and dosage on the volumetric properties and the electrical conductivity of the ECA mixture. This set includes one control (unmodified mixture) and three ECA mixtures prepared multiple types of mixes using only graphite at varying dosages (ranging from 10 to 40% by volume of binder). Mix design was conducted on this Mix Set, and the optimal binder content was determined for each graphite size and dosage. Graphite dosage was then optimized based on electrical resistivity tests conducted on this set of mixes. All mixtures in this set were prepared using the polymer-modified PG76-22 binder and at a target of 3.5 ± 0.5% air voids. The Superpave Gyratory Compactor (SGC) was employed to compact these mix sets to 50 Gyrations. Figure H below shows some of the asphalt mixtures prepared at this stage of the experiment.

Mix Set No. 2: This set represents mixes prepared for evaluating the impact of graphite additives on the mechanical performance of ECA. Mixtures in this set were prepared at the optimum Graphite dosage and the optimum binder content determined from Mix Set 1. However, the difference was that samples in this Mix Set were prepared at 7 ± 0.5% air voids level to facilitate performance testing and evaluate air voids' impact on electrical conductivity. Air voids' impact on asphalt mixtures' electrical conductivity was evaluated by comparing the electrical resistivity for this set and Set No. 1. The control and three ECA mixes prepared in Set No. 1 were used for this set. The Superpave Gyratory Compactor (SGC) was set to compact these mixtures to a specific height depending on each of the different tests' specifications. Figure I below shows some of the control and ECA specimens prepared at different heights.

Mix Set No. 3: This set included one control mix (designed using PG76-22 in Set No. 1) and three ECA mixes produced using graphite and carbon fiber. The control mix was produced at the optimum binder content determined in Set No. 1. Similarly, the ECA mixes containing carbon fiber were prepared at the optimal binder content and graphite dosages as determined for Set No. 1 ECA mixes. The samples for this set of mixtures were prepared at 7 ± 0.5% air voids. The mixtures were produced at the optimized dosage for each graphite grade, while Carbon Fiber dosage was limited to 1% by volume of binder in all cases. It is important to note here that some trial mixes were also prepared at 2% carbon fiber dosage; however, this resulted in a high air void level that would have compromised the ECA mixture's mechanical performance. Hence, the dosage was set to 1%, keeping with that with the literature's recommendations.

Mix Set No. 4: Mixtures in this set were prepared identical to Mix Set 2, with the difference being the binder grade used. While Mix Set 2 was prepared using a modified binder, this Mix Set included mixtures prepared using the neat PG64-22 at the same optimum binder contents and graphite dosages. The air void level was 7 ± 0.5%, and the electrical resistivity was compared to Set No. 2 samples to determine the impact of binder grade on ECA mixtures' conductivity.

3.3.3 Laboratory Testing Program

Table 10 presents the laboratory testing program followed in this study. Table 10 describes how the different Mix Sets discussed in the previous section were used to evaluate ECA mixtures' different properties. As shown in Table 10, All Mix Sets were tested for electrical resistivity and two of which were also used to assess the mechanical performance of Graphite-modified mixtures. Furthermore, the mixture with the lowest electrical resistivity was compacted in beams to evaluate its heating capability. The performance tests presented in Table 10 were selected to evaluate the rutting resistance, cracking resistance, and durability of the ECA mixes. Following is a brief description of how each of these tests was carried out in the lab .

Table 10

Testing Program to Evaluate the Electrical Resistivity and Performance of Electrically Conductive Asphalt Mixtures

Mix Set No. 1 (Mix Design and Optimal Graphite Dosage)					
Mix ID	**Binder Grade**	**Graphite Dosage (%)***	**Volumetric Mix Design**	**Electrical Resistivity (Air Voids 3.5%)**	**Cantabro Durability Test (Air Voids 3.5%)**
Control	PG 76-22	0	✓	✓	✓
Graphite-A		10-40	✓	✓	✓
Graphite-B		10-28	✓	✓	✓
Graphite-C		10-30	✓	✓	✓
Mix Set No. 2 (Performance Testing)					
Mix ID	**Binder Grade**	**Graphite Dosage (%)** **	**Rutting (APA and HWTD)**	**Cracking (SCB and IDEAL-CT)**	**Electrical Resistivity (Air Voids 7.0%)**
Control	PG 76-22	0	✓	✓	✓
Graphite-A		40	✓	✓	✓
Graphite-B		28	✓	✓	✓
Graphite-C		30	✓	✓	✓

Mix Set No. 3 (Impact of Carbon Fiber on Electrical Resistivity)				
Mix ID	**Binder Grade**	**Graphite Dosage (%)** **	**Fiber Dosage (%)**	**Electrical Resistivity (Air Voids 7.0%)**
Control	PG 76-22	0	1	✓
Graphite-A		40	1	✓
Graphite-B		28	1	✓
Graphite-C		30	1	✓

Mix Set No. 4 (Impact of Binder Grade on Electrical Resistivity)				
Mix ID	**Binder Grade**	**Graphite Dosage (%)** **	**Fiber Dosage (%)**	**Electrical Resistivity (Air Voids 7.0%)**
Control	PG 64-22	0	0	✓
Graphite-A		40	0	✓
Graphite-B		28	0	✓
Graphite-C		30	0	✓

* Graphite dosage varied with increments of 5%. The dosage percentage is calculated by volume of asphalt binder.
** Optimal graphite grade dosage determined based on electrical resistivity from Set No. 1 testing. Optimal dosage is defined as the dosage at which the increase in graphite content does not significantly improve a mix's electrical conductivity anymore.

3.3.3.1 Electrical Resistivity Using a Multimeter.

3.3.3.1.1 Electrical Resistivity Test Set-Up. As mentioned previously, asphalt mixtures' electrical conductivity is characterized in terms of electrical resistivity, a measure of the mixture's resistance to the electric current flow. To determine an asphalt mixture's electrical resistivity, the resistance must be measured using a multimeter and electrodes, according to ASTM D257- 91:1998. Studies in Literature reported the need for electrical contact between the sample and the electrode to ensure the surface's full conductivity (Chapter 2). Most studies in Literature reported using a silver paste, copper tape, and a multimeter; however, this option did not seem applicable for many mixes produced in this study.

A silver paste bottle was purchased for resistivity testing purposes; however, the silver paste was of a high price even for a low quantity that was insufficient for covering the two full surfaces of one compacted sample. Figure 10 below shows the silver paste bottle and the conductive tape used, and the specimen surface barely covered with silver using the entire available quantity. Thus, many other test setups were tried out until a practical, reasonably priced setup was selected and finalized to conduct the test on all the prepared mixtures.

Figure 10

Initial Electrical Resistivity Test Set-Up: (a) Silver Paste and Copper Tape (b) Specimen Covered with Silver Paste

(a) (b)

To measure the electrical conductivity and, and in effect, its conductivity, the two-probe method was used; a multi-meter (Keithley 2700) was used along with two highly conductive steel plates. The multi-meter used measured the electrical resistance of materials with very high resistance (up to 120 Mega-ohms). The procedure involved placing the two conductive plates at the top and bottom of a compacted asphalt mix sample as shown in Figure 11 and 12 . To ensure good contact between the plates and an asphalt sample, graphite powder was placed between each of the plates and the top or bottom of the sample. Each steel plate was then connected to the multi-meter using conductive tape. The multi-meter was also connected to a computer to record measurements for 30 seconds. The sample's resistance is reported as the average resistance for the data collected during the 30-seconds test duration. All resistance measurements were conducted at 25 C (room temperature). Once the resistance was measured, the conductivity and resistivity of asphalt mixes were determined based on Equations 1 and 2.

Figure 11

Resistance Testing Using the Two-Probe Method

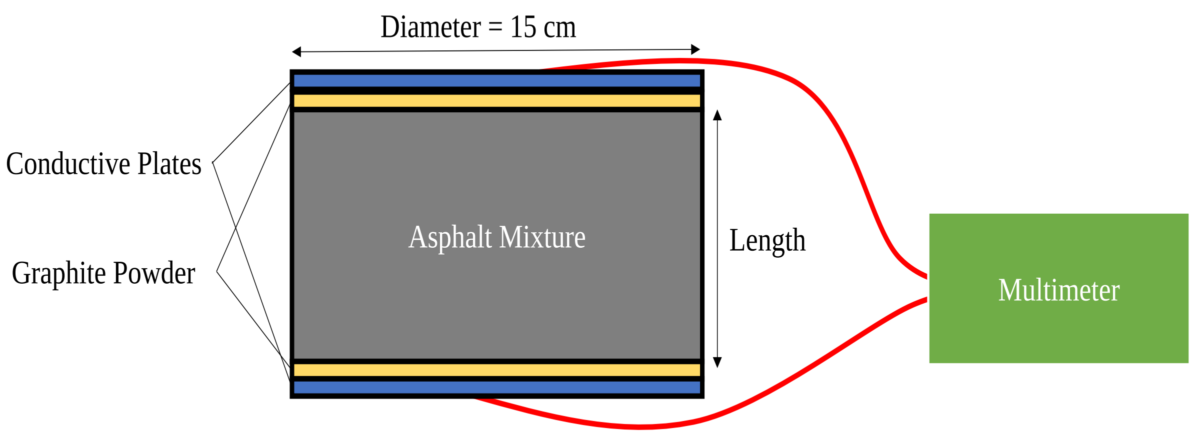
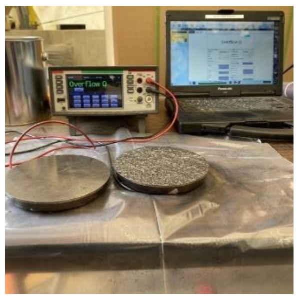


Figure 12

Procedure for Testing Conductivity of Asphalt Mixtures: (a): Placement of Graphite on Steel Plate (b): Testing Contact Resistance (c): Placement of Graphite Powder on Top of Sample (d): Testing Resistivity of Asphalt Sample



(a)

(b)

(c)

(d)

3.3.3.2 Rutting Resistance Using the Asphalt Pavement Analyzer (APA). The APA test was conducted according to AASHTO T 340 to evaluate the rutting resistance of the ECA asphalt mixtures compared to the control mix. In this test, asphalt samples are preconditioned to testing temperature (64 C in this study) for a minimum of six hours before testing. Once the sample reached temperature, a steel wheel is used to apply 100-lbf load on top of a pressurized rubber hose (100 psi pressure) placed on asphalt samples, as shown in Figure 13. One pass is considered complete when the steel wheel tracks on top of the rubber hose across the samples. The test is conducted for 8,000 passes, and a rut depth is measured as the difference between the sample surface elevations at pass 0 and pass 8,000. Lower rut depth values are desirable as they indicate that an asphalt mixture is more resistant to rutting. The test was conducted on samples having a target air voids level of 7.0 ± 0.5%. Three replicates (or six gyratory samples) were tested in the APA for each of the mixtures.

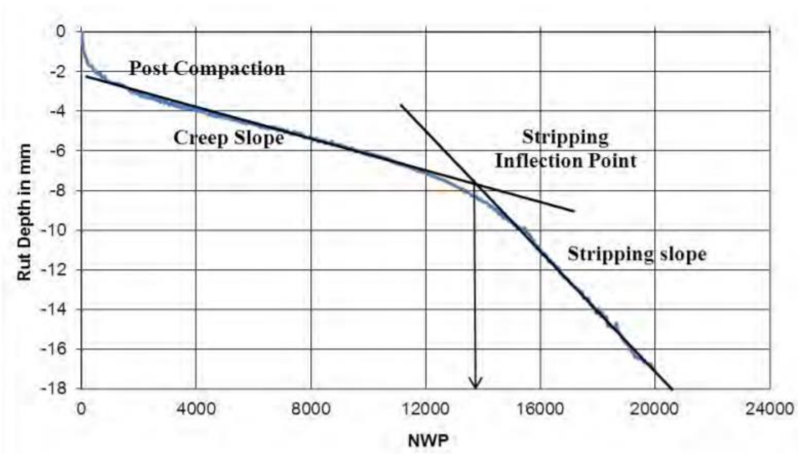
Figure 13

Asphalt Pavement Analyzer (APA) Test

3.3.3.3 Rutting Resistance Using the Hamburg Wheel Tracking Device. (HWTD, AASHTO T 324) . The HWTD test was conducted to investigate the combined effects of rutting and moisture damage (stripping) of the control and ECA mixtures. In this test, a steel wheel applied a load of 702N (or 158 lbf.) by rolling across the surface of a compacted asphalt mixture that is 150 mm. in diameter and 75 mm. in height. Loading was applied when the samples were immersed in hot water at a temperature of 50 C. The testing was continued until a total of 20,000 loading passes were applied, or the sample reached a maximum rut depth of 12.5 mm. The rutting depth, which is the surface elevation difference at passes 0 and 20,000 or failure pass, and Stripping Inflection Point (SIP) pass, were all evaluated. Lower rut depth values and higher SIP values are preferred for asphalt mixtures because they indicate greater resistance to rutting and moisture-induced damage. Figure 14 depicts typical Hamburg Wheel Tracking Device outcomes. For each mix, three replicates, a total of six gyratory specimens, were tested at a target air void of 7 ± 0.5%.

Figure 14

Typical Hamburg Wheel Tracking Device Test Results (Rahman et al., 2014)



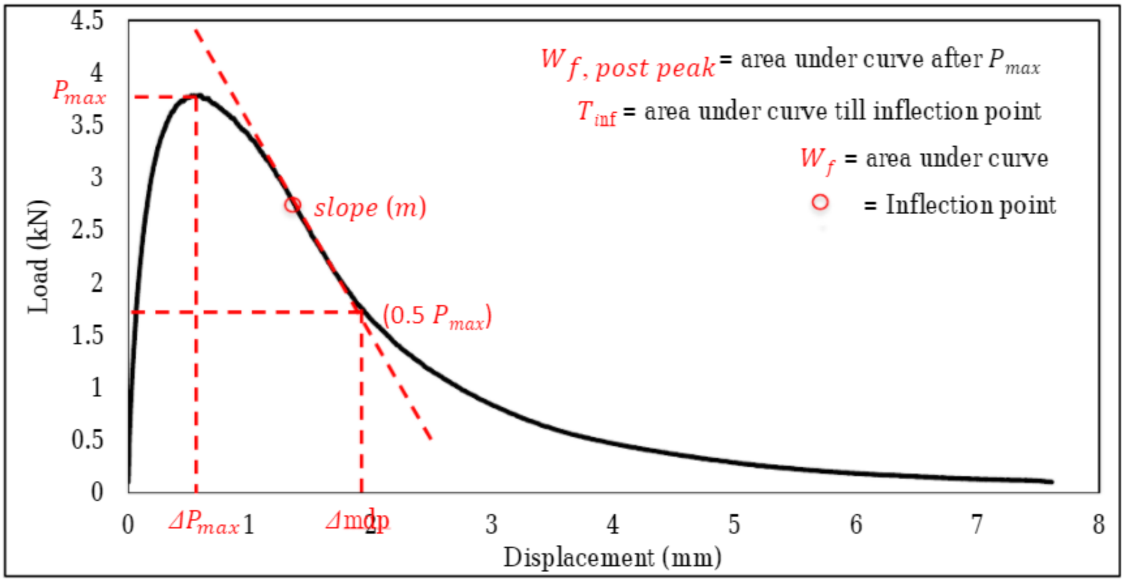
3.3.3.4 Cantabro Durability Test. The Cantabro Durability test was used to evaluate the resistance to breakdown (or durability) of the control and conductive mixtures. The specimens used for this test are the mix design samples (Mix Set 1) compacted using the Superpave gyratory at 50 gyrations with a height of 115 ± 5 mm and meeting target air voids of 3.5 ± 0.5%. Each sample was placed separately in the Los Angeles Abrasion (LA Abrasion) device and subjected to 300 revolutions, at a speed of 30-33 revolutions per minute, at room temperature (25oC). The samples were weighed before and after the test, and the Cantabro Loss was then calculated as the percent abrasion loss of compacted asphalt mix samples based on the difference between the weights. Lower percent materials loss values indicate a more durable asphalt mixture.

3.3.3.5 Cracking Resistance Using the Semi-Circular Bend (SCB). The SCB test was conducted according to AASHTO TP 124 to characterize the fracture properties of the control and graphite modified mixes at intermediate temperatures. A three-point load is applied on a semi-circular-shaped notched specimen until the specimen is broken. The test was employed to determine the Fracture Energy (G_f) and the Flexibility Index (FI) of graphite modified asphalt mixtures. The SCB test was performed on Superpave gyratory compacted specimens of 7.0 ± 0.5% air voids) that were cut in half and notched with a 1-mm wide, 15-mm long notch in this study. A loading rate of 50 mm/minute was used to break samples that had been conditioned for at least 4 hours at 25C (room temperature). Three replicates were tested for each mix.

To determine the SCB cracking parameters, the force applied in (kN) and the displacement (mm) corresponding to each load were recorded and plotted in a load-displacement curve. Figure 15 is an example of a typical load-displacement curve generated using the SCB output data. As can be seen from Figure 15, the peak load (P max), the inflection point (o), the slope at an inflection points after peak load(m), and the area under the load-displacement curve (W_f) can all be determined using the curve.

Figure 15

Typical SCB Load-Displacement Curve (Haslett, 2018)



The first parameter that was assessed is the Fracture Energy (G_f), and that is the energy required to create a new unit fracture surface in the body (Haslett, 2018). Gf in Joule /m2 is calculated using Equation (8), which is the area under the load-displacement curve (W_f) normalized by fracture area, with the fracture area being calculated as the product of the specimen width (t) and the ligament length (a).

$$Gf = \frac{Wf}{t * a} \qquad (8)$$

The Flexibility Index can be calculated after calculating Gf. One of the primary benefits of normalizing G_f by another parameter is that it allows for better differentiation of fracture resistance between mixtures. Different mixtures may have extremely high peak loads and steep post-peak softening slopes, or vice versa. Equation (9) denotes the formula used to determine FI.

$$FI = A \times \frac{Gf}{|m|} \tag{9}$$

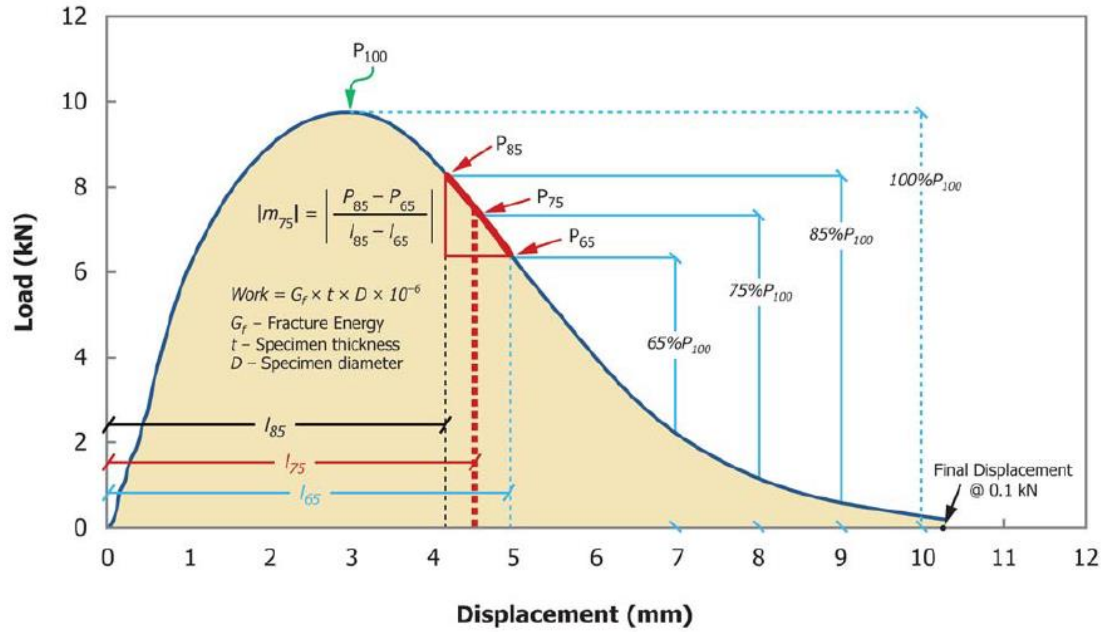
Where A is a calibration factor coefficient, default to be 0.01,

m is the slope at inflection point after peak load.

3.3.3.6 Cracking Resistance Using the Indirect Tension Asphalt Cracking Test (IDEAL-CT). The IDEAL-CT test was performed at 25°C following ASTM D8225-19 standards to assess the fatigue cracking resistance of the control and graphite modified asphalt mixtures. A constant loading rate of 50mm/min was applied until a specimen is broken. Three replicates with a 150 mm diameter, 62 ± 1 mm height, and target air voids of 7%±0.5% were tested for each mixture. The recorded load and displacement were plotted, analyzed, and Fracture Energy (Gf) and Cracking Test Index (CT-Index) were determined using Equations (10) and (11). Figure 16 presents an example of an IDEAL-CT load-displacement curve with the parameters required to determine the cracking performance. Higher Gf and CT-Index values indicate better resistance to fatigue cracking.

Figure 16

Typical IDEAL-CT Load-Displacement Curve (ASTM D8225-19)



$$\mathrm{Gf} = \frac{Wf}{D \times t} \times 10^6 \qquad (10)$$

where:

Gf = failure energy (Joules/m^2),

Wf = work of failure (Joules),

D = specimen diameter (mm), and

t = specimen thickness (mm).

$$CT\,index = \frac{t}{62} \times \frac{l75}{D} \times \frac{Gf}{|m75|} \times 10^6 \qquad (11)$$

where:

CT Index = cracking tolerance index,

Gf = failure energy (Joules/m2),

|m75| = absolute value of the post-peak slope m75 (N/m),

l75 = displacement at 75 % the peak load after the peak (mm),

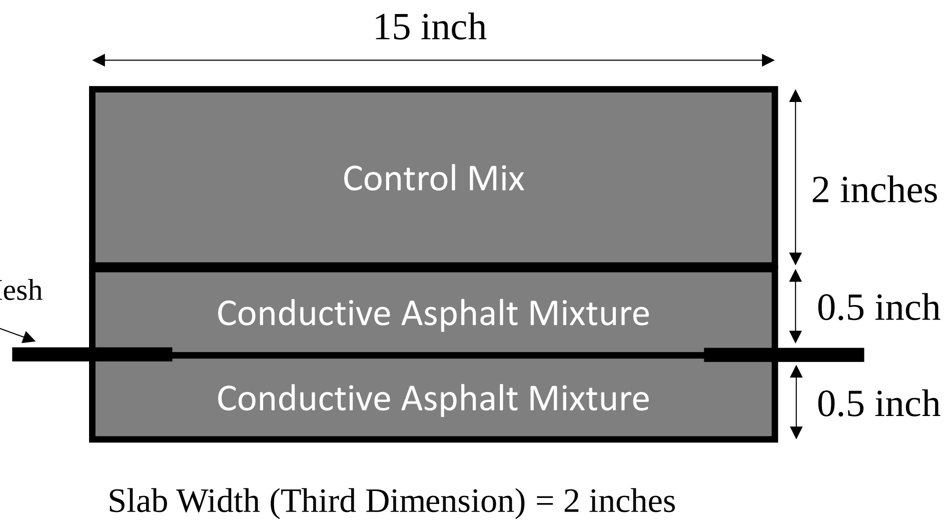
D = specimen diameter (mm), and

t = specimen thickness (mm).

3.3.3.7 Heating Capability of Electrically Conductive Asphalt Mixtures. To provide more comprehensive proof of concept of the use of ECA mixtures for electrically heated asphalt pavements, the mixture with the lowest electrical resistivity, that is, a mixture produced using 30% Graphite C and 1% carbon Fiber (both by volume of binder), was used to construct small-scale electrically heated slabs. In an actual electrically heated pavement, the electrically conductive layer must be completely insulated with no less than 2 inches of non-conductive mixture for personnel safety (FAA, 2011). For this reason, and to simulate an actual electrically heated pavement system, one inch of the electrically conductive mixture was placed in a rectangular mold and then covered with two inches of unmodified control mix.

Figure 17

Side View of Small-Scale Electrically Heated Slab



The Asphalt Vibratory Compactor (AVC), a machine that operates to compact asphalt mixtures into beams using compression action to simulate the field compaction, was used to fabricate asphalt beams to a target air void of 7±1%. The AVC simulates the vibratory compaction rollers used in the field, as it compacts the mixture at the same amplitude, frequency, and relative weight that contractors use when constructing pavements.

Four slabs were constructed with a 1-inch layer of ECA mixture followed by 2 inches of the control HTPO mix layer. A conductive mesh was embedded in the middle of the conductive layers to allow for power measurements throughout the mix as shown in Figure 17 . The dimensions of the Beam rectangular specimens are (15 x 2 inches), and the weight of the mix was determined based on the Gmm of the mixtures and the mold volume.

Figure 18 below shows the electrically conductive asphalt beams with a conductive mesh embedded in the conductive layer. An ammeter was connected to the conductive mesh and was utilized to measure the voltage difference and the electric current passing through the mixture. A non-contact thermometer was used to determine the change of temperature at the non-conductive surface of the slab. The measurements were taken at a 5-minute interval, the resistance and the power needed to heat the non-conductive surface were determined using Equations 3 and 12, and the change of the surface temperature with time was observed.

$$P = I \times V \qquad (12)$$

Where:

V: Voltage (volts)

P: Power (watt)

I: Current (amps)

Figure 18

Electrically Conductive Asphalt Beams with a Conductive Mesh Embedded in the Conductive Layer

3.4 Statistical Analysis

Statistical analysis of the results was performed using R version 4.0.3. The t-test was used to determine if there is a significant difference between the means of the two groups. Specifically, it was used to determine the optimum graphite dosage at which the further increase in graphite does not significantly enhance the electrical conductivity of the ECA mixtures. It was also used to assess the significance of air void levels, the addition of carbon fibers, and the binder grade on the electrical resistivity of ECA mixtures. The P-value was compared to a significance level (α) of 0.05. When the p-value was smaller than 0.05, the null hypothesis (all the means are equal) was rejected. Hence, concluding that there is a significant difference between the means.

Concerning the performance testing results, hypothesis testing was used to determine if the means of multiple groups are different. Those are the Control mixes and

ECA mixtures prepared with Graphite A, B, and C. Therefore, a one-way analysis of variance (ANOVA) test was performed using R version 4.0.3. When the p-value of the ANOVA test was smaller than the significance level of 0.05, the null hypothesis (all means are equal) was rejected, concluding that at least one of the four groups is different in terms of the examined performance. In this case, an adjustment of the p-value was required to determine which groups of mixtures are significantly different than the others. The adjustment method used is called Holm (1979), a pairwise comparison using t-test, which results in a numeric vector of corrected p-values between every two groups. Correspondingly, statistical significance was determined between all mixtures.

Chapter 4

Design, Electrical Resistivity, And Performance of Electrically Conductive Asphalt Mixtures: Results, Analysis, And Discussion

The study's first objective was to design a control unmodified mix and graphite modified asphalt mixtures using the three different graphite particle sizes A, B, and C (explained in Chapter 3). The mixtures were designed unmodified, and graphite was then introduced gradually at different dosages ranging in increments of 5% by volume of the binder according to the Superpave volumetric mix design procedure. As explained in Chapter 2, graphite (similarly to any other conductive additive) must be incorporated in a specific quantity into the asphalt mixture to achieve the lowest possible electrical resistivity with minimal effect of the mechanical properties of the mix as wells as the lowest cost; this dosage is referred to as the optimum dosage and is different each graphite particle size. The electrical resistivity of designed mixtures was assessed, and the dosage was optimized accordingly for each of the graphite sizes. The effect of various factors on the electrical resistivity of ECA mixtures at optimized dosages was investigated. Finally, the mechanical performance of these mixtures was evaluated compared to the control mix. This Chapter presents the results of the mix design, electrical resistivity, and mechanical performance of ECA mixtures.

4.1 Mix Design of Electrically Conductive Asphalt Mixtures

This section presents the mix design results, precisely the volumetric properties and the optimum binder asphalt content of ECA at varying graphite dosages and particle sizes, and the optimal graphite dosage.

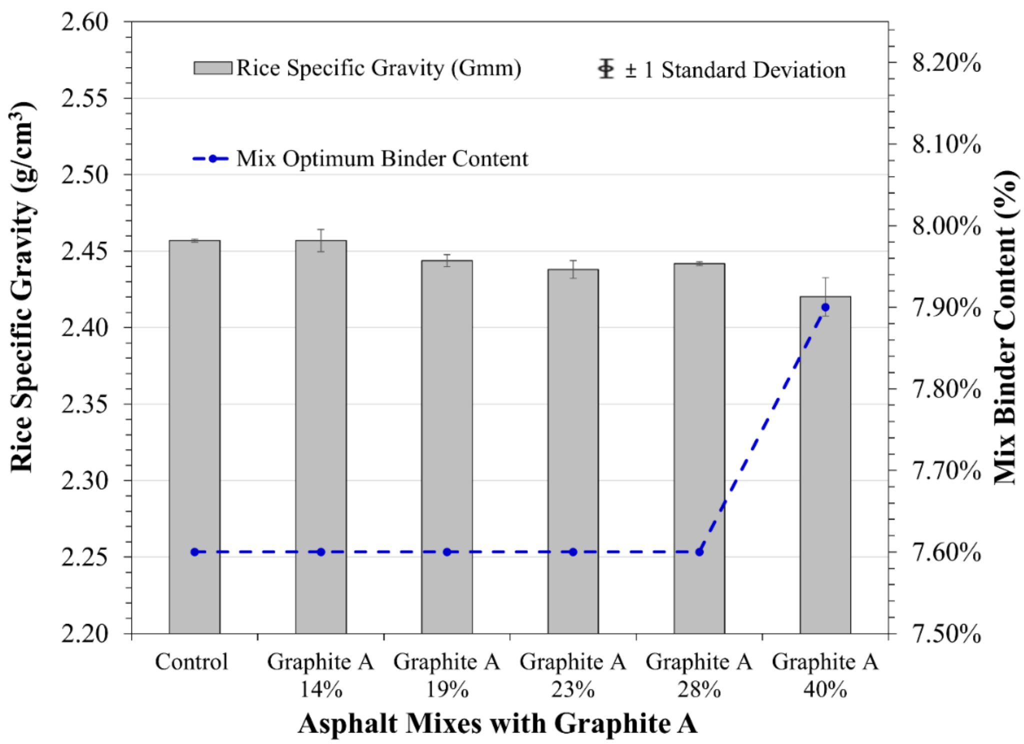
4.1.1 Impact of Graphite Dosage and Particle Size on the Volumetric Properties of Electrically Conductive Asphalt Mixtures

This section presents the impact of graphite dosage and particle size on the volumetric properties of ECA mixtures. All the mixtures in this study were designed to satisfy the New Jersey Department of Transportation (NJDOT) requirements for HPTO mix presented in Chapter 3, and the impact on the volumetric properties as the graphite dosage and size changes was investigated. Table A4 in the Appendix presents the Rice Specific Gravity (G_{mm}), Bulk Specific Gravity (G_{mb}), Air Voids level, Voids in Mineral Aggregate (VMA %), Voids Filled with Asphalt (VFA %), and Dust to Binder Ratio of all designed mixtures with varying graphite grades and dosages. Figures 19,20, and 21 present the change in Gmm and optimum binder content required to maintain a 3.5 ± 0.5% air voids level at varying dosages for the three graphite grades A, B, and C, respectively.

Figure 19 shows that mixtures prepared with Graphite-A, the smallest particle size graphite, maintained a constant optimum binder content of 7.6% by total mix weight when graphite was introduced at dosages ranging from 14% to 28% % by volume of asphalt binder—introducing Graphite-A in dosages up to 28% by volume of binder did not impact the optimum binder content for ECA mixes. However, when Graphite A dosage was increased to 40%, an additional binder was required to satisfy the HPTO mix design requirements, leading to a decreased Gmm of the mix. It must be pointed out that at a lower than 7.9% binder content, the mixture prepared with Graphite A at 40% dosage did not meet the air voids requirement. This may be attributed to the increased binder absorption when replacing aggregates at such a high dosage of this graphite grade.

Figure 19

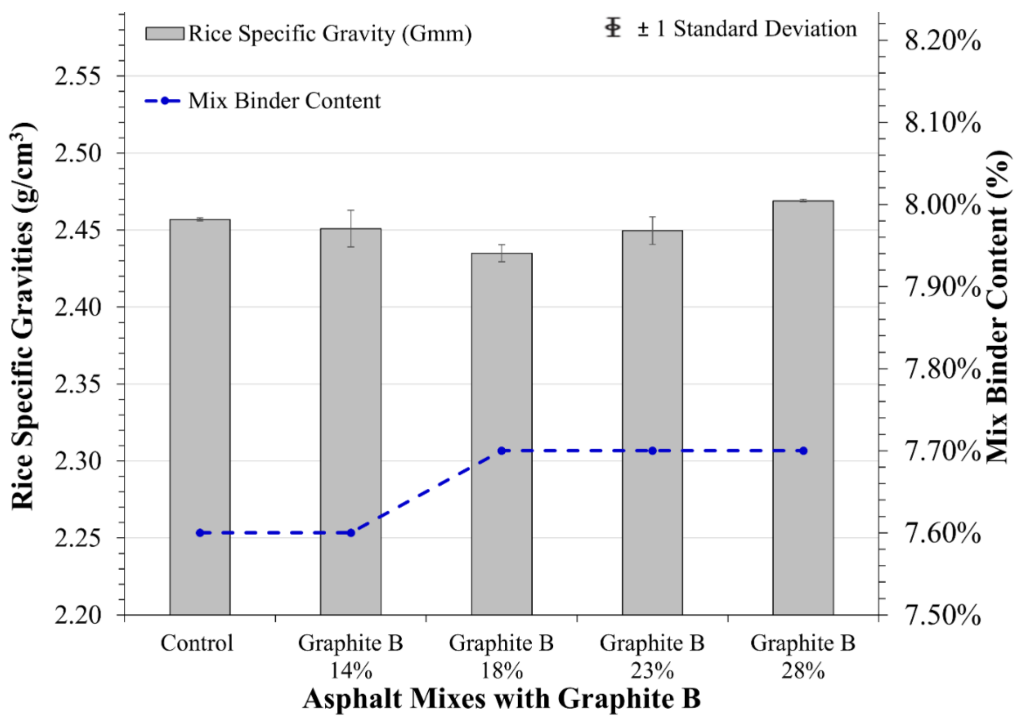
Impact of Graphite A Dosage on Rice Specific Gravity of Electrically Conductive Asphalt Mixes



Graphite B, which is of larger particle size than Graphite-A, required an increase in binder content at a lower dosage of 18%. Figure 20 shows that introducing Graphite B at a dosage of 14% by volume of binder did not affect the Gmm or the mixture's optimum binder content compared to the control mix. However, when Graphite B dosage increased from 14% to 18%, a slight increase in the binder content from 7.6% to 7.7% was needed to satisfy the mix design requirements. Moreover, the increase in Graphite B dosage from 18% to 23% and 23% to 28% did not require an extra binder to achieve the air-void level of 3.5 ± 0.5%, maintaining an optimum binder content of 7.7%.

Figure 20

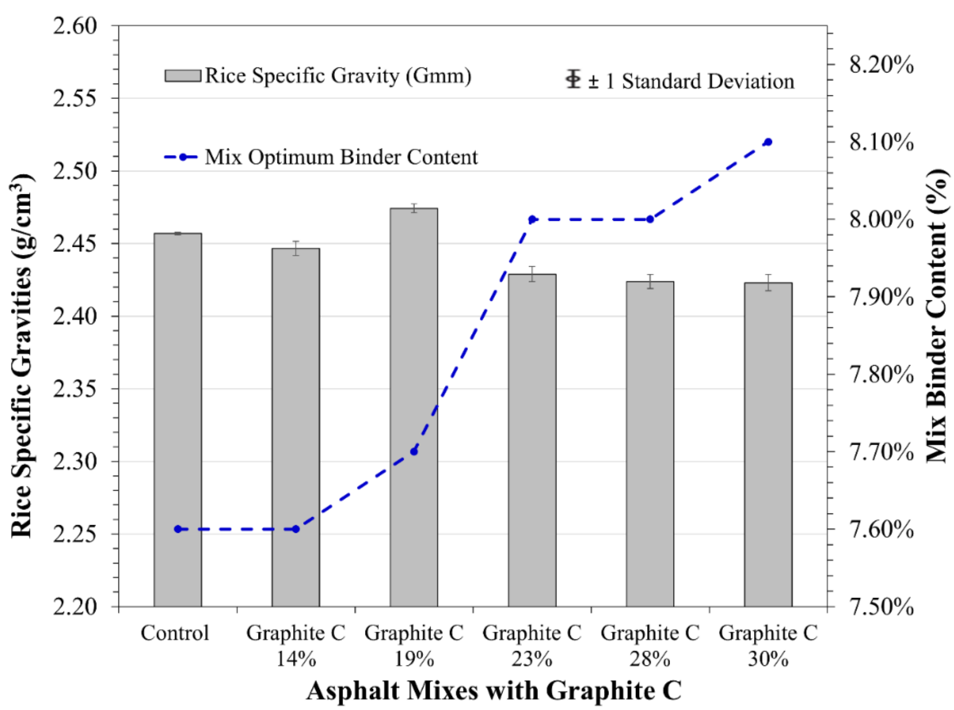
Impact of Graphite B Dosage on Rice Specific Gravity of Electrically Conductive Asphalt Mixes



In the case of Graphite C, which is of the largest size, Figure 21 demonstrates that higher binder contents were required as the dosage of this graphite grade increased, similar to other graphite grades. However, the impact of Graphite C on the optimum binder content is more prominent than that of Graphite A and Graphite B, which are of smaller particle sizes. For instance, at a specific graphite dosage of 28%, the binder content required to satisfy the air voids requirement was 7.6%, 7.7%, and 8% for Graphite A, B, and C, respectively. This emphasizes that both graphite particle size and dosage impact the ECA mixtures' volumetric properties, with larger particle sizes and higher dosages requiring more binder content to meet the mix design requirements.

Figure 21

Impact of Graphite C Dosage on Rice Specific Gravity of Electrically Conductive Asphalt Mixes



4.1.2 Mix Design Results for the Control and Electrically Conductive Asphalt Mixtures Produced at Optimal Graphite Dosages.

Table 11 presents the mix design results for the control and ECA mixes prepared at optimal graphite dosages. The optimal graphite dosages were determined based on the electrical resistivity results (explained in the next section 4.2.1). Table 11 shows that the optimum binder content for the control mix was 7.6% by the total weight of the mixture. For the ECA mixtures prepared using the three graphite grades, higher optimum binder contents were needed to meet the volumetric mix design requirements for the HPTO mix. These results are mainly attributed to the absorption of asphalt binder by the graphite in the ECA mixes. With graphite absorbing more of the asphalt binder in ECA mixes, higher air voids are created; thus, justifying the need for an additional binder to fill up these voids to meet the HPTO volumetric mix design requirements.

The impact of graphite on the optimum binder content also varied based on the dosage and particle size of the graphite additive. Graphite C, the largest particle size graphite, needed the highest binder content of 8.1 % at a dosage of 30%, a 0.5 % increase from the control mix to meet the volumetric design criteria. Graphite B, at an optimal graphite dosage of 28%, only needed a 0.1 % binder increase compared to the control mixture. Graphite A required a 0.3 % binder increase at the optimal graphite dosage of 40%. Resultantly, higher binder contents, up to 0.5 % for the graphite grades tested in this study, are needed to meet the design criteria for graphite with the largest particle size. Furthermore, at a higher graphite dosage, more binder is needed to meet volumetric mix design requirements.

Table 11

Superpave Mix Design Results

Mix ID	Optimal Graphite Dosage (%)	Optimum Binder Content (%)	Avg. Air Voids (%)*	Voids in Mineral Aggregates (VMA, %)*	Dust-to-Binder Ratio (%)*
Control	0	7.6	3.65	19.70	0.63
Graphite-A	40	7.9	3.56	21.21	0.61
Graphite-B	28	7.7	3.58	19.45	0.62
Graphite-C	30	8.1	3.72	21.14	0.60

* Target air voids: 3 ± 0.5%, Min. VMA: 18%, and Target Dust to Binder Ratio: 0.6–1.2

4.2 Electrical Resistivity of Electrically Conductive Asphalt Mixtures

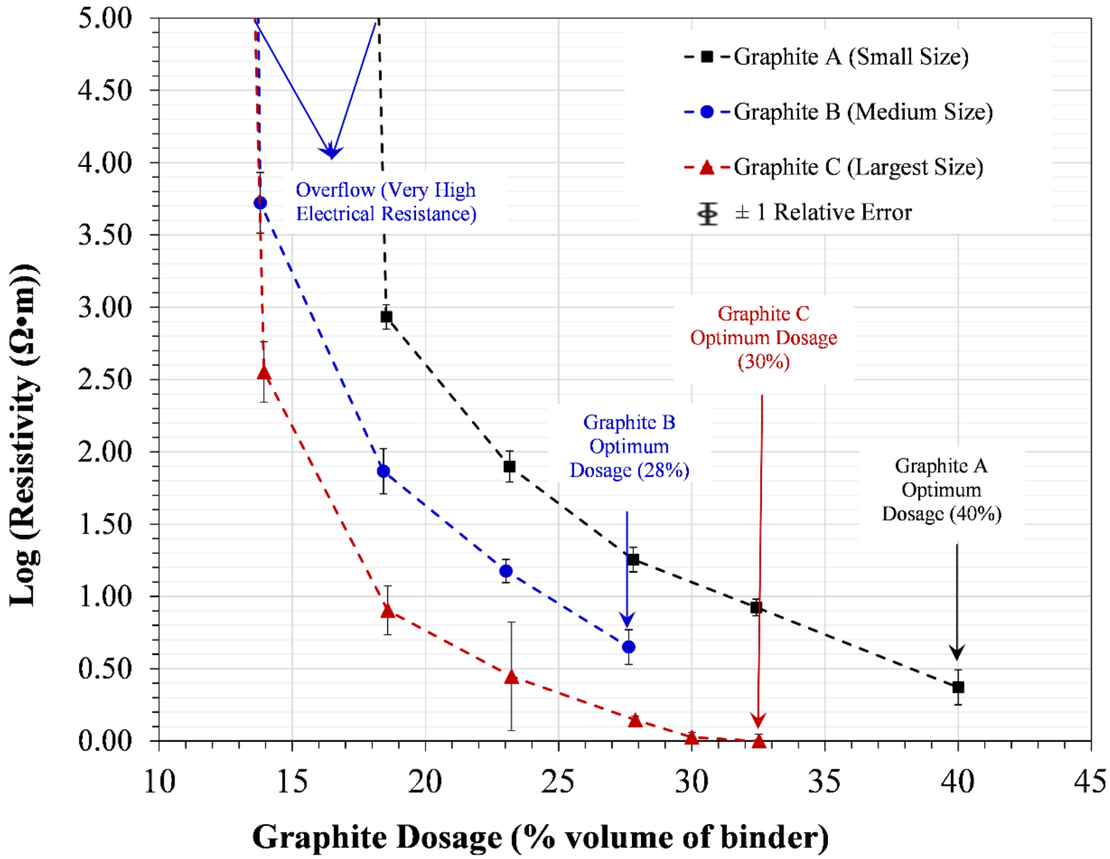
This section discusses the effect of different factors on the electrical resistivity of graphite-modified mixtures. These include the graphite dosage and particle size, the air void level of the mix, the type of binder used, and the addition of 1% carbon fiber by volume of binder.

4.2.1 Impact of Graphite Particle Size and Dosage on Electrical Resistivity Asphalt Mixtures

The average resistivity values measured for each graphite grade at varying dosages were recorded and presented in Table A5 in the Appendix. Figure 22 illustrates the relationship between graphite dosage and electrical resistivity of ECA mixtures prepared using the three graphite grades A, B, and C. As shown in Figure 22, the increase in graphite dosage lowers the electrical resistivity of asphalt mixtures for all the graphite grades examined in this study. However, it can also be observed that the reduction rate is not constant and decreases at higher dosages of graphite. Figure 22 also shows that a sudden drop in electrical resistivity happened at dosages between 10% and 15% for all graphite grades, suggesting that the percolation thresholds exist between 10% and 15% by volume binder. As a consequence of these observations, it can be inferred that graphite enhances the electrical conductivity of asphalt mixtures when applied at dosages of 10% to 15% by volume of binder.

Figure 22

Impact of Graphite Dosage on Electrical Resistivity of Asphalt Mixtures



Additionally, comparing the electrical resistivity measured for all three graphite grades (A, B, and C) indicates that the improvement in electrical conductivity (conveyed as electrical resistivity reduction) varies for each graphite grade (particle size). To elaborate more, the largest particle size graphite, Graphite C, reduced the electrical resistivity of the control mixture at a lower dosage than the other two graphite grades. For example, at a 25% graphite dosage, Graphite C had a resistivity of about 2 Ω-m. At the exact dosage (25%), Graphite B reduced the electrical resistivity to around 8 Ω-m, while Graphite A (smallest particle size) had an electrical resistivity of about 40 Ω-m.

The optimum dosages determined for each of the graphite grades are also illustrated in Figure 22. The optimum graphite dosage leads to an asphalt mixture with the lowest electrical resistivity with minimal effect on the mix's skeletal structure. That is either the maximum graphite dosage that could be substituted or the dosage at which the further increase in graphite does not lead to a further significant reduction in the electrical resistivity. Figure 22 demonstrates that Graphite A had an optimal dosage of 40%, Graphite B had an optimal dosage of 28%, and Graphite C had an optimal dosage of 30%, all by volume of asphalt binder. In the case of Graphite C, an increase in the dosage from 30% to 33% decreased the electrical resistivity from 1.06 Ω-m to 1.00 Ω-m. The p-value of the t-test was large (p-value = 0.7276) compared to a significance level of (α = 0.0500), demonstrating that the further increase in dosage after the optimum dosage of 30% did not lead to any significant reduction in electrical resistivity. On the other hand, such a dosage could not be achieved for other graphite grades as the maximum dosage that could be substituted was 40% and 28% for Graphite A and B, respectively. (See substitution process explained in Chapter 3, Section 3.3.1).

Furthermore, when comparing the optimal dosages and electrical resistivity values for all three graphite grades (Figure 22), it has been shown that Graphite A (smallest size) required a higher dosage to achieve a reasonably comparable electrical resistivity to

Graphite B (medium size). Graphite C (largest size) increased the electrical conductivity of the control mix the most at the optimum dose. These findings add to the growing body of evidence that the particle size (or grade) of graphite influences the electrical conductivity of asphalt mixtures; that is, using graphite with larger particle sizes improves the electrical conductivity of asphalt mixtures. Graphite of better size distribution forms stronger conductive paths than poorly graded graphite , thus creating an enhanced conductive network that facilitates the flow of current in the ECA mixture.

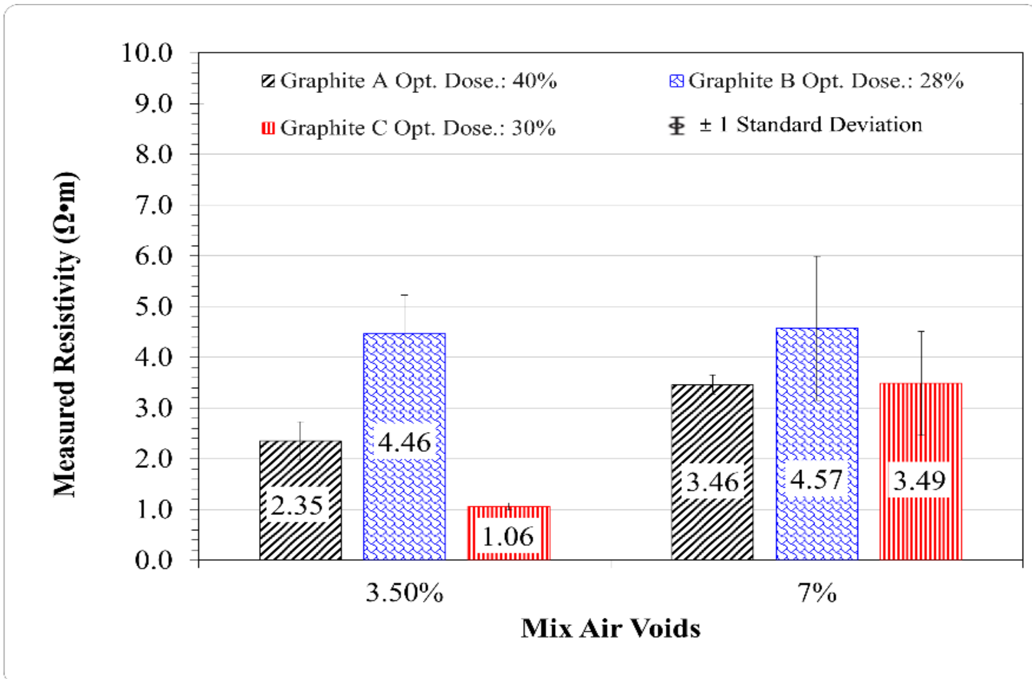
4.2.2 Effect of Air Voids Level on Electrical Resistivity of Electrically Conductive Asphalt Mixtures

The average electrical resistivity values of ECA mixtures prepared at the optimal graphite dosages at 3.5% and 7% air voids levels are presented in Figure 23. Figure 23 shows that the electrical resistivity of ECA mixtures increased as the air voids level increased for mixtures prepared with Graphite A and Graphite C, but not for those prepared with Graphite B. The p-value of the t-test was small (0.003 and 0.039) for Graphite A and C, respectively, and large (0.467) for Graphite B, all compared to a significance level of ($\alpha = 0.050$). This suggests that the air voids' effect on the electrical resistivity of ECA mixes is more prominent in mixtures with lower resistivity values (Graphite A and C).

Furthermore, Graphite-B-mixtures, which had an average resistivity of 4.57 Ω-m, were not significantly affected by the decrease of air void level from 7% to 3.5%. Whereas the exact change in air void level decreased the resistivity values in percentages of 32% and 70% for Graphite A and C, respectively, which had an initial average electrical resistivity of about 3.5 Ω-m. Therefore, it can be concluded that the effect of air voids level on the electrical resistivity of ECA mixtures was significant for mixtures with resistivity values of about 3.5 Ω-m and below. As a result, ECA mixtures should be compacted to higher densities (or lower air voids) to achieve lower electrical resistivity.

Figure 23

Impact of Sample Air Voids on Electrical Resistivity of Asphalt Mixtures



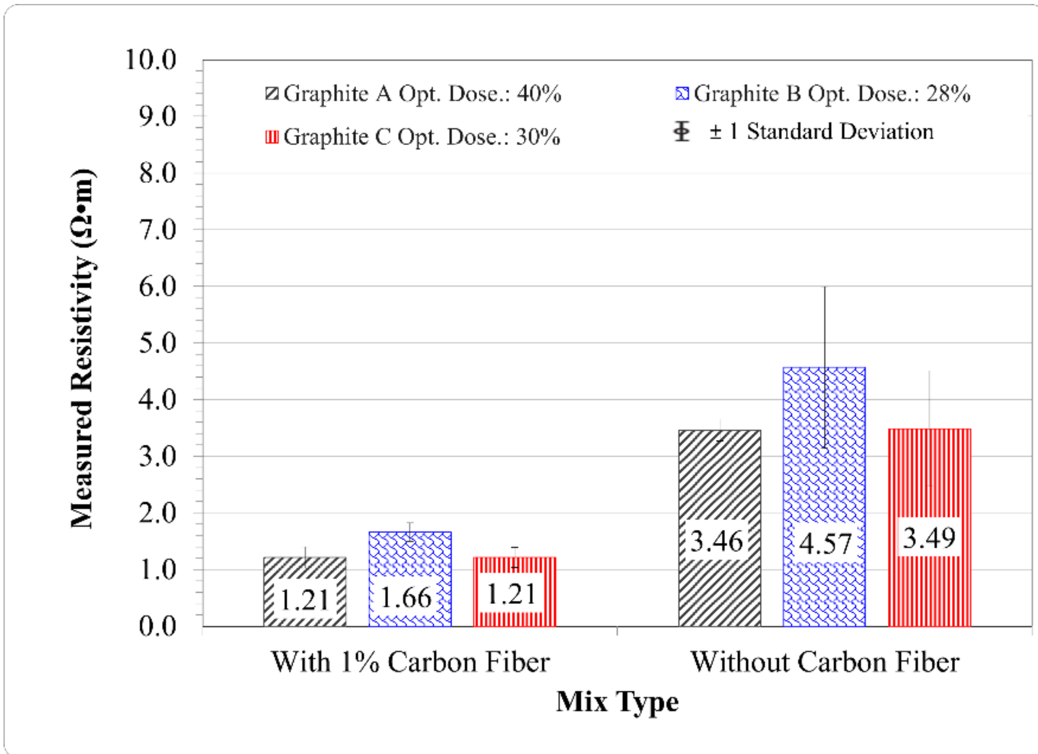
4.2.3 Effect of Carbon Fiber on Electrical Resistivity of Electrically Conductive Asphalt Mixtures

Figure 24 shows the electrical resistivity of ECA mixtures prepared with and without the carbon fibers at 7% air voids. When carbon fibers were added to graphite-modified mixtures at 1% by volume of binder, the mixtures' electrical resistivity was reduced significantly compared to those prepared without carbon fibers. The p-value of the t-test was (0.003, 0.050, and 0.045) for Graphite A, B, and C, respectively. On average, adding carbon fibers to graphite modified mixes decreased their electrical resistivity by approximately 65 % for the three ECA mixtures. Furthermore, the ECA mixtures prepared with the three graphite grades have a similar electrical resistivity value within 0.4 Ω-m. This was true regardless of the graphite dosage or particle size in the ECA mixtures, implying that carbon fiber, even at a small quantity of 1% by volume of binder, enhances the conductivity significantly of asphalt mixtures prepared with graphite at the optimal graphite dosage.

It is also worth noting that the control mix was not conductive when only carbon fibers without graphite were added to the mixture and did not reach the percolation threshold. The resistance measured by the multimeter was recorded as "overflow," indicating a resistance higher than the sensitivity limits of the device. Thus, the improvement in electrical conductivity is attributed to the bridging effect of carbon fiber that helps the conductive network initially created by the graphite to expand and grow in all directions.

Figure 24

Impact of Carbon Fiber on the Electrical Resistivity of Graphite-Modified Mixtures

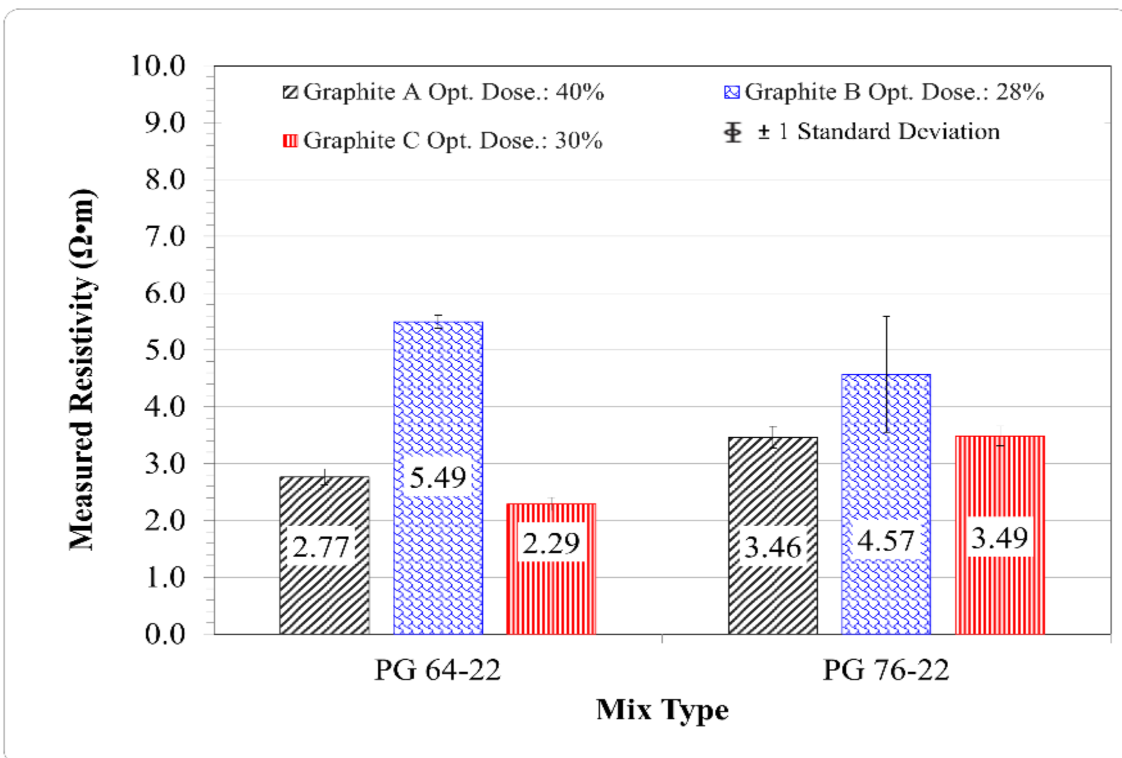


4.2.4 Effect of Binder Grade on Electrical Resistivity of Electrically Conductive Asphalt Mixtures

The effect of binder grade on the electrical resistivity of graphite-modified mixtures is presented in Figure 25. The difference between the two binders is the presence of a polymer modifier in the PG 76-22. Polymers are electrical insulators (Comyn,1985); thus, explaining the need to investigate the effect of different binder grades on the electrical conductivity of ECA mixtures. According to Figure 25, asphalt mixtures prepared with Graphite A and Graphite C using the neat PG 64-22 asphalt binder had lower electrical resistivity (by around 0.69 to 1.2 Ω-m) than those prepared with the modified PG 76-22 asphalt binder. However, ECA mixtures prepared with Graphite B had a higher electrical resistivity in the case of PG 64-22 than PG 76-22 (by around 0.92 Ω-m). The p-value of the t-test was large (0.156, 0.623, and 0.137) in case of Graphite A, B, and C, respectively, compared to a significance level of ($\alpha = 0.050$). This suggests that the effect of binder grade on the electrical resistivity of graphite-modified mixtures is statistically insignificant at the optimum dosage of graphite.

Figure 25

Impact of Binder Grade on Electrical Resistivity of ECA Mixtures



4.3 Impact of Graphite on the Mechanical Performance of Asphalt Mixtures

This section discusses the rutting resistance, durability, and cracking resistance of graphite modified mixtures compared to the control mix.

4.3.1 Rutting Resistance of Graphite Modified Mixtures

The Asphalt Pavement Analyzer (APA) and Hamburg Wheel Tracking Device (HWTD) test results were used to evaluate the rutting resistance of the ECA mixtures.

4.3.1.1 The Asphalt Pavement Analyzer (APA) Test Results. The average rutting depths obtained from the APA test for the control and graphite modified asphalt mixtures are presented in Figure 26. (See Appendix, Tables 6, 7, 8, 9, and 10 for final rutting depths). As shown in Figure 26, on average, the rut depth measured for the unmodified control mix was 42% greater than that obtained for all graphite modified asphalt mixes. The control mix had a rutting depth that was 1.5 times higher than the ECA mixtures prepared with Graphite C, which had the highest rutting depth.

Furthermore, the APA rutting depths for all graphite modified mixes were relatively similar in rutting resistance within 0.4 mm. The P-value of the ANOVA test was low (p-value 0.002) compared to a significance level of 0.05, indicating that at least one of the mixture groups (Control, A, B, and C) is significantly different from the others in terms of APA rutting depths. Table 12 presents the adjusted p-values using the Holm adjustment method are presented in the following matrix. The p-values indicate that a significant difference exists between the rutting depths of the control and all three graphite modified mixtures at a significance level of 0.05. However, the large p-value between the mixtures prepared with Graphite A, B, and C indicates that all ECA mixtures have the same rutting depths. These findings reveal that the addition of graphite to asphalt mixtures, regardless of the size of the graphite size and dosage, improves the mixtures' rutting resistance.

Figure 26

Asphalt Pavement Analyzer (APA) Rutting Depths

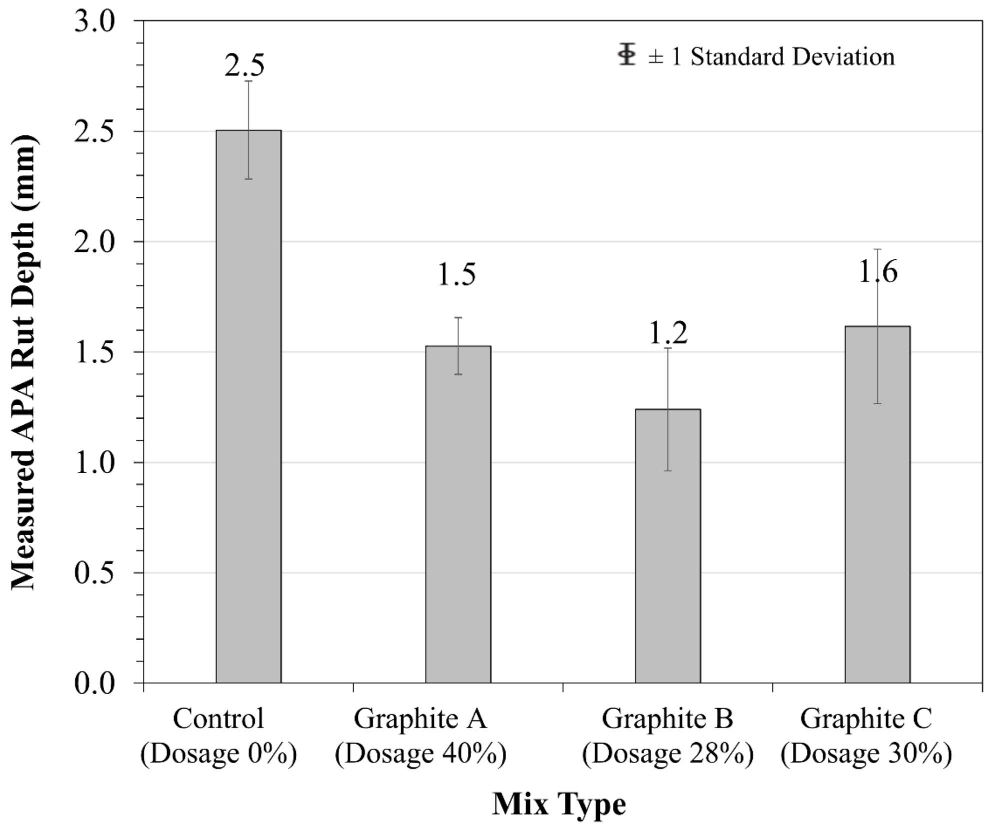


Table 12

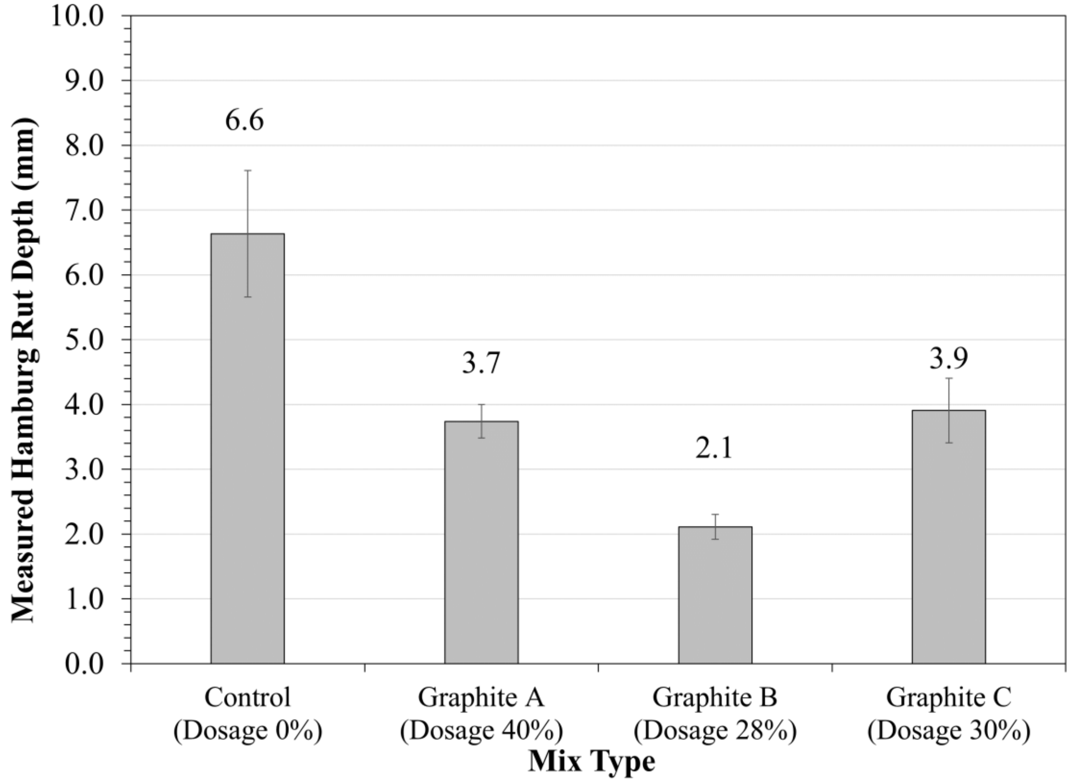
The P Values Indicating the Statistical Difference Between the APA Rutting Depths for Each Pair of Mixture Sets.

Mix ID	Graphite A	Graphite B	Graphite C
Graphite B	0.417	-	-
Graphite C	0.682	0.332	-
Control	0.008	0.002	0.012

4.3.1.2. Hamburg Wheel Tracking Device (HWTD) Test Results. The results of the HWTD, a wet rutting resistance test, are presented in Tables A11, A12, and A13 in the Appendix and illustrated in Figures 27 and 28 below. Figure 27 demonstrates that the unmodified control mix had an average HWTD rutting depth that is, on average, two times higher than the rutting depth of the graphite-modified mixtures. The rutting depth of the control mix is 40% higher than the rutting depth of Graphite-C-mixture, the ECA mixture with the highest rutting depth. This was true even though all graphite modified mixes' optimum binder contents were higher than the unmodified mixture.

Figure 27

Hamburg Wheel Tracking Device (HWTD) Average Rut Depths



The p value of the one-way ANOVA test was small (p-value = 8.05e-05 < 0.05 = α), indicating that at least one of the mixtures has a statistically different HWTD rutting depth. Table 13 presents the adjusted p-values between the HWTD rutting depths for each pair of mixtures. The results show that a statistical difference exists between the rutting depths of the control mix and all other ECA mixtures at a significance level of 0.05. Nonetheless, the large p-value between Graphite A and Graphite C (0.730) suggests that the difference between the rutting depths of mixtures prepared with 40% of Graphite A and 30% of Graphite C is statistically insignificant at a significance level of 0.05.

Table 13

The P Values Indicating the Statistical Difference Between the HWTD Rutting Depths for Each Pair of Mixture Sets.

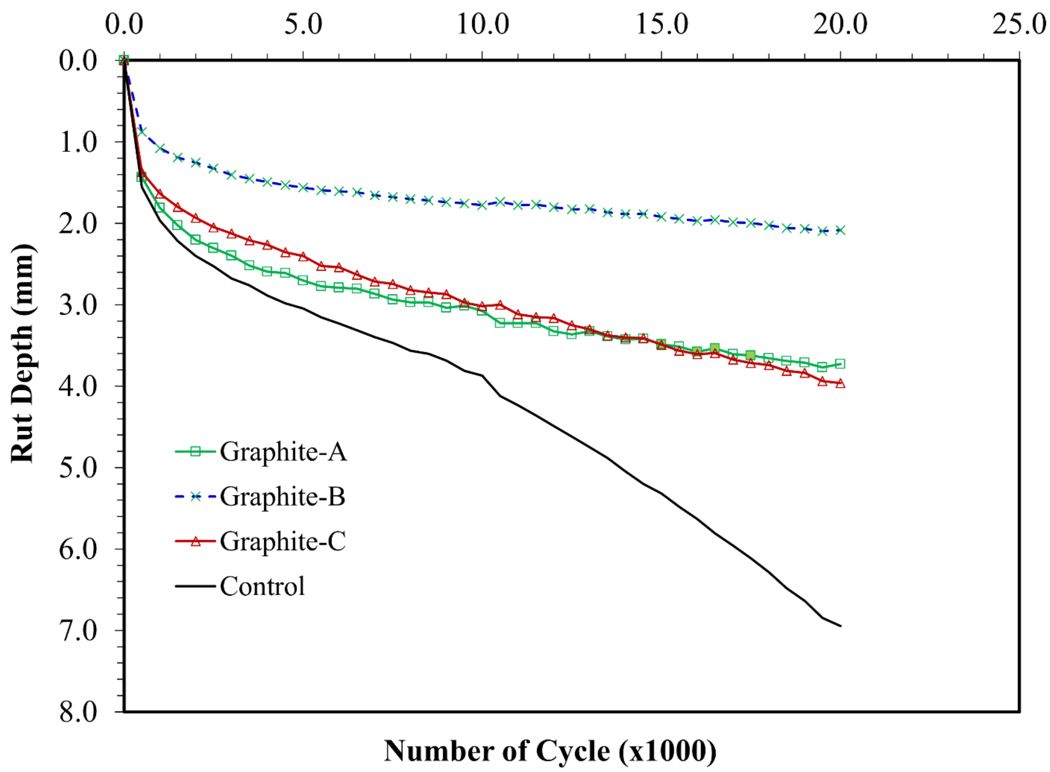
Mix ID	Graphite A	Graphite B	Graphite C
Graphite B	0.016	-	-
Graphite C	0.730	0.015	-
Control	0.001	0.000	0.002

These results are consistent with the findings of the APA test and supports the conclusion that adding graphite to asphalt mixtures of any size improves their resistance to rutting, whether in dry or wet conditions. Interestingly, by comparing the results of the APA and HWTD tests (Figure 26 and 27), it can be seen that the rutting depths are following the same trend in the two cases. For instance, mixtures modified with Graphite B (medium size) always had the lowest rut depth measured by the APA and HWTD tests. Mixtures prepared with Graphite A and C had approximately similar rutting depths, higher than Graphite B mixtures and still lower than the unmodified control mix. These results indicate that Graphite B was the most effective at improving the rutting resistance of asphalt mixtures. However, it should be noted that the asphalt mix modified with Graphite B had a lower optimum binder content of 7.7% than those produced with Graphite A and Graphite C, which may explain the further improvement in rutting performance when compared to other ECA mixtures.

The Stripping Inflection Point (SIP) is another parameter assessed using the HWTD test . SIP is the number of passes after which moisture damage dominates the mixture's performance causing stripping. As a result, it is a good indicator of a mixture's ability to withstand moisture-induced damage. Figure 28 shows the average rutting depths of all mixtures corresponding to the number of cycles to identify the SIP. As shown in Figure 28 , the SIP for the control mix was observed after approximately 10,784 loading passes. However, there was no SIP in the HWTD data for any of the graphite-modified asphalt mixtures. This could imply that adding graphite improves the ability of asphalt mixtures to withstand moisture-induced damage.

Figure 28

Average Rutting Depths Corresponding to the Number of Cycles for the Control and ECA Mixtures

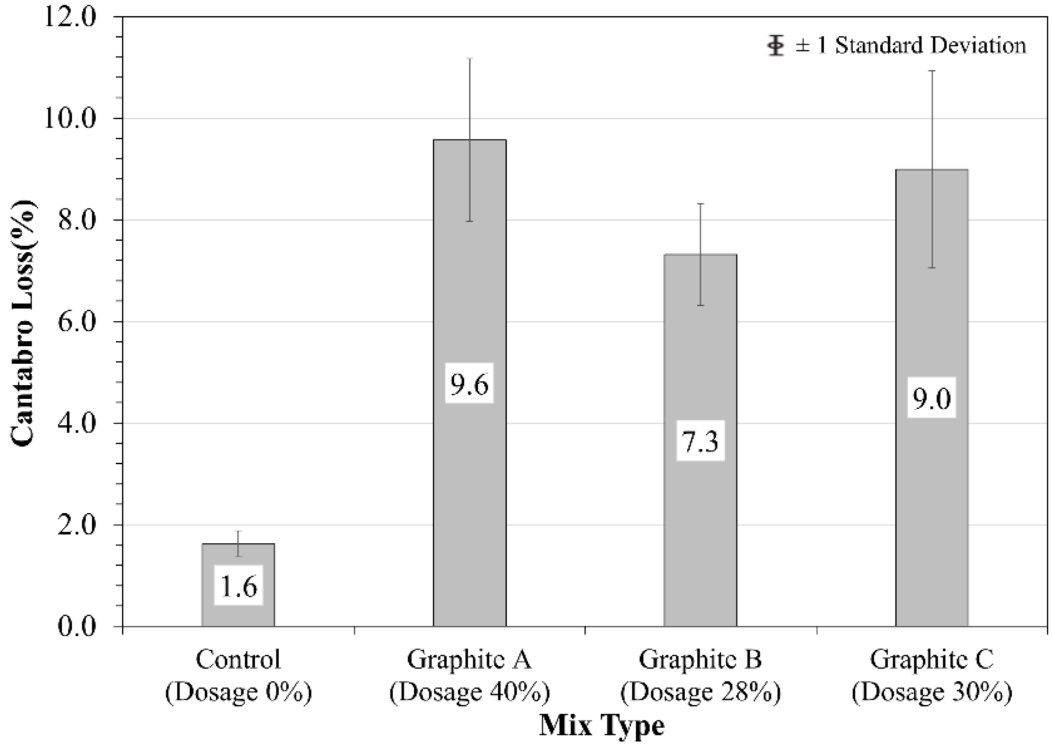


4.3.2 Durability of Graphite Modified Mixtures

The Cantabro loss test results were used to assess the durability of ECA mixtures. The results of the Cantabro durability test are presented in Tables A14 and A15 in the Appendix and are illustrated in Figure 29 below. The control mix, on average, had a Cantabro loss that is around 80% lower than all ECA mixtures modified with graphite. This could be due to the weak Van der Waals forces that hold graphite plates together within an asphalt mix (Lui and Wu 2013). This suggests that graphite-modified asphalt mixtures are more prone to breakdown than conventional asphalt mixes (control mix). As a result, evaluating the durability of graphite modified mixes during the mix design stage is critical to ensuring that these mixes last in the field.

Figure 29

Average Cantabro Loss



The statistical analysis of the Cantabro Loss test results supports the conclusion that the Cantabro loss of the control mix differs significantly from the three graphite modified mixtures. The P-value of the one-way ANOVA test is small (p-value = $0.005 < 0.05 = \alpha$). This indicates that at least one group has a Cantabro loss that is statistically different from other groups. Table 14 shows the p-values for all pairs of mixtures using the Holm adjustment method. The results show that all ECA mixtures have a significantly different Cantabro loss than the control mix, with p-values lower than 0.05. However, the large p-values between Groups A, B, and C indicate that the Cantabro loss was similar for mixtures prepared using the three graphite grades at their optimal dosages.

Table 14

The P Values Indicating the Statistical Difference Between the Cantabro Loss for Each Pair of Mixture Sets

Mix ID	Graphite A	Graphite B	Graphite C
Graphite B	0.189	-	-
Graphite C	0.572	0.572	-
Control	0.006	0.039	0.017

4.3.3 Cracking Resistance of Graphite Modified Mixtures

The cracking performance of ECA mixtures compared to the unmodified control mix was evaluated using the Semi-Circular Bend (SCB) test and the Indirect Tension Asphalt Cracking (IDEAL-CT) test results.

4.3.3.1 Semi-Circular Bend (SCB) Test Results. Tables A16, A17, and A18 in the Appendix represent the SCB results for each tested sample. The equations presented in Chapter 3 (Section 3.3.3.5) were used to determine the Fracture Energy (Gf) and the Flexibility Index (FI) of all mixtures. Figure 30 depicts the fracture energy obtained from the SCB test for the control and graphite modified asphalt mixtures. The fracture energy obtained for the control mixture was, on average, two times higher than that of the average value for all graphite-modified asphalt mixtures. This implies that graphite-modified asphalt mixtures have lower cracking resistance and are more susceptible to cracking than conventional unmodified mixtures.

Furthermore, Figure 30 shows that mixtures produced using Graphite B had the lowest fracture energy compared to those produced using Graphite A and C, which had relatively similar fracture energy values. However, with the high standard deviation bar, the three graphite modified mixtures appear to have similar fracture energy. The statistical analysis results support this finding, with the p-value of the ANOVA test being small (p-value = 9.06e-06 < 0.05 = α), suggesting that one of the groups had fracture energy mean that is statistically different. The p-values of the Fracture Energy for each pair of mixtures are presented in Table 15. The results suggest that the three graphite modified mixture sets have the same SCB fracture energy that is significantly different from the fracture energy of the control mix.

Figure 30

Average Fracture Energy of the Semi-Circular Bend (SCB) Test

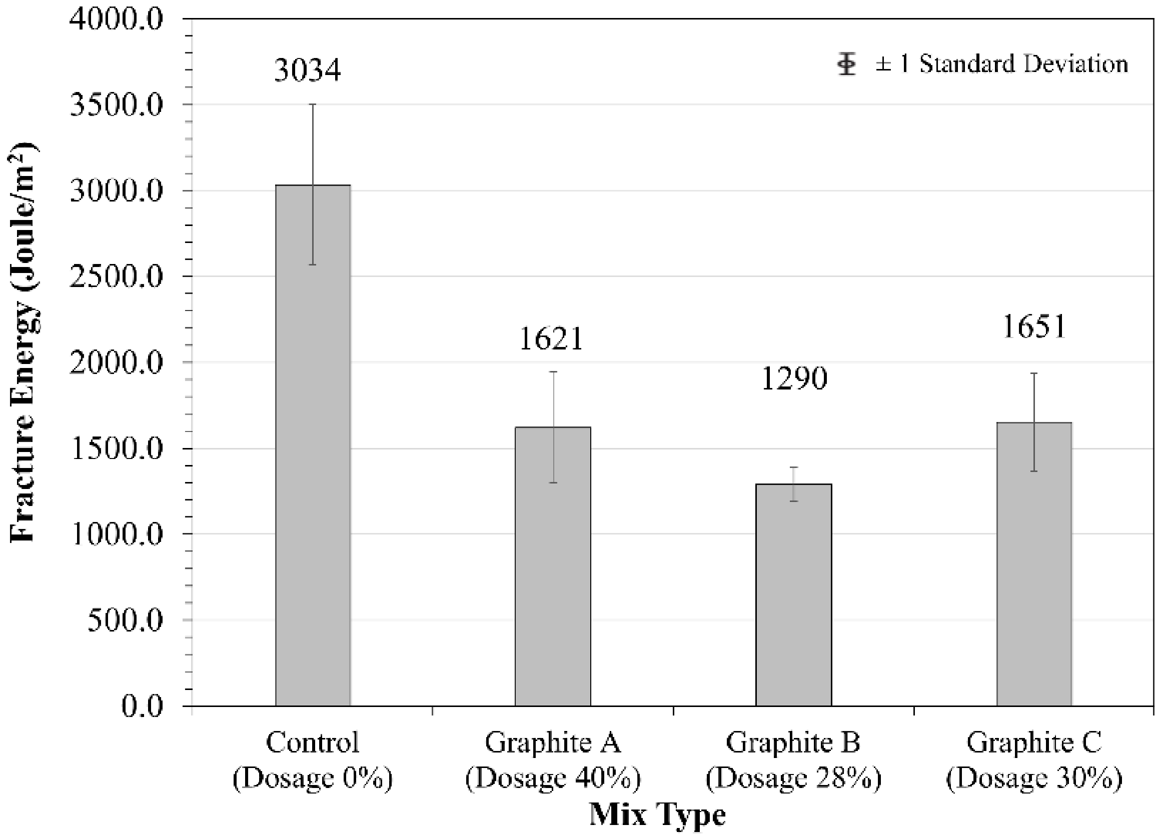


Table 15

The P Values Indicating the Statistical Difference Between the Fracture Energy Obtained from the SCB Test for Each Pair of Mixture Sets.

Mix ID	Graphite A	Graphite B	Graphite C
Graphite B	0.319	-	-
Graphite C	0.894	0.319	-
Control	0.000	0.000	0.000

The SCB Flexibility Index (FI) averages for the unmodified control and graphite modified asphalt mixtures are shown in Figure 31. As illustrated in Figure 31, all three graphite-modified mixtures had lower FI values than the control mix. On average, the graphite modified mixtures had a FI that was 69% lower than that of the control mix. The lower FI values obtained for the graphite modified mixes indicate that adding graphite to asphalt mixtures results in deteriorated cracking resistance. This was true even though the control mix contained less optimum binder than all graphite-modified binders. The FI values shown in Figure 31 also show that the mix prepared with Graphite B was the most susceptible to cracking, followed by those prepared with Graphite A and Graphite C, which have similar cracking resistance based on their FI values and the statistical significance results.

Figure 31

Average Flexibility Index of the Semi-Circular Bend (SCB) Test

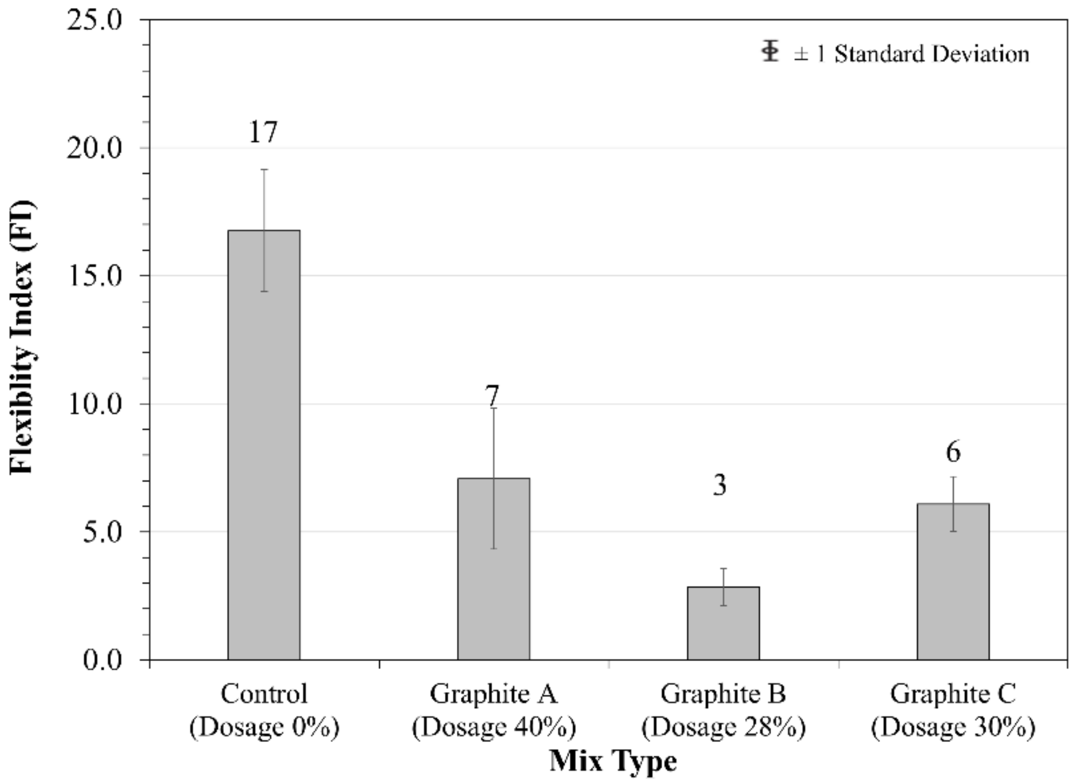


Table 16 presents the statistical analysis results for the Flexibility Index results obtained from the SCB test. It can be seen from Table 16 that the control mix has a significantly different FI than all graphite-modified mixtures. The large p-value (p-value = 0.465 > 0.05 = α) between mix sets (Graphite A and Graphite C) indicates that the mixtures prepared using these two graphite grades have statistically similar FI values.

Table 16

The P Values Indicating the Statistical Difference Between the Flexibility Index Obtained from the SCB Test for Each Pair of Mixture Sets .

Mix ID	Graphite A	Graphite B	Graphite C
Graphite B	0.015	-	-
Graphite C	0.465	0.047	-
Control	0.000	0.000	0.000

4.3.3.2 The Indirect Tension Asphalt Cracking (IDEAL-CT) Test Results. The results of the IDEAL-CT test, including Fracture Energy (Gf) and the CT-Index, as obtained using the equation presented in Chapter 3 Section 3.3.3.6, are presented in Tables 19 in the Appendix. Figures 30 and 31 present the average Fracture Energy (Gf) and the CT-Index, respectively, as obtained from IDEAL-CT test results. As can be seen from Figure 32, On average, the Fracture Energy (Gf) of the unmodified control mix is about 40% higher than the graphite modified mixtures. The p-value of the one-way ANOVA test is small ($p\text{-value} = 8.18e\text{-}05 < 0.05 = \alpha$), showing that at least of the mix sets had a significantly different Fracture Energy mean. Table 17 presents the p-values of the Fracture Energy results obtained from the IDEAL-CT test for each pair of mixture sets. According to the hypothesis testing results (Table 17), the IDEAL-CT results reveal that the ECA mixtures prepared using Graphite A, B, and C have an identical Fracture Energy value that is significantly different from the fracture energy of the unmodified control mix.

Figure 32

Average Fracture Energy of the Indirect Tension Asphalt Cracking (IDEAL-CT) Test

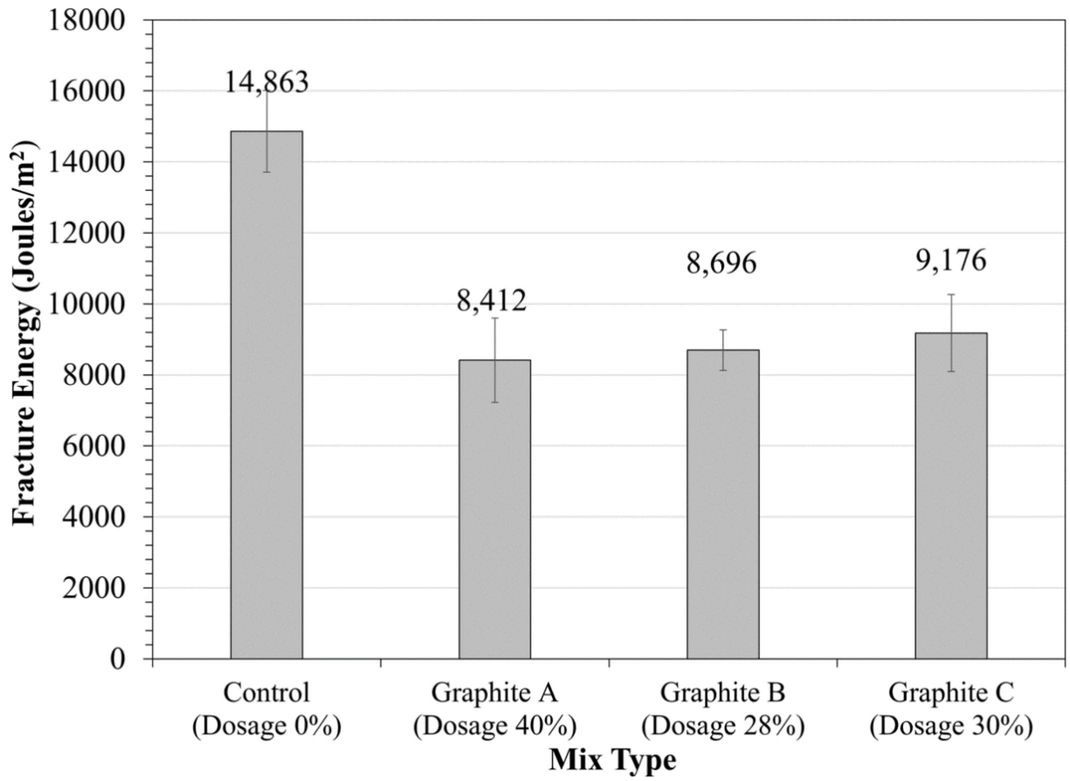


Table 17

The P Values Indicating the Statistical Difference Between the Fracture Energy Obtained from the IDEAL-CT Test for Each Pair of Mixture Sets.

Mix ID	**Graphite A**	**Graphite B**	**Graphite C**
Graphite B	1.000	-	-
Graphite C	1.000	1.000	-
Control	0.000	0.000	0.000

Figure 33 shows that, on average, the CT-Index for the control mix was 78% higher than that obtained for all three graphite-modified mixtures designed in this study. This observation provides more evidence that modifying asphalt mixtures using graphite deteriorates the cracking performance of asphalt mixture. When comparing the CT-Index values obtained for the graphite modified asphalt mixtures, it can be seen that Graphite A and Graphite C mix had, on average, higher CT-Index values than that produced using Graphite B. However, the statistical analysis results presented in Table 18 show that all three asphalt mixtures have statistically similar CT-Index values that are significantly different from those obtained for the unmodified control mix. This observation again supports the findings from the SCB test that the mixtures prepared with Graphite A, B, and C had the same level of cracking resistance and were more susceptible to cracking compared to the unmodified control mixtures.

Figure 33

Average CT-Index of the Indirect Tension Asphalt Cracking (IDEAL-CT)

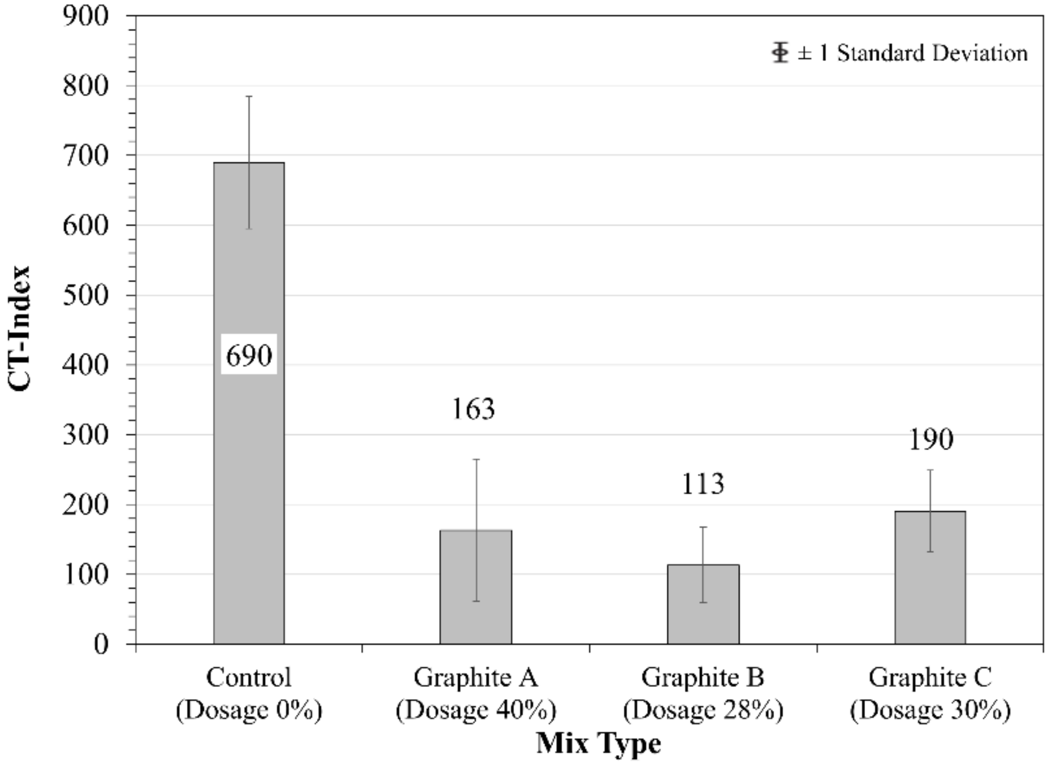


Table 18

The P Values Indicating the Statistical Difference between the CT Index of the IDEAL-CT Test for Each Pair of Mixtures.

Mix ID	**Graphite A**	**Graphite B**	**Graphite C**
Graphite B	0.71	**-**	**-**
Graphite C	0.81	0.69	**-**
Control	0.000	0.000	0.000

4.4 Heating Capability of Electrically Conductive Asphalt Mixtures

The compaction of one inch of electrically conductive asphalt mixture (30% Graphite C and 1% carbon fibers by volume of binder), covered by two inches on the unmodified control mix, provided a proof of concept of the heating ability of that the electrically heated asphalt pavement. The Asphalt Vibratory Compactor (AVC) was used to compact the mix in 15 x 2 inches beam rectangular specimens to a of 7±1% target air voids, simulating with that the field compaction of asphalt mixtures using the vibratory compaction rollers. The simulation of the electrically heated pavement experiment provided a proof of concept that the pavement surface could be heated when a layer of conductive asphalt mixture is placed and connected to a power source. The time, voltage, electric current, surface temperature records were used to find the electrical resistance, power requirement, and the surface heating rate, and available in Tables A20, A21, A22, and A23 in the Appendix.

Table 19 below presents the average values for the four beams examined. At a voltage difference of 24 volts and for a 1-inch conductive layer covered with 2 inches of non-conductive asphalt mixture, the surface of the beam could be heated at an average (5.4 C/ hour). Although this heating rate is quite low, it is a case-specific value that changes with a change of the voltage and the thickness of both the conductive and the insulating layer. The heating rate can be increased by using a higher voltage difference that will, in turn, allow for a higher electric current to pass, generating with that more heat, thus heating the surface of the slab at a faster rate.

Table 19

Average Heating Rate and Power Requirement of Beams Simulating the Electrically Heated Pavement

Beam ID	Average /STD	Voltage (V)	Current (A)	Resistance (Ω)	Power (W)	Heating Rate (C/hour)
1	Average	24.03	0.668	36.1	16.1	5.2
	StDev	0.003	0.038	1.889	0.907	
2	Average	24.03	0.799	30.1	19.2	4.1
	StDev	0.003	0.017	0.651	0.417	
3	Average	24.03	0.956	25.2	23.0	6.7
	StDev	0.000	0.012	0.305	0.285	
4	Average	24.03	0.752	32.0	18.1	5.5
	StDev	0.000	0.015	0.645	0.365	
Overall	Average	**24.03**	**0.794**	**30.85**	**19.1**	**5.4**
	StDev	**0.00**	**0.104**	**3.914**	**2.505**	

Chapter 5

Summary, Conclusions, Recommendations & Future Work

5.1 Summary of Findings

The goal of the research was to develop Electrically Conductive Asphalt (ECA) mixtures with optimized electrical and mechanical properties for use in electrically heated asphalt pavements for deicing and anti-icing applications. The ECA mixtures were designed using three graphite grades with different particle sizes at varying dosages. Additionally, one virgin aggregate type, two asphalt binders (polymer-modified PG 76-22 and neat PG 64-22), and one carbon fiber were used to produce ECA mixtures of various properties. Mixtures were designed using the three graphite grades A, B, and C, with Graphite A having the smallest particle size and Graphite C the largest particle size. The mixtures were designed at varying dosages, and the optimum dosage, leading to an asphalt mixture with the lowest electrical resistivity with minimal effect on the mix's skeletal structure, was determined for each graphite grade. Several factors affecting the electrical conductivity of ECA mixtures were investigated, including the graphite particle size and dosage, the air voids level, the addition of carbon fiber, and binder PG used. The rutting, cracking, and durability of graphite modified mixtures was assessed using the Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), Semi-Circular Bend (SCB), Indirect Tension Cracking Test (IDEAL-CT), and Cantabro loss tests. Finally, the mixture with the most improved electrical conductivity was used to construct beams simulating the electrically heated asphalt pavement system.

The summary of the findings from this study were:

5.1.1 Graphite Dosage & Electrical Conductivity

The three graphite grades A, B, and C improved the electrical conductivity of asphalt mixtures when introduced at dosages of 10% to 15% or higher by volume of binder. As the graphite dosage increased, the electrical resistivity of asphalt mixtures decreased, but the reduction rate slowed until the optimum graphite dosage was reached. For instance, Introducing Graphite A into an asphalt mixture in dosages of 19%, 23%, and 28% reduced the electrical resistivity to 857.4 Ω-m. 79.2 Ω-m and 18.0 Ω-m, respectively.

5.1.2 Graphite Particle Size & Electrical Conductivity

At a constant graphite dosage, Graphite C (largest size) reduced the electrical resistivity the most, followed by Graphite B and Graphite A (smallest size). For instance, at a 25% graphite dosage, Graphite C had a resistivity of about 2 Ω-m. At the exact dosage (25%), Graphite B reduced the electrical resistivity to around 8 Ω-m, while Graphite A had an electrical resistivity of about 40 Ω-m.

5.1.3 Graphite Dosage and Particle Size & Volumetric Properties

As the dosage and graphite particle sizes increased, the mixtures required higher binder contents to meet the Superpave volumetric design requirements. For instance, the mixture prepared using 30% of Graphite C (largest particle size) needed the highest binder content among all mixtures of 8.1%, a 0.5 % increase from the unmodified control mix.

5.1.4 Air Voids & Electrical Resistivity

The reduction of air voids from 7% to 3.5% decreased the electrical resistivity of asphalt mixtures prepared with Graphite A and C in percentages of 32% and 70%, however mixtures prepared with Graphite B maintained the same electrical resistivity level. Mixtures A, B and C had an initial electrical resistivity of 3.49 Ω-m, 4.57 Ω-m and 3.49 Ω-m , respectively, at 7% air void s level.

5.1.5 Carbon Fibers & Electrical Resistivity

Adding carbon fibers into graphite modified mixtures in a dosage of 1% by volume of binder reduced the electrical resistivity significantly by approximately 65 % for the three ECA mixtures. The ECA mixtures prepared with the three graphite grades at their optimal dosages had a similar electrical resistivity value within 0.4 Ω-m when carbon fibers were introduced. The control mix was not conductive when only carbon fibers without graphite were added to the mixture.

5.1.6 Binder Grade & Electrical Resistivity

Asphalt mixtures prepared with Graphite A and Graphite C using the neat PG 64-22 asphalt binder had lower electrical resistivity (by around 0.69 to 1.2 Ω-m) than those prepared with the modified PG 76-22 asphalt binder. Mixtures prepared with Graphite B had a higher electrical resistivity in the case of PG 64-22 than PG 76-22 (by around 0.92 Ω-m). The statistical analysis showed that the effect of binder grade on the electrical resistivity of graphite-modified mixtures at the optimum graphite dosage is statistically insignificant at a significance level of 0.05.

5.1.7 Graphite & Rutting Resistance

The APA rutting depth measured for the unmodified control mix was around 42% greater than that obtained for all graphite modified asphalt mixes. The APA rut depth measurements for three graphite modified mixes (A, B, and C) were statistically similar. The HWTD test results showed that the unmodified control mix had an average HWTD rutting depth that is, on average, two times higher than the rutting depth of the graphite-modified mixtures. The Stripping Inflection Point (SIP) of the control mix was observed at 10,784 loading passes while there was no SIP in the HWTD data for any of the graphite-modified asphalt mixtures.

5.1.8 Graphite & Durability

The control mix had a Cantabro loss that is around 80% lower than all ECA mixtures modified with graphite.

5.1.9 Graphite & Cracking Resistance

The SCB test results showed that the Fracture Energy of the graphite modified mixture is half of that obtained for the unmodified control mix. The Flexibility Index of the graphite modified mixtures was 69% lower than that of the control mix. The IDEAL-CT test results show that the Fracture Energy of the unmodified control mix is about 40% higher than the graphite modified mixtures, with a CT-Index that is 78% higher for the control mix than that obtained for all three graphite-modified mixtures.

5.1.10 ECA Mixtures & Heating Capability

The surface of beams constructed using a one-inch layer of ECA mixture covered with 2 inches insulating layer of the control mix was heated with an average of 5.4 C/ hour when the conductive mixture was connected to a power source of 24 volts.

5.2 Conclusions

5.2.1 Dosage & Electrical Conductivity

Graphite improves the electrical conductivity of asphalt mixtures when introduced at dosages of 10% to 15% or higher by volume of binder. As the graphite dosage increases, the electrical resistivity decreases, but the rate of reduction slows until the optimum graphite dosage was reached. The optimal graphite dosage ranges from 28% to 40% by volume of binder, depending on the size distribution of the graphite particles.

5.2.2 Graphite Particle Size Distribution & Electrical Conductivity

Graphite grades with larger particle sizes and better particle size distribution better improve the conductivity of asphalt mixtures than asphalt mixtures prepared at the exact dosage of a poorly distributed and smaller particle size graphite. Smaller and poorly distributed particle size graphite is required in higher dosages to achieve the same electrical resistivity level as larger graphite and better-distributed graphite.

5.2.3 Graphite Dosage, Particle Size & Volumetric Properties

A higher optimum binder content is required to design ECA mixtures at higher graphite dosages and using larger graphite particle sizes.

5.2.4 Air Voids & Electrical Resistivity

Graphite-modified mixtures compacted to lower air void levels tend to have a lower electrical resistivity than the same mixtures prepared at higher air voids. The effect of air voids level on the electrical resistivity of asphalt mixtures is significant for asphalt mixture with an electrical resistance of around 3.5 Ω-m or lower.

5.2.5 Carbon Fibers & Electrical Resistivity

The addition of 1% carbon fiber by volume of binder to ECA mixture prepared using different graphite grades at their optimal dosages reduces the electrical resistivity significantly to approximately the same level, regardless of the graphite dosage and particle size in the ECA mixtures. This is because of the bridging effect of carbon fiber that helps the conductive network initially created by the graphite to expand and grow in all directions.

5.2.6 Binder Grade & Electrical Resistivity

It does not appear that the binder grade used in graphite-modified mixtures significantly affects their electrical resistivity.

5.2.7 Graphite & Performance

Introducing graphite into asphalt mixtures improves their ability to resist rutting and withstand moisture-induced damage. However, it deteriorates their resistance to breakdown and cracking.

5.2.8 ECA Mixtures & Heating Capability

The heating capability experiment provided a proof of concept that the pavement surface could be heated when the conductive asphalt mixture layer is connected to a power source.

5.3 Recommendations

5.3.1 Dosage & Electrical Conductivity

It is imperative to optimize the graphite dosage when designing ECA mixtures because introducing a graphite grade beyond its optimal dosage increases the cost of these mixtures with no noticeable improvement in conductivity.

5***.3.2 Graphite Particle Size & Electrical Conductivity***

Using graphite grades with larger particle sizes as a conductive additive when designing electrically conductive asphalt mixture is recommended for better enhancement of the electrical conductivity of asphalt mixtures.

5.3.3 Graphite Dosage , Particle Size & Volumetric Properties

It is recommended to perform a cost-analysis considering the trade-off between the extra cost associated with higher graphite dosage when smaller particle size graphite is used, and extra cost associated with higher binder content requirement when larger particle size graphite is used to achieve a certain electrical resistivity level with the lowest possible cost.

5.3.4 Air Voids & Electrical Resistivity

It is recommended to compact ECA mixtures in the field to higher densities, and in effect, lower air voids to achieve lower electrical resistivity of these mixtures. Furthermore, it is recommended to employ stricter quality control/quality assurance protocols for compacting ECA mixtures in the field.

5.3.5 Carbon Fibers & Electrical Resistivity

When preparing an ECA mixture with a combination of graphite and carbon fibers, it is advised to optimize both the graphite and carbon fiber dosages at the same time to avoid the extra cost associated with higher graphite dosages and particle sizes.

5.3.6 ***Binder Grade & Electrical Resistivity***

It is recommended to conduct more research on the effect of binder modifiers on the electrical conductivity of ECA mixtures. It is also critical to consider the type of modifiers used when designing an ECA mixture.

5.3.7 Graphite &Performance

It is recommended to evaluate the durability and cracking resistance of graphite modified mixes during the design stage to ensure satisfactory performance in the field. The evaluation of ECA mixtures' low-temperature and moisture susceptibility properties is also recommended as the areas of application of electrically heated pavements would be cold regions.

5.3.8 ECA Mixtures & Heating Capability

It is recommended to use a higher voltage difference (than 24 Volts) to allow for a higher electric current to pass through the conductive layer, generating more heat, thus heating the surface of the slab at a faster rate.

5.3.9 ECA Mixtures & Electrically Heated Asphalt Pavements

It is recommended to conduct more experiments on slabs or beams simulating the actual structure of an electrically heated asphalt pavement using different voltages and conductive layer thicknesses in order to expand the knowledge regarding the power requirement and the heating capability of such systems.

5.4 Future Work

As the second phase of this work, one of the ECA mixtures designed in this study was utilized in a full-scale construction of an electrically heated asphalt pavement at the Center for Research and Education in Advanced Transportation Engineering Systems (CREATEs). The construction work included a conventional asphalt pavement section with no heating element (Control Section) and an electrically heated pavement section with a 1-inch thick electrically conductive asphalt mixture interlayer covered with 2 inches of the standard HPTO mix. The selected mix was modified with 30% Graphite C and 1% carbon fiber (all by volume of binder) at an optimum binder content of 8.1%. The electrodes were embedded in the conductive layer at a different spacing to determine the optimum spacing. The construction and testing of the accelerated pavement testing facility will bring insight into the practicality, heating capability, and power requirements, feasibility, and reliability of electrically heated pavement systems as an alternative deicing technique.

It is recommended to perform a Life-Cycle-Cost analysis to decide if the increased capital cost associated with an electrically heated pavement system can substitute for reducing the maintenance costs and the operational costs required for the labor work and heavy truck movement associated with other deicing techniques.

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Appendix

Table A1

Aggregate Gradation and Binder Content Control Points for HMA Mix

Sieve Size	Control Points	
	Min.	**Max.**
3/8”	100	-
No. 4	68.9	76.9
No. 8	41.0	49.0
No. 16	26.2	32.2
No. 30	17.0	23.0
No.50	11.7	15.7
No. 100	7.7	11.7
No. 200	6.0	8.0
Binder Content	7.3	8.1

Table A2

Optimum Aggregate Gradation for HPTO Mix

Sieve Size	Percentage Passing
3/8”	100.00%
No. 4	69.73%
No. 8	44.57%
No. 16	28.16%
No. 30	18.03%
No.50	12.23%
No. 100	7.68%
No.200	4.80%

Table A3

Properties of Graphite Used for Preliminary Trials (Showed No Electrical Conductivity Due to Small Particle Size)

Mesh Size/Property	Flake-Graphite	Amorphous
%+100 Mesh (150	1.75	55.55
%+200 Mesh (75	4.25	8.8
%+325 Mesh (44	8.95	1.6
%-325 Mesh (<44	85.05	4.03
%Carbon	83.45	78.88

Table A4

The Volumetric Properties of Designed ECA Mixtures with Varying Dosages and Graphite Grades

Mix ID (Graphite Grade- Dosage)	**Binder Content**	**Average G_{mm}**	**Average G_{mb}**	**Avg. Air Voids**	**Air Voids Stdev**	**Voids in Mineral Aggregate (VMA %)**	**Percent Voids Filled with Asphalt (VFA %)**	**Dust/Asphalt Ratio**
Control	7.6%	2.457	2.369	3.58	0.40	19.70	81.84	0.63
Graphite A 14%	7.6%	2.444	2.363	3.31	0.05	19.91	83.39	0.63
Graphite A 19%	7.6%	2.438	2.355	3.41	0.20	20.18	83.10	0.63
Graphite A 23%	7.6%	2.442	2.357	3.47	0.06	20.14	82.75	0.63
Graphite A 28%	7.6%	2.468	2.382	3.50	0.17	19.29	81.86	0.63
Graphite A 40%	7.9%	2.420	2.333	3.56	0.08	21.21	83.21	0.61
Graphite B 14%	7.6%	2.451	2.361	3.68	0.31	19.98	81.60	0.63
Graphite B 18%	7.7%	2.435	2.355	3.30	0.10	20.28	83.71	0.62
Graphite B 23%	7.7%	2.450	2.372	3.19	0.14	19.70	83.81	0.62
Graphite B 28%	7.7%	2.469	2.379	3.65	0.34	19.45	81.25	0.62
Graphite C 14%	7.6%	2.447	2.361	3.51	0.14	19.98	82.41	0.63
Graphite C 19%	7.7%	2.474	2.380	3.80	0.07	19.41	80.40	0.62
Graphite C 23%	8.0%	2.429	2.351	3.20	0.10	20.64	84.52	0.60
Graphite C 28%	8.0%	2.424	2.329	3.93	0.02	21.41	81.62	0.60
Graphite C 30%	8.1%	2.423	2.339	3.72	0.36	21.14	82.41	0.60

Table A5

The Average Resistivity Values Measured for Each Graphite at Varying Dosages

Dosage %	Electrical Resistivity (Ω.m)	Standard Deviation
Graphite A (Small Size)		
0	1.54E+37	0.000
9	1.54E+37	0.000
12	1.54E+37	0.000
14	1.54E+37	0.000
19	857.4	47.719
23	79.2	4.219
28	18.0	1.532
32	8.4	0.483
40	2.4	0.377
Graphite B (Medium Size)		
0	1.54E+37	0.000
9	1.54E+37	0.000
12	1.54E+37	0.000
14	5275.8	1414.829
18	73.4	12.222
23	15.0	2.040
28	4.5	0.762
Graphite C (Largest Size)		
0	1.54E+37	0.000
9	1.54E+37	0.000
14	357.3	74.950
19	8.0	1.350
23	2.8	1.042
28	1.4	0.037
30	1.1	0.070
33	1.0	0.035

Table A6

Asphalt Pavement Analyzer (APA) Final Rutting Depths for the Control Mix

Summary of APA Results (After 8000 Cycles)					
Sample ID	**Slot 1**	**Slot 2**	**Slot 3**	**Slot 4**	**Avg. Rut Depth (mm.)**
1	3.05	2.95	2.78	1.74	2.63
2	3.16	3.06	2.86	1.45	2.63
3	1.88	2.45	2.74	1.92	2.25
Overall Rut Depth Avg. (mm)	**2.50**				

Table A7

Asphalt Pavement Analyzer (APA) Final Rutting Depths for 40% - Graphite A – Mix

Summary of APA Results (After 8000 Cycles)					
Sample ID	**Slot 1**	**Slot 2**	**Slot 3**	**Slot 4**	**Avg. Rut Depth (mm.)**
1	1.83	2.04	1.71	1.00	1.65
2	1.78	1.82	1.87	0.71	1.54
3	1.50	1.73	1.64	0.69	1.39
Overall Rut Depth Avg. (mm)	**1.53**				

Table A8

Asphalt Pavement Analyzer (APA) Final Rutting Depths for 28% - Graphite B – Mix

Summary of APA Results (After 8000 Cycles)					
Sample ID	**Slot 1**	**Slot 2**	**Slot 3**	**Slot 4**	**Avg. Rut Depth (mm.)**
1	1.01	0.91	1.03	1.03	0.99
2	1.23	1.14	1.25	1.12	1.18
3	2.08	1.64	1.30	1.14	1.54
Overall Rut Depth Avg. (mm)	**1.24**				

Table A9

Asphalt Pavement Analyzer (APA) Final Rutting Depths for 30% - Graphite C – Mix

Summary of APA Results (After 8000 Cycles)					
Sample ID	**Slot 1**	**Slot 2**	**Slot 3**	**Slot 4**	**Avg. Rut Depth (mm.)**
1	1.54	1.78	1.61	0.61	1.38
2	2.25	2.05	1.66	2.11	2.02
3	1.55	1.57	1.38	1.29	1.45
Overall Rut Depth Avg. (mm)	**1.62**				

Table A10

Asphalt Pavement Analyzer (APA) Average Rutting Depths

Mix ID	Optimum Graphite Dosage	APA Average Rut Depth (mm)	StDev
Control	0%	2.5	0.222
Graphite A	40%	1.5	0.129
Graphite B	28%	1.2	0.277
Graphite C	30%	1.6	0.349

Table A11

Average Hamburg Wheel Tracking Device (HWTD) Rut Depths Corresponding to Each Cycle

Cycle (x1000)	Rutting Depth (mm)			
	Control	Graphite A	Graphite B	Graphite C
0.00	0.00	0.00	0.00	0.00
0.50	1.56	1.44	0.88	1.37
1.00	1.97	1.81	1.08	1.64
1.50	2.22	2.02	1.19	1.80
2.00	2.40	2.21	1.25	1.93
2.50	2.53	2.30	1.33	2.05
3.00	2.68	2.40	1.41	2.12
3.50	2.76	2.52	1.45	2.21
4.00	2.89	2.59	1.49	2.26
4.50	2.98	2.61	1.53	2.36
5.00	3.05	2.70	1.56	2.40
5.50	3.15	2.77	1.59	2.52
6.00	3.23	2.79	1.61	2.54
6.50	3.31	2.80	1.62	2.63
7.00	3.40	2.87	1.66	2.72
7.50	3.47	2.94	1.68	2.75
8.00	3.56	2.97	1.70	2.82
8.50	3.60	2.97	1.72	2.85
9.00	3.69	3.04	1.74	2.87

Cycle (x1000)	**Rutting Depth (mm)**			
	Control	**Graphite A**	**Graphite B**	**Graphite C**
9.50	3.81	3.01	1.75	2.97
10.00	3.87	3.08	1.78	3.02
10.50	4.12	3.23	1.74	3.00
11.00	4.23	3.23	1.78	3.12
11.50	4.36	3.23	1.77	3.15
12.00	4.49	3.33	1.80	3.16
12.50	4.62	3.36	1.83	3.25
13.00	4.75	3.33	1.82	3.30
13.50	4.88	3.39	1.87	3.38
14.00	5.05	3.43	1.89	3.40
14.50	5.20	3.42	1.88	3.41
15.00	5.32	3.48	1.92	3.49
15.50	5.48	3.51	1.94	3.56
16.00	5.63	3.58	1.97	3.61
16.50	5.81	3.54	1.96	3.59
17.00	5.96	3.61	1.99	3.68
17.50	6.12	3.62	2.00	3.71
18.00	6.29	3.66	2.02	3.74
18.50	6.48	3.69	2.06	3.81
19.00	6.64	3.71	2.06	3.84
19.5	6.84	3.77	2.09	3.94

Table A12

Average Hamburg Wheel Tracking Device (HWTD) Rut Depths and the Stripping Inflection Points (SIP)

Sample ID	Graphite	Graphite Dosage	Fiber Dosage	Binder Grade	Rut Depth (mm)	SIP
1	Control	0%	0	PG 76-22	5.59	12.537
2	Control	0%	0	PG 76-22	7.52	10.99
3	Control	0%	0	PG 76-22	6.79	8.824
1	A	28%	0	PG 76-22	3.97	No SIP Reached
2	A	28%	0	PG 76-22	3.79	No SIP Reached
3	A	28%	0	PG 76-22	3.46	No SIP Reached
1	B	40%	0	PG 76-22	2.066	No SIP Reached
2	B	40%	0	PG 76-22	1.946	No SIP Reached
3	B	40%	0	PG 76-22	2.324	No SIP Reached
1	C	30%	0	PG 76-22	4.48	No SIP Reached
2	C	30%	0	PG 76-22	3.68	No SIP Reached
3	C	30%	0	PG 76-22	3.56	No SIP Reached

Table A13

Average Hamburg Wheel Tracking Device (HWTD) Rut Depths

Mix ID	Optimum Graphite Dosage	Hamburg Average Rut Depths	StDev
Control	0%	6.6	0.974
Graphite A	40%	3.7	0.258
Graphite B	28%	2.1	0.194
Graphite C	30%	3.9	0.499

Table A14

Cantabro Loss Test Results

Mix Type	Optimum Graphite Dosage	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Cantabro Loss	Average	Std. Dev
Control	0%	4701.1	4633.6	67.5	1.44	1.62	0.258
		4699.3	4614.7	84.6	1.80		
Graphite A	40%	4709.8	4296.2	413.6	8.78	9.57	1.598
		4709.6	4221.8	487.8	10.36		
		4705.7	4142.1	563.6	11.98		
Graphite B	28%	4707.4	4396.4	311	6.61	7.31	0.996
		4701	4324.2	376.8	8.02		
Graphite C	30%	4701.7	4214.6	487.1	10.36	8.99	1.934
		4703.9	4345.2	358.7	7.63		

Table A15

Average Cantabro Loss

Mix ID	Optimum Graphite Dosage	Avg. Cantabro Loss %	StDev
Control	0%	1.6	0.258
Graphite A	40%	9.6	1.598
Graphite B	28%	7.3	0.996
Graphite C	30%	9.0	1.934

Table A16

Semi-Circular Bend (SCB) Test Results

Sample ID	Graphite Grade	Graphite Dosage	Fiber Dosage	Binder Grade	Fracture Energy	Flexibility Index
1	Control	0%	0	PG 76-22	2467	13.4
2	Control	0%	0	PG 76-22	3010	18.4
3	Control	0%	0	PG 76-22	3039	18.6
4	Control	0%	0	PG76-22	3618	16.6
1	A	40%	0	PG 76-22	1990	9.9
2	A	40%	0	PG 76-22	1792	9.0
3	A	40%	0	PG 76-22	1334	4.7
4	A	40%	0	PG76-22	1370	4.7
1	B	28%	0	PG 76-22	1227	2.6
2	B	28%	0	PG 76-22	1192	2.0
3	B	28%	0	PG 76-22	1269	2.6
4	B	28%	0	PG76-22	1316	3.0
5	B	28%	0	PG76-23	1445	4.0
1	C	30%	0	PG 76-22	1434	4.7
2	C	30%	0	PG 76-22	1523	7.2
3	C	30%	0	PG 76-22	2067	6.4
4	C	30%	0	PG76-22	1581	6.0

Table A17

Average Fracture Energy of the Semi-Circular Bend (SCB) Test

Mix ID	Optimum Graphite Dosage	Fracture Energy	StDev
Control	0%	3034	469.760
Graphite A	40%	1621	322.173
Graphite B	28%	1290	98.406
Graphite C	30%	1651	283.568

Table A18
Average Flexibility Index of the Semi-Circular Bend (SCB) Test

Mix ID	Optimum Graphite Dosage	Flexibility Index	StDev
Control	0%	17	2.392
Graphite A	40%	7	2.760
Graphite B	28%	3	0.728
Graphite C	30%	6	1.067

Table A19

Indirect Tension Asphalt Cracking (IDEAL-CT) Test Results

Optimum Graphite Dosage	Avg. ITS	StDev	Avg. Peak Load	StDev	Avg. Frac. Energy	StDev	Avg. IDEAL-CT	StDev
0%	0.9	0.031	13.2	0.474	14863	1149.496	690	94.493
40%	0.8	0.091	12.1	0.868	8412	1187.877	163	102.086
28%	1.0	0.102	14.3	10.493	8696	571.171	113	54.170
30%	0.8	0.055	11.9	0.817	9176	1082.874	190	58.648

Table A20

Heating Rate and Power Requirement of Beam 1 Simulating the Electrically Heated Pavement

Time	**Voltage (V)**	**Current (A)**	**Resistance (Ω)**	**Power (W)**	**Temperature(C)**
4:15	24.02	0.766	31.4	18.4	23.0
4:20	24.03	0.712	33.8	17.1	23.3
4:25	24.03	0.682	35.2	16.4	23.4
4:30	24.03	0.668	36.0	16.1	23.6
4:35	24.03	0.66	36.4	15.9	24.1
4:40	24.03	0.656	36.6	15.8	24.8
4:45	24.03	0.65	37.0	15.6	25.2
4:50	24.03	0.64	37.5	15.4	25.4
4:55	24.03	0.64	37.5	15.4	26.2
5:00	24.03	0.641	37.5	15.4	26.7
5:05	24.03	0.634	37.9	15.2	27.3
Average	**24.03**	**0.668**	**36.1**	**16.1**	

Table A21

Heating Rate and Power Requirement of Beam 2 Simulating the Electrically Heated Pavement

Time	Voltage (V)	Current(A)	Resistance (Ω)	Power (W)	Temperature(C)
3:10	24.02	0.836	28.7	20.1	23.9
3:15	24.03	0.824	29.2	19.8	24.1
3:20	24.03	0.812	29.6	19.5	24.4
3:25	24.03	0.8	30.0	19.2	24.2
3:30	24.03	0.808	29.7	19.4	24.6
3:35	24.03	0.804	29.9	19.3	24.9
3:40	24.03	0.8	30.0	19.2	25.7
3:45	24.03	0.791	30.4	19.0	25.9
3:50	24.03	0.788	30.5	18.9	25.9
3:55	24.03	0.784	30.7	18.8	27.1
4:00	24.03	0.785	30.6	18.9	27.4
4:05	24.03	0.778	30.9	18.7	27.8
4:10	24.03	0.774	31.0	18.6	28.0
Average	**24.03**	**0.799**	**30.1**	**19.2**	

Table A22

Heating Rate and Power Requirement of Beam 3 Simulating the Electrically Heated Pavement

Time	Voltage (V)	Current (A)	Resistance (Ω)	Power (W)	Temperature (C)
12:50	24.03	0.99	24.3	23.8	22.6
12:55	24.03	0.971	24.7	23.3	23.1
13:00	24.03	0.959	25.1	23.0	23.3
13:05	24.03	0.952	25.2	22.9	23.7
13:10	24.03	0.948	25.3	22.8	24.1
13:15	24.03	0.947	25.4	22.8	24.9
13:20	24.03	0.954	25.2	22.9	25.8
13:25	24.03	0.952	25.2	22.9	26.4
13:30	24.03	0.949	25.3	22.8	27.2
13:35	24.03	0.948	25.3	22.8	27.8
13:40	24.03	0.947	25.4	22.8	28.0
13:45	24.03	0.948	25.3	22.8	28.9
13:50	24.03	0.957	25.1	23.0	29.3
Average	**24.03**	**0.956**	**25.2**	**23.0**	

Table A23

Heating Rate and Power Requirement of Beam 4 Simulating the Electrically Heated Pavement

Time	Voltage (V)	Current (A)	Resistance (Ω)	Power (W)	Temperature (C)
2:00	24.03	0.784	30.7	18.8	23.1
2:05	24.03	0.777	30.9	18.7	23.4
2:10	24.03	0.768	31.3	18.5	24.2
2:15	24.03	0.76	31.6	18.3	24.4
2:20	24.03	0.758	31.7	18.2	24.7
2:25	24.03	0.754	31.9	18.1	24.9
2:30	24.03	0.744	32.3	17.9	25.9
2:35	24.03	0.744	32.3	17.9	26.4
2:40	24.03	0.74	32.5	17.8	26.6
2:45	24.03	0.739	32.5	17.8	27.0
2:50	24.03	0.738	32.6	17.7	27.7
2:55	24.03	0.739	32.5	17.8	28.1
3:00	24.03	0.735	32.7	17.7	28.6
Average	**24.03**	**0.752**	**32.0**	**18.1**	