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EXPERIMENTAL INVESTIGATION OF MECHANICAL AND ELECTROMAGNETIC PERFORMANCE OF ASPHALT CONCRETE CONTAINING DIFFERENT RATIOS OF GRAPHITE POWDER AS A FILLER TO BE POTENTIALLY USED AS PART OF WIRELESS ELECTRIC ROADS

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Abstract. This study experimentally investigates the usability of asphalt concrete pavement containing five different ratios of graphite powder (0%, 1.25%, 2.5%, 3.75% and 5% by weight of the aggregate blend or 0%, 25%, 50%, 75% and 100% of the filler content) as a filler to be potentially used as part of wireless electric roads (ER). As part of the study, first, optimum asphalt binder

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content for the asphalt mixes without graphite powder was determined as 5%. Then, using the determined optimum asphalt binder content, asphalt mixes containing five different ratios of graphite powder as a filler were prepared and their mechanical and volumetric properties based on Marshall mix design methodology were evaluated. As graphite powder ratios in the asphalt mixes increased, their Marshall stability, flow, voids filled with asphalt and unit weight test results mostly decreased but their air content and voids in mineral aggregate test results increased. Possible reasons for this could be: (1) lower bulk specific gravity of graphite powder, (2) higher asphalt absorbance, (3) having greater surface area compared to that of limestone filler, and (4) weak bonds between sheet-like graphite layers. Furthermore, another batch of asphalt mixes containing five different ratios of graphite powder were prepared and tested in the frequency range of 3–18 GHz for their electromagnetic permittivity properties. It was observed in this study that, except for the specimens with 100% graphite powder ratios, transmission magnitudes of all specimens were above 50% up to 8 GHz, indicating that they had comparably high transmission magnitudes so as comparably low tangent loss values. In the frequency range of 3–13 GHz, transmission magnitudes of the specimens with 25% and 50% graphite powder ratios were consistently higher than that having no graphite powder, the ones with 25% powder ratios had the highest transmission magnitudes in most of the cases in this frequency range. Considering the mechanical, volumetric and electromagnetic property test results of the asphalt mixes with five different ratios of graphite powder, it can be concluded that the use of 25% graphite powder ratio (corresponding to 1.25% of the aggregate blend used in the mixes), has a comparably lower negative effect on mechanical and volumetric properties of asphalt mixes and has a positive effect on electromagnetic permittivity properties of asphalt mixes. Asphalt mixes produced with this graphite powder ratio can be considered to be used as part of wireless ER.

Keywords: asphalt concrete, electromagnetic performance of asphalt concrete, graphite powder, wireless electric roads.

Introduction

Due to the increase in population in the world, the transportation network is constantly expanding, and, as a result, environmental pollution is increasing. For this reason, environmentally friendly technologies that meet the needs of people are being researched, developed and applied. Recently, many countries have focused on reducing the use of gasoline and diesel vehicles in urban areas and expanding the use of electric vehicles (TRL, 2015). Although electric vehicles are an environmentally friendly solution, they have some problems such as high charging time. However, studies on electric road technologies have been carried out to overcome this problem and some electric road technologies have been developed. Electric roads are a transportation technology that allows electric vehicles to move without requiring a charging or fuel station and to be able to charge while moving. Thanks to this technology, vehicles will be able to travel long distances without the need for large batteries, and energy efficiency will be increased by reducing the dependency on fuel and eliminating factors that adversely affect the environment such as greenhouse gas emissions, air pollution and noise caused by internal combustion engines (Gustavsson et al., 2021). Electric road (ER) systems consist of five components: electricity supply, road, power transmission, road operation and vehicle. While electricity supply deals with the transmission, distribution and management of electricity, power transmission deals with vehicle power transmission and control. The structure, barriers and auxiliary components of the roads should be designed in accordance with the electric road systems. Vehicles must also be either equipped to convert electricity from the powertrain subsystem as electrical input to the vehicle battery or directly use electricity while driving (ERS, 2021). ER technologies could be divided into three groups: conductive rail, conductive overhead and inductive (wireless) electric roads (Kaya, 2021). In the conductive rail electric road technology, the rails are mounted on the superstructure and power is transferred between the vehicle and the rail by means of a pick-up located underneath the vehicle. In conductive overhead road technology, power is distributed via overhead catenary systems installed at the roadside. Wireless ER technology is based on the inductive power transfer technology whose power is transferred from a coil located beneath the road surface to another coil (receiver) mounted underneath a moving vehicle or a vehicle in park. Wireless ER technology has several advantages compared to other two ER technologies such as: (1) convenience as it does not need a physical connection between the coil beneath the road surface and the vehicle, (2) low maintenance, (3) environment friendly, and (4) since there is no cable connection, there are no obsolete cables, plugs, sockets and cables hanging from vehicles, and the risk arising from these elements is naturally eliminated. Furthermore, it provides a platform for all types of vehicles such as buses, trucks, cars, and autonomous vehicles (Ezer and Tongur, 2020). However, it should be stated that wireless ER technology has a lower power rating compared to two other conductive technologies (Bateman et al., 2018). Although wireless power transmission technology has been known for a long time, various experimental projects have been carried out and some trial road sections have been constructed to demonstrate the applicability of this technology in the field of electric roads (Suh and Kim, 2013; Amditis et al., 2014; Olsson, 2013). However, as of 2022, there are no commercially available projects using this technology on a large scale. There may be two reasons for this: low technology readiness and high costs (Ezer and Tongur, 2020).

As mentioned above, inductive (wireless) electric road technology is based on the principle of wirelessly transferring power between two different coils. One of these coils is placed under the road surface (transmitter) and one (receiver) is placed under the vehicle. The efficiency of this power transfer between the coils is related to the transmission of electromagnetic waves by the layers (asphalt layer and air layer) between the coils. The increase in the transmission of electromagnetic waves (electromagnetic permittivity) of the asphalt layer to be placed between the coils will reduce the loss in power transmission between the coils and increase the energy efficiency. Asphalt concrete contains coarse aggregate, fine aggregate, asphalt binder and mineral fillers. If a material can store energy when an external electric field is applied, it is classified as a dielectric material (Düşmez, 2015). This energy storage capacity of materials is measured by the dielectric constant value. Materials with high dielectric constant values have a high energy storage capacity and, therefore, lower electromagnetic wave permittivity. Dielectric constants of asphalt mixtures are generally between 4 and 10, and it has been observed that it is a material with low electromagnetic permittivity (Porubiaková and Komačka, 2015).

Studies investigating the electromagnetic properties of asphalt concrete can be divided into two groups: The first one refers to the studies conducted regarding the Ground Penetrating Radar (GPR) technology, a non-destructive test method, used to evaluate the amount of compaction, and to map the detection of fractures and defects in the structure of asphalt concrete (Lai et al., 2018; Fernandes and Pais, 2017). The other group of studies is related to the heating of asphalt concrete with microwave technology (microwave heating) (Wang et al., 2019; Trigos et al., 2020; Gallego et al., 2013; Norambuena-Contreras and Garcia, 2016). Furthermore, there are some studies mostly using cement-based materials modified with some other materials (such as metals, polymers or inorganic non-metallic materials) to improve their electromagnetic shielding effectiveness (lowering electromagnetic permittivity) (Ozturk et al., 2020; Yeoh et al., 2020; Chen et al., 2021; Lv et al., 2018; Cui et al., 2017; Xie et al., 2020). In the literature, carbon-based materials such as carbon fibre (Wu and Chung, 2002; Yang et al., 2007), carbon black (Geetha et al., 2009; Spahr et al., 2017; Kausar, 2016), carbon nanotubes (Sun et al., 2011; Popov, 2004), graphite and graphene (Geim, 2009; Joshi and Datar, 2015; Das and Prusty, 2013) have been used to modify materials in order to increase their electromagnetic shielding effectiveness. However, graphite was mostly used either in nano-scale (Han et al., 2015; Du and Dai Pang, 2015; Peyvandi et al., 2013; Du et al., 2016; Saafi et al., 2014; Le et al., 2014), or along with cement-based materials (Dai et al., 2010, Guan et al., 2006; Ji et al., 2011) or in large percentages (more than 5% of the mixes) (Chandrasekaran et al., 2013; Ji et al., 2011; Raza et al., 2011; Yu et al., 2007). Almost all of the studies encountered in the literature using graphite powder as part of asphalt concrete have focused on evaluating the effect of graphite powder on the electrical conductivity of asphalt concretes rather than evaluating its effect on electromagnetic permittivity (Wu et al., 2005; Liu et al., 2008; Chen and Balieu, 2020; Vo et al., 2017). However, in the literature search, no study was found investigating the electromagnetic permittivity properties of the asphalt concrete with different percentages of graphite powder within the scope of wireless ER technologies.

This study experimentally investigates the usability of asphalt concrete pavement containing five different ratios of graphite powder (0%, 1.25%, 2.5%, 3.75% and 5% by weight of the aggregate blend or 0%, 25%, 50%, 75% and 100% of the filler content) as a filler to be potentially used as part of wireless electric roads. As part of the study, first, optimum asphalt binder content for the asphalt mixes without graphite powder was determined. Then, using the determined optimum asphalt binder content, asphalt mixes containing five different ratios of graphite powder as a filler were prepared and their mechanical and volumetric properties based on Marshall mix design methodology were evaluated. Furthermore, another batch of asphalt mixes containing five different ratios of graphite powder were prepared and tested for their electromagnetic permittivity.

1. Materials and method

1.1. Materials

In this study, as aggregate, crushed limestone, obtained from a local quarry located in southeastern part of Turkey was used. In terms of the aggregate gradation, an aggregate blend to be within the limits specified by Turkish Highway Technical Specification (HTS, 2013) for the asphalt wearing courses was prepared (Table 1). Table 2 shows physical and mechanical properties of the aggregates, determined based on American (ASTM) standards, used in this study. In terms of filler content (materials passing 0.075 mm sieve), Turkish Highway Technical Specification specifies that filler content for the asphalt wearing courses must be between 3–8% of the aggregate blend. Therefore, a filler

Table 1. Gradation and specification limits

Sieve diameter, mm	Limit values	Gradation of mixture	Weight, g
	% passing (HTS, 2013)	% passing	
25 mm	100	100.0	0.0
19 mm	100	100.0	0.0
12.5 mm	88–100	91.7	95.9
9.5mm	72–90	81.6	116.0
4.75 mm	42–52	48.6	378.9
2.00 mm	25–35	29.6	218.3
0.425 mm	10–20	12.6	195.5
0.180 mm	7–14	7.2	62.7
0.075 mm	3–8	5.0	25.2
Filler	-	-	57.5
Total	100%	100%	1150

Table 2. Physical and mechanical properties of aggregates

Properties		Results	Tests Standards
Coarse aggregate	Apparent specific gravity	2.727	ASTM C127
	Bulk specific gravity	2.692	
Fine aggregate	Apparent specific gravity	2.708	ASTM C128
	Bulk specific gravity	2.654	
Filler	Bulk specific gravity	2.732	ASTM C128
Combined Bulk Specific Gravity, Gsb, of Aggregate Blend		2.678	
Abrasion loss, % (Los Angeles)		21.5	ASTM C131
Flatness index, %		17.0	ASTM D4791

Table 3. Physical properties of the asphalt binder

Properties	Results	Test Standards
Penetration Grade, 25 °C	77 (70/100)	ASTM D5
Softening Point, °C	48.0	ASTM D36/D36M
Specific Gravity, g/cm^3	1.040	ASTM D70-09e1
Ductility, 25 °C	>100 cm	ASTM D113-07
Loss on Heating, %	0.43	ASTM D6-95
Flash Point, °C	280	ASTM D92-05a
Viscosity (at 135 °C, cP)	312.5	ASTM D4402-06
Viscosity (at 165 °C, cP)	100.0	ASTM D4402-06

content of 5%, a value between 3–8% of the aggregate blend, was used throughout this study.

Graphite powder used in this study was obtained from a local supplier. Typical size distribution of graphite particles reported by another study found that 95% of the particles had a diameter below 0.075 mm, median diameter was 0.046 mm (Zhang et al., 2017). Therefore, it has the same size as a filler. In this study, graphite powder was used as a filler replacement.

An asphalt binder with a 70–100 penetration grade (found as 77 in this study) was used throughout this study. The physical properties of this binder are provided in Table 3.

1.2. Methodology

1.2.1. Determination of optimum binder content

As part of this study, first, asphalt concrete specimens with various asphalt binder contents (3.5%, 4%, 4.5%, 5%, 5.5% and 6%) were prepared using the aggregate blends with a gradation shown in Table 1. In each asphalt binder content case, three specimens were prepared. The prepared specimens were compacted with 75 Marshall hammer blows on each side based on the specification criterion for asphalt wearing courses (HTS, 2013). Then, the prepared specimens were tested based on Marshall stability (MS) test (ASTM D 6927) and their stability and flow values were measured. Their volumetric properties such as air content, voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and unit weight results were also obtained in order to determine optimum binder content (Figure 1).

Considering the results presented in Figure 1, optimum binder content of the asphalt mixes was calculated based on the Asphalt Institute procedure (Asphalt Institute, 1997) as follows:

1. Binder content for the maximum stability (found as 4.30%);
2. Binder content for the maximum unit weight (found as 4.75%);
3. Binder content for the 4% air content (found as 5.90%).

Optimum binder content of the asphalt mixes was calculated as 5% by taking average of the binder contents corresponding to the maximum stability, unit weight and 4% air content:

$$\frac{4.30+4.75+5.90}{3}=5\%.$$

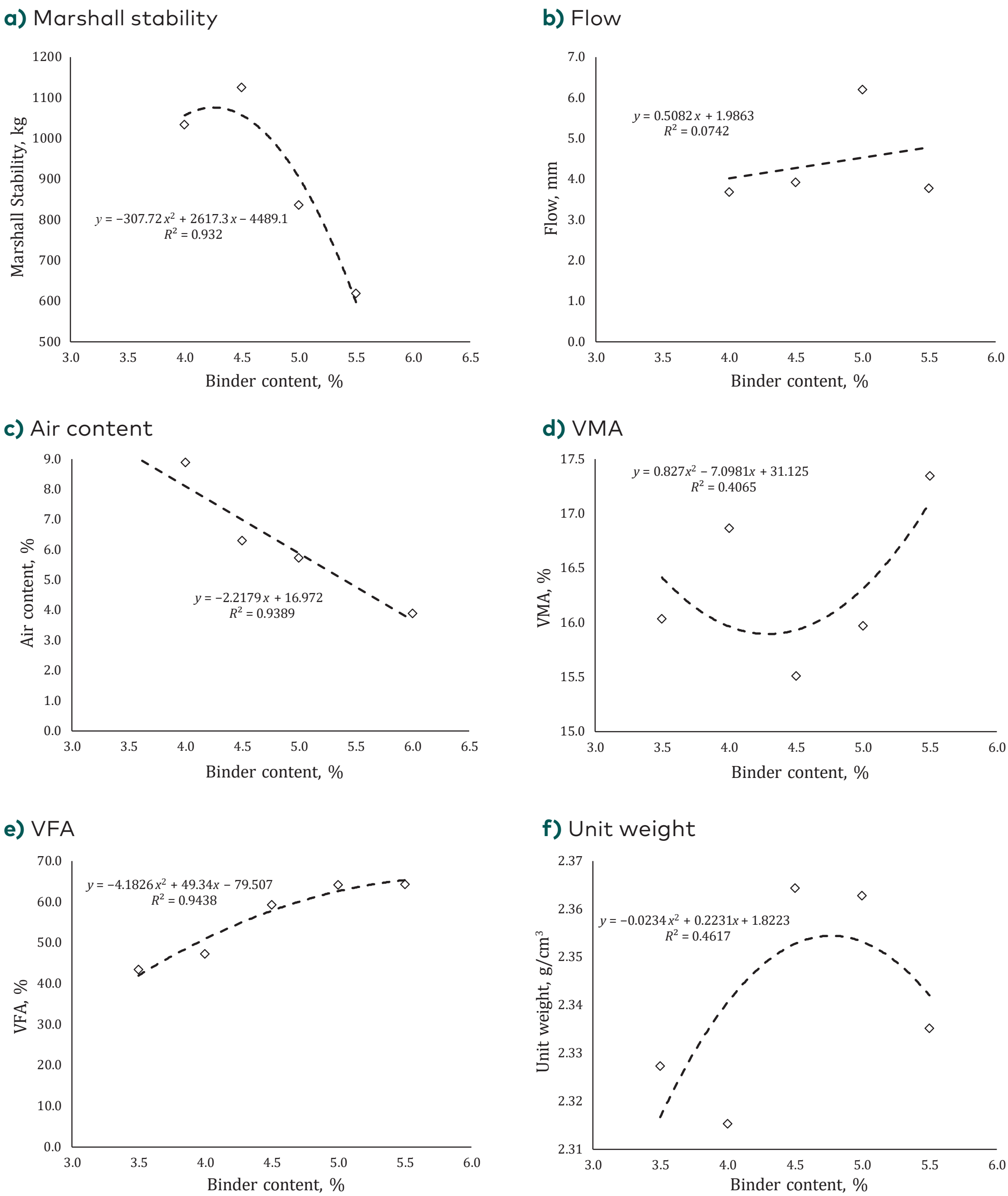

Figure 1. Mechanical and volumetric test results of the asphalt specimens with various asphalt binder contents

1.2.2. Preparation of test specimens

After determining the optimum binder content, an experimental matrix of asphalt mixes of 30 specimens was prepared (Table 4). A half of the specimens (15 specimens) was prepared for the measurements of mechanical and volumetric properties, while the other half of the specimens (15 specimens) was prepared for the measurements of electromagnetic properties. In each set of specimens (15 specimens), 5% binder and 5% filler contents were used where ratios of graphite powders in the 5% filler content were varied (0%, 25%, 50%, 75% and 100% of the limestone filler was replaced by graphite powder, corresponding to 0%, 1.25%, 2.5%, 3.75% and 5% of the total aggregate blend, respectively) (Table 4). The 15 test specimens used to measure mechanical and volumetric properties were prepared as standard Marshall test specimens, compacted with 75 Marshall hammer blows on each side, and then they were tested for their stability, flow, air content, VMA, VFA and unit weight values.

To better characterise asphalt concrete samples in terms of their electromagnetic properties, based on some previous studies that used the same equipment as in this study (Oztürk et al., 2018; Oztürk et al., 2020), asphalt concrete specimens with a shape of a square prism, having the sizes 150 mm × 150 mm × 23.25 mm, were prepared. To prepare the specimens, a mould with the previously-mentioned sizes was designed and produced along with a half-centimetre thick steel plate in order to homogenously compact the specimens. The prepared specimens had the same volume as the standard Marshall specimens,

Table 4. Experimental test matrix used in this study

Sample Type	Number of test specimens	Total filler content in the aggregate blend, %	Limestone in filler, %	Graphite powder in filler, %
Mechanical and Volumetric	3	5	5	0
	3	5	3.75	1.25
	3	5	2.5	2.5
	3	5	1.25	3.75
	3	5	0	5
Electromagnetic	3	5	5	0
	3	5	3.75	1.25
	3	5	2.5	2.5
	3	5	1.25	3.75
	3	5	0	5

having the same amount of graphite powder, and it was ensured that they had the same degree of compaction as their Marshall specimen counterparts.

1.2.3. Electromagnetic characterisation of test specimens

Electromagnetic characteristics of the prepared test samples were determined using a vector network analyser (VNA), operating in a wide frequency band (Figure 2). Along with the VNA, two linearly polarized, high gain horn antennas were used. To obtain the transmitted and reflected signals, the network analyser was calibrated with the help of an appropriate calibration kit. The network analyser measures the scattering parameters, also called S-parameters. S11 and S22 parameters refer to the power reflected from one port to the other, whereas S12 and S21 parameters refer to the power transmitted from one port to the other in a two-port system. As part of this study, the test specimens were tested at the operating frequency band of 3–18 GHz in Super High Frequency Band (SHF). The horn reference antennas used in this study were also selected according to the operating frequency band. In order to reduce errors and uncertainties, Time-Domain Gating (TDG) techniques were used. TDG used in this study is known to be effectively used to filter most of the interferences affecting free space measurements (Micheli et al., 2014). As part of this study, transmission coefficients (S12 or S21) for the asphalt concrete specimens containing

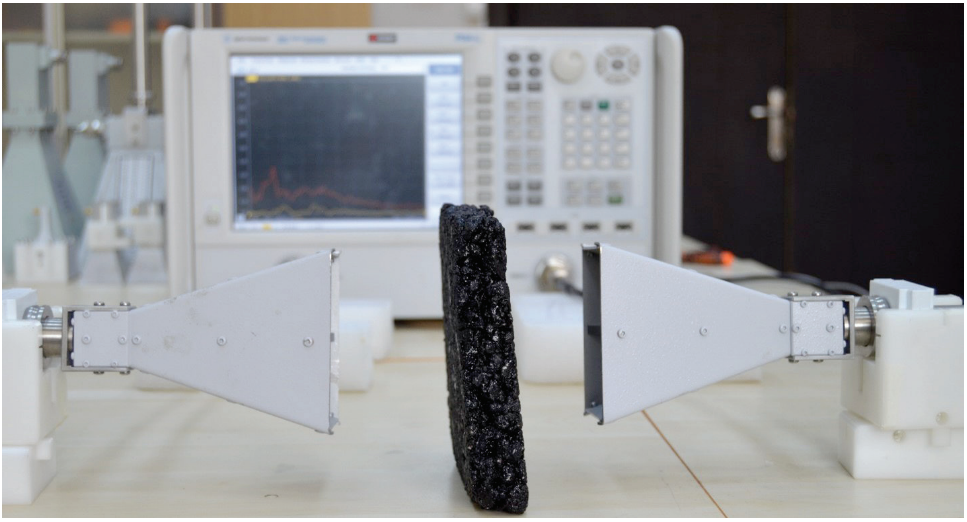

Figure 2. Electromagnetic characterisation setup

five different ratios of graphite powder were measured in the frequency range of 3–18 GHz to evaluate the effect of graphite powder on the electromagnetic transmitting properties of asphalt concretes.

2. Results and discussion

2.1. Mechanical and volumetric properties

In this section of the paper, MS, flow, air content, VMA, VFA and unit weight test results of the 15 Marshall specimens, containing five different ratios of graphite powder contents (0%, 25%, 50%, 75% and 100% filler replacement), are presented as box and whisker charts (they show the distribution of data based on quartiles including mean values) (Figure 3). As graphite powder ratios in the asphalt mixes increased, their MS, flow, VFA and unit weight test results mostly decreased but their air content and VMA test results increased.

As can be seen in Figure 3a, as graphite powder ratio in the filler increased, MS results tended to decrease. The decrease in MS values between the cases of 0% and 100% graphite powder ratios was about 32%. This finding was supported by some other previous studies such as Kök et al. (2017), investigating the effect of graphite powder on the mechanical properties of stone matrix asphalt. They found that an increase in graphite powder resulted in a decrease in Marshall stability values.

One of the possible reasons why MS, flow, VFA and unit weight test results decreased and air content and VMA test results increased with the increase in graphite powder ratio could be that graphite powder had a lower bulk specific gravity compared to that of limestone filler. Limestone filler used in this study has a bulk specific gravity of 2.732, whereas bulk specific graphite powder of the graphite powder has been reported to be around 2.15 (Kök et al., 2017). In this study, graphite powder has been replaced by weight of filler content. Therefore, 0%, 1.25%, 2.5%, 3.75% and 5% of the total aggregate blend was replaced by graphite powder, by weight, corresponding to about 0%, 1.56%, 3.11%, 4.67% and 6.23% of the total aggregate blend, by volume, respectively (each graphite powder ratio value, by weight, was multiplied by 2.15/2.732 to calculate the values by volume). Having higher level of graphite content in the asphalt mix by volume causes the mixes to have more surface area due to more graphite powder content. Therefore, having more surface area in the mixes might need more binder content to reach optimum binder content. It was also reported by some other studies that graphite particles have sheet-like structures that have more surface areas compared to that of same number of mineral fillers. Their sheet-like structures have been observed to weakly bond to sheet-like graphite layers located above and below (Liu et al., 2008; Wu et al, 2005; Liu, 2011). Mechanical or chemical energy can be used to break these weak bonds. Graphite powder consists of graphenes connected to each other by Van der Waals bonds. Since these Van der Waals bonds are very weak, these bonds could be broken under influences such as

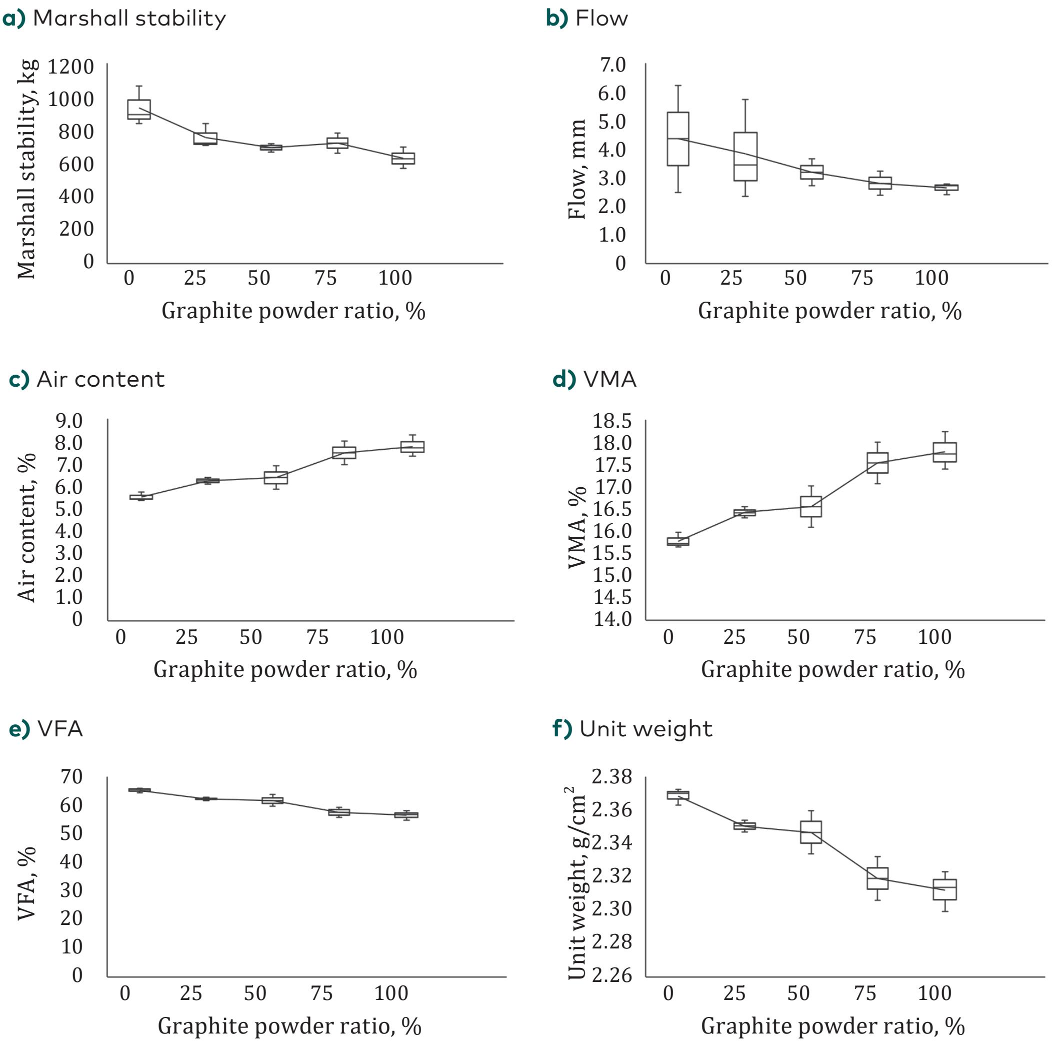

Figure 3. Mechanical and volumetric test results of the asphalt specimens with various graphite powder replacement ratios of the filler

temperature or pressure (Choi et al., 2010). Increase in the amount of these weakly bonded layers with the increase in graphite powder ratios in the mixes might have caused reductions in their stability and flow test results.

In this study, while producing Marshall specimens with different graphite powder ratios, it was realised that, as graphite powder ratio in the asphalt mixes increased, they became dryer and had lighter colours (Figure 4). This might be because that graphite powders have been reported by some other previous studies to have a higher absorbance of asphalt binders, especially lightweight fractions of asphalt binders, compared to mineral fillers (Wang et al., 2020; Pan et al., 2014). Becoming dryer with the increase in their graphite powder ratios caused the mixes to have less unit weight and much air content.

It was also observed in the air content, VMA, VFA and unit weight test results (Figures 3c, 3d, 3e and 3f, respectively) that as graphite powder ratios of the asphalt mixes increased, their air content and VMA values increased but their VFA and unit weight values decreased. These figures show that as graphite content in the mixes increased, more percentages of binder contents in the mixes were absorbed and used to coat graphite powder particles. Therefore, VMA results of the mixes increased and VFA test results decreased, meaning that there was less film thickness (less amount of effective asphalt binder) in the mixes. Asphalt binder film thickness is one of the important factors providing cohesion and adhesion in the asphalt mixes and thereby affecting durability and bonding performance of asphalt mixes (Al-Khateeb, 2018). Durability of asphalt mixes is highly dependent on their volumetric properties (Karim et al., 2021). Excessive VFA and air contents and inadequate VMA might signal possible durability issues (Hislop and Coree, 2000).

Figure 4. Asphalt specimens with 0% (left) and 100% (right) graphite powder replacement ratios of the filler

It could be inferred based on the test results presented in Figure 3 that effective binder contents in the mixes decreased with the increase in graphite powder ratio. Therefore, in order not to much negatively affect stability, flow and other volumetric parameters of asphalt mixes with the graphite powder ratios, it might be better to use lower graphite ratios rather than higher graphite ratios, and optimum asphalt binder contents might have been determined for each graphite powder ratio case.

2.2. Electromagnetic transmission properties

The transmission magnitudes of the asphalt concrete specimens containing five different graphite powder ratios were measured in the frequency range of 3–18 GHz. The reason why this frequency range was chosen in this study was to observe electromagnetic transmission properties of asphalt concrete specimens in various communication fields. It was ensured that the measurements were taken in free space conditions. It was also ensured that the specimens were placed as far from horn antennas as possible according to the maximum wavelength in the range to minimize near-field effects. Transmission parameter (S12) was properly measured when directional high gain antennas were used. In this study, two linearly polarized high gain horn antennas were used in the frequency range of 3–18 GHz to measure transmission responses of the asphalt concrete specimens containing five different graphite powder ratios. Furthermore, transmission coefficients of the asphalt concrete specimens containing five different graphite powder contents were compared with each other to evaluate the effect of graphite powder ratio on their electromagnetic transmission properties. In the field of electromagnetic transmission, the imaginary part of electromagnetic permittivity quantifies the loss due to the absorption of waves. In other words, having higher transmission magnitude means having lower imaginary part of the electromagnetic permittivity. This study aimed to ensure high level of transmission of electromagnetic waves. For this reason, the electromagnetic permittivity with lower imaginary part allowed for a higher level of transmission and a lower level of loss. Figure 5 shows transmission measurements of the samples with five different graphite powder ratios in the filler (0%, 25%, 50%, 75% and 100% of the filler content) in the frequency range of 3–18 GHz. As can be seen in Figure 5, except for the specimens with 100% graphite powder ratios, transmission magnitudes of all specimens were above 50% up to 8 GHz, indicating that they had comparably high transmission magnitudes so as comparably low imaginary parts of electromagnetic permittivity values. As frequency values increased, transmission magnitudes tended to decrease for all specimens investigated. In the frequency range of 3–13 GHz, transmission magnitudes of the specimens with 25% and 50% graphite powder ratios were consistently higher than that having no graphite powder, the ones with 25% powder ratios had the highest transmission magnitudes in most of the cases in this frequency range. Considering the frequency range of 3–6 GHz, the average transmission magnitude of specimens with 25% graphite powder ratio was greater than 80%, indicating a low level of imaginary part of electromagnetic permittivity. Furthermore, considering the frequency range of 9–12 GHz, transmission magnitude of the specimens with 25% graphite powder ratio was almost twice as much as of that with no graphite powder. The difference between transmission magnitudes of the asphalt concrete specimens with different graphite powder ratios decreased with the increase in frequency range. Considering the specimens with 75% and 100% graphite powder ratios, their transmission magnitudes were mostly lower than the ones with no graphite powder, the ones with 100% graphite powder ratio consistently had the lowest transmission magnitudes.

Having lower transmission of the specimens with 75% and 100% graphite powder ratios was directly related to their high electromagnetic lossy characteristics. These losses could be due to comparably higher graphite powder concentrations of the specimens. As the concentration of graphite powders in the specimens increased, they might form sheet-like clusters, due to the sheet-like structures of graphite particles, so that these clusters might contact each other to form continuous electrically conductive paths as a reflector. The specimens with higher electrical conductivity were expected to demonstrate higher losses due to a greater value of imaginary part of electromagnetic permittivity. The asphalt concrete specimens with 25% and 50% graphite powder ratios had higher transmission magnitudes compared to that with 0% graphite powder; however, the specimens with 75% and 100% graphite powders had mostly lower transmission values. The reason for this behaviour might be that up to around 25% graphite powder ratio, graphite particles did not form electrically conductive paths and somewhere after around 25% graphite powder ratio, they formed continuous electrically conductive paths as continuous reflectors. A value of around 25% graphite powder ratio behaves like a percolation threshold value. The concept of percolation threshold value has been used by some other previous studies to explain this concept. Dai et al. (2010) investigated the electromagnetic wave absorbing characteristics along with the electrical conductivity properties of carbon black cement-based composites (CBCC). They found an electrical percolation threshold zone (a sudden change in the measurements) of CBCC containing 0.7–2.5 wt.% (or 0.36–1.34 vol.%) of carbon black. Sun et al. (2017) experimentally investigated the mechanical, electrical, and electromagnetic properties of cementitious composites filled with different content of multi-layer graphenes (MLGs). They found a percolation threshold of 2% (by volume) of the MLGs when they compared the electrical resistivity of the cementitious composites containing different ratios of MLGs. They also evaluated shieldness effectiveness of the cementitious composites containing different ratios of MLGs and observed that shieldness effectiveness values of the composites containing 0, 1 and 2% (by volume) of MLG were very similar to each other especially in the frequency range of 2–8 GHz, whereas shieldness effectiveness values increased as MLGs contents increased especially after 5% MLGs contents.

As can be seen in Figure 5, the reason why the electromagnetic transmission properties of the asphalt specimens with various GP ratios were measured in a wide spectrum (3–18 GHz) was to demonstrate their frequency-dependent performance. With the increase in frequency, the transmission coefficient of the system was found to be mostly decreasing due to the loss factor variation with frequency (Dai et al. 2010). Evaluation of the changes in the transmission coefficient

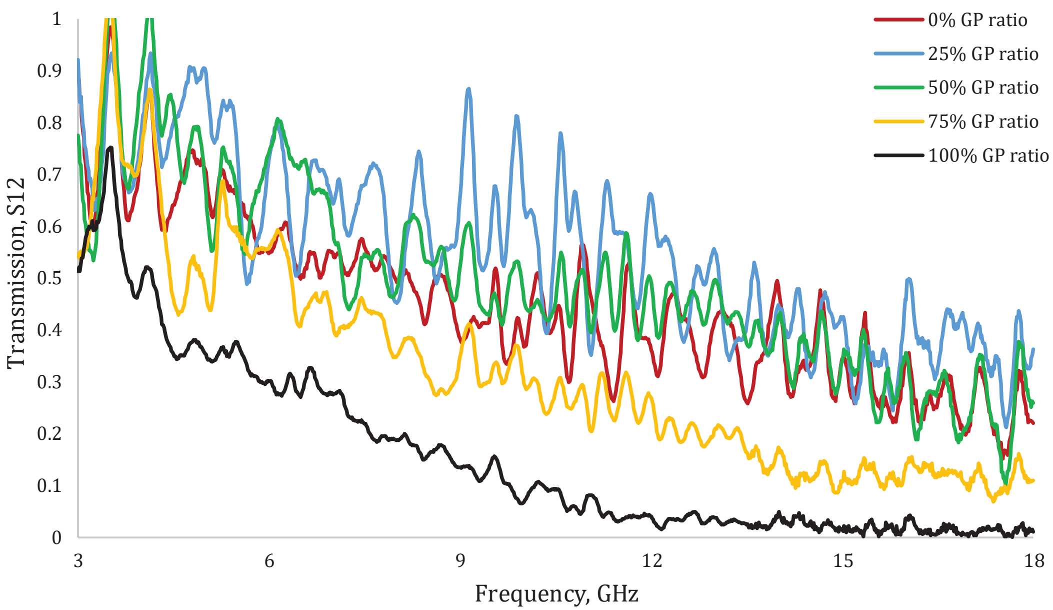

Figure 5. Transmission magnitude (S12 or S21) results of the asphalt concrete specimens containing five different ratios of graphite powder

values with the changes in frequency values help determine the typical operating frequency value for the energy transfer systems. For example, considering the asphalt specimen with the 25% GP ratio, the specimen having the most efficient transmission ratio result, the operating frequency value could be selected as 5.4 GHz as the specimen with 25% GP ratio resulted in the highest transmission ratio value (90%) in this operating frequency value. Another reason for this frequency point selection is its wide range of usage in electrical energy and communication fields.

3. Summary and conclusions

This study experimentally investigated the usability of asphalt concrete pavement containing five different ratios of graphite powder (0%, 1.25%, 2.5%, 3.75% and 5% by weight of the aggregate blend or 0%, 25%, 50%, 75% and 100% of the filler content) as a filler to be potentially used as part of wireless electric roads.

As part of the study, first, optimum asphalt binder content for the asphalt mixes without graphite powder was determined. To do that, asphalt concrete specimens with various asphalt binder contents (3.5%, 4%, 4.5%, 5%, 5.5% and 6%) were prepared and tested for their MS, flow, air content, VMA, VFA and unit weight test results. Optimum binder content of the asphalt mixes was calculated as 5% by taking an average of the binder contents corresponding to the maximum stability, unit weight and 4% air content.

Then, using the determined optimum asphalt binder content, asphalt mixes (15 specimens) containing five different ratios of graphite powder as a filler (0%, 25%, 50%, 75% and 100% of the limestone filler was replaced by graphite powder, corresponding to 0%, 1.25%, 2.5%, 3.75% and 5% of the total aggregate blend, respectively) were prepared and their mechanical and volumetric properties based on Marshall mix design methodology were evaluated. It was found in this study that as graphite powder ratios in the asphalt mixes increased, their MS, flow, VFA and unit weight test results mostly decreased but their air content and VMA test results increased. Possible reasons for this could be: (1) lower bulk specific gravity of graphite powder, (2) higher asphalt absorbance, (3) having greater surface area compared to that of limestone filler, and (4) weak bonds between sheet-like graphite layers.

Furthermore, another batch of asphalt mixes (15 specimens) containing five different ratios of graphite powder (0%, 25%, 50%, 75% and 100% of the filler content) were prepared and tested in the frequency range of 3–18 GHz for their electromagnetic permittivity properties. It was observed in this study that, except for the specimens with 100% graphite powder ratios, transmission magnitudes of all specimens were above 50% up to 8 GHz, indicating that they had comparably high transmission magnitudes so as comparably high electromagnetic permittivity values. As frequency values increased, transmission magnitudes tended to decrease for all specimens investigated. In the frequency range of 3–13 GHz, transmission magnitudes of the specimens with 25% and 50% graphite powder ratios were consistently higher than that having no graphite powder, the ones with 25% powder ratios had the highest transmission magnitudes in most of the cases in this frequency range. Considering the frequency range of 3–6 GHz, the average transmission magnitude of specimens with 25% graphite powder ratio was greater than 80%, indicating a low level of imaginary part of electromagnetic permittivity. Furthermore, considering the frequency range of 9–12 GHz, transmission magnitude of the specimens with 25% graphite powder ratio was almost twice as much as of that with no graphite powder. Difference between transmission magnitudes of the asphalt concrete specimens with different graphite powder ratios decreased with the increase in the frequency range. Considering the specimens with 75% and 100% graphite powder ratios, their transmission magnitudes were mostly lower than the ones with no graphite powder, the ones with 100% graphite powder ratio consistently had the lowest transmission magnitudes. The reason for this behaviour might be that, up to around 25% graphite powder ratio, graphite particles did not form electrical conductive paths and somewhere after around 25% graphite powder ratio, they formed continuous electrical conductive paths. A value of around 25% graphite powder ratio behaves like a percolation threshold value.

Considering the mechanical, volumetric, and electromagnetic properties test results of the asphalt mixes with five different ratios of graphite powder, it could be concluded that the use of 25% graphite powder ratio (corresponding to 1.25% of the aggregate blend used in the mixes) had a comparably lower negative effect on mechanical and volumetric properties of asphalt mixes and had a positive effect on electromagnetic permittivity properties of asphalt mixes. Asphalt mixes produced with this graphite powder ratio could be considered to be used as part of wireless ER.

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