Magnetically enhanced bitumen for wireless power transfer in electric roads: Mechanical, rheological, and electromagnetic evaluation of magnetite-modified bitumen

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ABSTRACT: The increasing demand in transportation has led to higher petroleum consumption and greenhouse gas emissions, emphasizing the need for sustainable solutions. Inductive Electric Road Systems (ERS) enable wireless power transfer (WPT) to electric vehicles, but their efficiency is limited by energy losses and low magnetic permeability in conventional asphalt layers. This study develops magnetite-modified bitumen binders to enhance magnetic permeability and system efficiency. Magnetite was incorporated into bitumen at varying concentrations, and its mechanical, rheological, and electromagnetic properties were evaluated. Results indicate a 56% increase in hardness, a 17% improvement in thermal stability, and up to a 3.66% gain in power transfer efficiency, enhancing their suitability for ERS applications. These findings highlight the potential of multifunctional asphalt materials to enhance pavement performance and support road electrification.

1 INSTRUCTION

The rapid growth of the transportation sector has led to increased petroleum consumption and greenhouse gas (GHG) emissions, intensifying environmental challenges. Global initiatives emphasize the urgent need for sustainable energy solutions, with transportation electrification at the forefront (Madurai Elavarasan *et al.*, 2022). Electric vehicles (EVs) are a key component of this transition, projected to represent 50% of global car sales by 2035, significantly reducing oil demand and carbon emissions (Iea, 2024). However, the widespread adoption of EVs would be facilitated by intelligent infrastructure capable of providing efficient, continuous recharging while in motion. (Kuttah, 2022).

Electric Road Systems (ERS), particularly those employing Wireless Power Transfer (WPT), offer a promising solution by enabling energy transfer between road-embedded transmitters and vehicle receivers (Soares and Wang, 2022; Chen, Taylor and Kringos, 2015). Despite their significant potential, WPT systems face critical efficiency challenges, primarily due to factors such as coil misalignment, the separation between them, and the electromagnetic properties of the materials involved, which limit the overall system efficiency (Panchal, Stegen and Lu, 2018; Machura and Li, 2019; Gulisano *et al.*).

Research highlights magnetite (Fe_3O_4) as a promising additive to improve the electromagnetic properties of bitumen. With high magnetic permeability, magnetite enhances energy transfer efficiency, stiffness, and durability, making it ideal for ERS applications. By reducing reluctance and improving coil coupling, Fe_3O_4 enhances magnetic resonant coupling (MRC) in WPT systems, optimizing power transfer (Rhee *et al.*, 2024). However, potential oxidation and long-term aging effects must be addressed to ensure sustained performance. Incorporating magnetite into bitumen improves structural performance and interaction with advanced road technologies (Al-Kheetan *et al.*, 2022; Giustozzi *et al.*, 2018).

This study examines the optimization of mechanical and electromagnetic properties in magnetite-modified bitumen to enhance WPT system efficiency. Its objectives, methodology, results, and conclusions offer key insights for developing smarter, more sustainable road infrastructure.

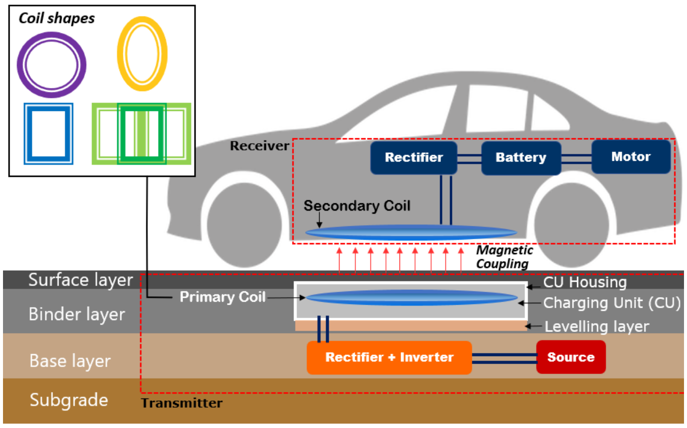

Figure 1. WPT systems in pavements. Source: Author's elaboration

2 SCOPE AND OBJECTIVES

This study aims to develop and evaluate magnetite-modified bitumen with enhanced magnetic permeability to improve the efficiency of Electric Road Systems (ERS), particularly for wireless power transfer (WPT) applications for electric road vehicles.

3 MATERIALS

The study utilized 50/70 bitumen, characterized according to the UNE-EN 12591 standard, as the base material (Figure 2a). Synthetic magnetite (Fe_3O_4) was incorporated as a filler, with particle sizes below 0.01 mm. Magnetite's high density approximately 5.18 g/cm³ (Figure 2b), and its hardness (5.5–6.5 on the Mohs scale) contribute to improved mechanical strength and thermal conductivity, enhancing the material's resistance to deformation and cracking (Patti *et al.*, 2018).

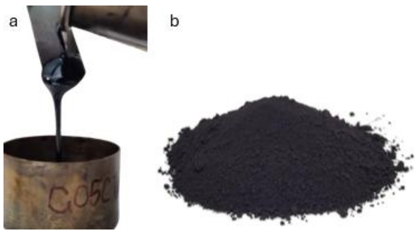

Figure 2. a) Bitumen 50/70 b) Magnetite filler F_3O_4

4 METHODOLOGY

This study evaluated the mechanical, rheological, and electromagnetic properties of 50/70 bitumen modified with magnetite filler. Magnetite was added volumetrically at 0% (Reference), 2% (M-2%), 5% (M-5%), and 10% (M-10%) to ensure uniform dispersion in the bitumen matrix. Given its high density (~5.18 g/cm³), these correspond to 0%, 11%, 28%, and 50% by weight, respectively. Volumetric measurement was chosen for consistent mixing and material evaluation.

Bitumen was mixed at 160°C using a high-shear mixer (1400 rpm, 5 min), followed by 10 min of additional mixing for homogeneity.

Mechanical properties were assessed through penetration and softening point tests, while viscosity was measured using a Brookfield viscometer. Rheological behavior was analyzed with a Dynamic Shear Rheometer (DSR) to evaluate deformation resistance. Electromagnetic tests focused on magnetic permeability and energy transfer efficiency, determining the modified bitumen's suitability for Electric Road Systems (ERS).

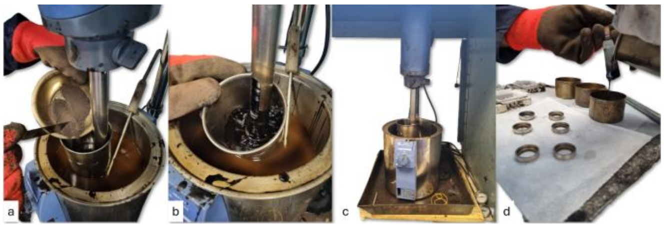

Figure 3. Manufacturing process of magnetite-modified bitumen: a) Addition of magnetite filler; b) Mixing at a velocity of 1400 rpm; c) High-shear mixing at 160°C; d) Pouring mixture into molds for testing.

4.1 *Mechanical Tests*

Penetration (ASTM D5): Evaluated bitumen consistency by measuring the penetration depth of a needle under a 100 g load at 25°C for 5 seconds. Three measurements were taken for each of the three samples per magnetite content.

Softening Point (ASTM D36): Assessed thermal susceptibility using the ring and ball test. The softening point was recorded as the temperature at which a steel ball penetrated the bitumen. Tests were performed on three samples for each magnetite content.

Dynamic Viscosity (ASTM D4402): A Brookfield viscometer measured the bitumen's resistance to flow at high temperatures (90°C to 160°C), providing insights into its handling and pumping properties.

Rheological Properties (ASTM D7175): Examined viscoelastic behavior with a Dynamic Shear Rheometer (DSR). Tests included frequency sweeps (0.1–10 Hz) and temperature ranges (25°C–75°C), determining complex shear modulus (|G*|) and phase angle (δ) to evaluate deformation resistance. The master curve of |G*| was constructed using the Standard logistic Sigmoid model and the shift factor was calculated by the Williams-Landel-Ferry (WLF) shift function (Xue *et al.*, 2024).

Figure 4. a) Penetration test b) Softening point test c) Viscometer Brookfield d) Dynamic Shear Rheometer (DSR)

4.2 *Electromagnetic Tests*

Resistance was measured using the four-probe method, applying an input voltage (1V-1000V) through outer probes and recording voltage between inner probes with a high-impedance voltmeter, eliminating parasitic resistances (Dieval *et al.*, 2024). Samples, 40 mm cubes with 10 mm height, were prepared with preheated molds at 100°C for optimal wire placement and consistent testing conditions (Figures 5a-c).

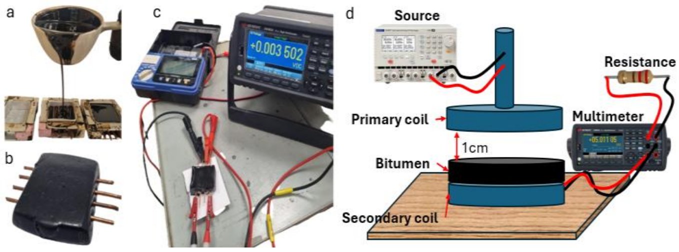

Figure 5. Electrical characterization: a) Sample fabrication; b) Prepared sample with copper probes; c) 4-probe test circuit setup. d) Magnetic characterization setup

Magnetic characterization measured induced voltage drops and current variation using two coils separated by 1.5 cm, with a diameter of 2 cm, and bitumen samples placed between them. A 30V AC source powered the primary coil at 85 kHz, while the secondary coil recorded voltage. Tests were conducted at 20°C, with multiple measurements ensuring reproducibility. Averaged values assessed the effect of magnetite content on power transfer efficiency, and results were compared to the reference sample under consistent environmental conditions.

5 RESULTS AND DISCUSSION

The results demonstrate that incorporating magnetite into bitumen significantly enhances its mechanical and electromagnetic properties. Table 1 presents the principal findings of this study.

Table 1. Summary of Results for Magnetite-Modified Bitumen.

Test	Reference 50/70	2% Magnetite	5% Magnetite	10% Magnetite
Penetration (mm/10)	68	46	40	29
Softening Point (°C)	48	51	53	56
Viscosity at 120°C (cP)	750	1456	1584	2072
Viscosity at 160°C (cP)	90	189	208	283

Penetration decreases by 56.74% with 10% magnetite (Table 1), enhancing resistance to traffic and heat, but flexibility must be balanced to prevent cold cracking. Similarly, softening point tests show a progressive increase in thermal resistance, with a 14.28% rise at 10% magnetite compared to the reference, indicating improved durability under high-temperature conditions.

The viscosity results significantly increase with higher magnetite content (Table 1), confirming its impact as a filler. At 10% magnetite, viscosity increases by 176.27% at 120°C and more than threefold at 160°C, while 2% magnetite results in a 94.13% increase at 120°C compared to the reference. This rise enhances flow resistance and stiffness but requires higher mixing temperatures, with 10% magnetite necessitating ~160°C for optimal handling, highlighting the need for careful adjustment in production.

Rheological analysis (Figure 6) further supports these findings, showing that the complex shear modulus (|G*|) increases with magnetite content, particularly at higher frequencies, while the phase angle (δ) decreases. This shift toward more elastic behavior decreases the viscous contribution, leading to higher stiffness and improved resistance to deformation. The reduced penetration and increased softening point indicate that magnetite-modified bitumen behaves similarly to harder conventional grades or polymer-modified bitumen. However, increased stiffness may limit relaxation and heighten susceptibility to thermal cracking in cold conditions, warranting thermal fracture testing.

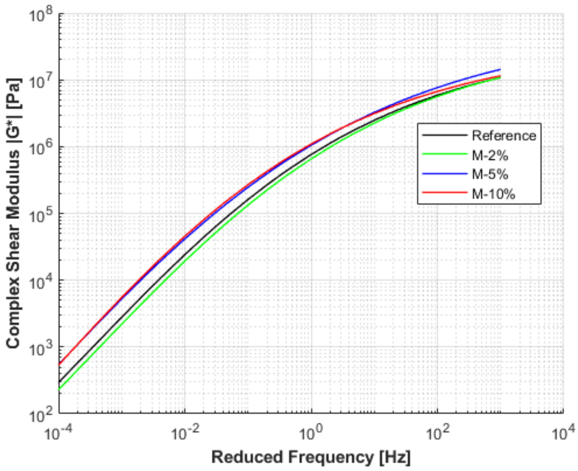

Figure 6. Master curves of the complex shear modulus |G*| at 25ºC.

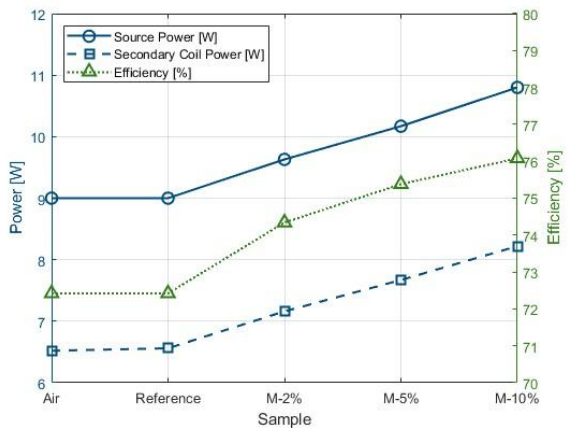

Figure 7. Power Transmission and Efficiency in WPT.

Electromagnetic tests confirm that magnetite does not affect electrical conductivity within the tested voltage range. However, magnetic measurements (Figure 7) show a steady increase in WPT efficiency with higher magnetite content. At 10% magnetite, efficiency improves by 3.66%, attributed to increased magnetic permeability. Magnetic flux concentration reduces circuit reluctance and enhances coil coupling, optimizing energy transfer. This confirms that the improvement stems solely from increased permeability, not electrical conduction.

6 CONCLUSION

This study confirms that incorporating magnetite into bitumen enhances its mechanical and magnetic properties. Up to 10% magnetite increases stiffness and thermal stability, reducing penetration by 56.74% and raising the softening point by 14.28%. These modifications improve bitumen durability under high traffic loads and varied climates. However, higher viscosity requires adjusting mixing and application temperatures, with 10% magnetite needing ~160°C for optimal handling. Rheological results indicate increased shear modulus and lower phase angle, favoring elasticity under dynamic loads. However, greater stiffness may limit relaxation, potentially increasing susceptibility to thermal cracking in cold conditions. Further studies are required to assess low-temperature flexibility and ensure long-term performance.

Electromagnetic tests show a 3.66% increase in WPT efficiency with 10% magnetite due to higher magnetic permeability. Although moderate, this improvement could enhance energy efficiency, particularly in dynamic charging. Even small gains may impact charging speed, transfer time, and economic viability in large-scale projects, requiring further study in real applications. Magnetite does not alter electrical conductivity but reduces circuit reluctance and enhances coil coupling, improving energy transfer. These results highlight its potential for electrified roads, increasing durability and enabling in-motion EV charging while reducing fossil fuel dependence. Future research should assess its impact on inductance and coupling efficiency in dynamic WPT systems, frequency-dependent effects on resonant coupling, and long-term durability, including Fe_3O_4 oxidation, hydration, and mitigation strategies. Additionally, thermal fracture tests should evaluate stiffness effects on low-temperature cracking.

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