International Association of Chinese Infrastructure Professionals

Wireless power transfer tuning model of electric vehicles with pavement materials as transmission media for energy conservation

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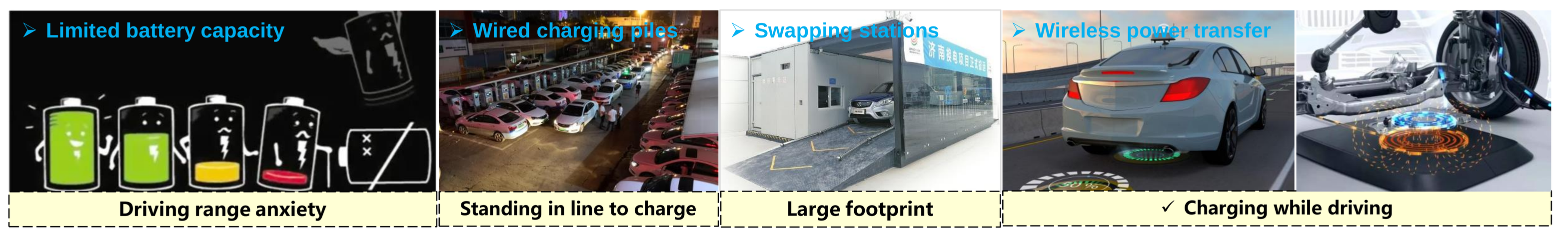
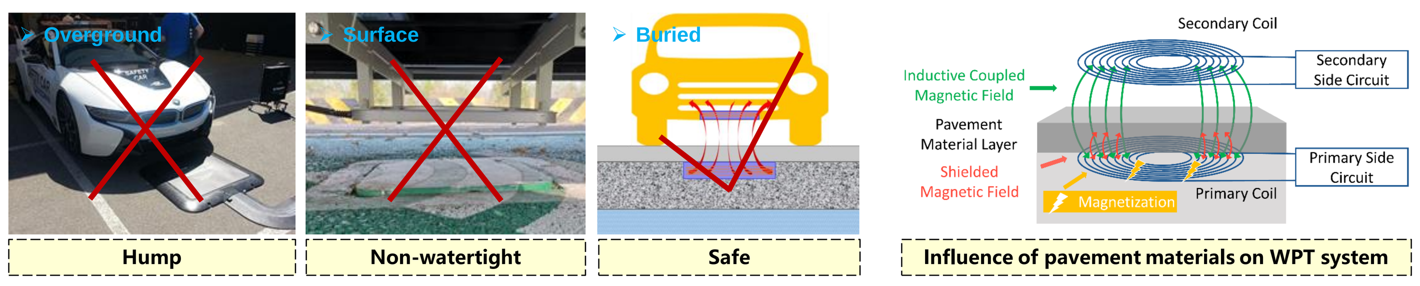
Introduction

- Compared with petrol vehicles, electric vehicles are beneficial to achieving carbon net zero in transportation.
- However, the energy storage capacity of electric vehicle batteries is limited, leading to the driving range anxiety.
- **Wireless power transfer (WPT)** technology is considered to be one of the ways to alleviate the charging difficulties.



- In practice, to ensure the durability of pavement, and prevent the circuits to become obstacles for driving, the primary circuits should be buried in the pavement structure.
- Then, the transmission media-air between primary and secondary coil is replaced by pavement materials.
- Previous study indicated that pavement materials can adversely affect the resonant induction coupling process of WPT, reducing the power and efficiency of charging.
- However, the influence mechanism and how to reduce the influence remains unclear.



Objectives

- To quantitatively evaluate the magnetization properties of pavement materials by equivalent magnetic circuit model.
- To evaluate the influence mechanism of pavement materials on the resonant induction coupling process.
- To provide the calculate formulae of resonant frequency for system tuning to reduce the energy loss due to the insertion of pavement materials.

Materials and Modeling

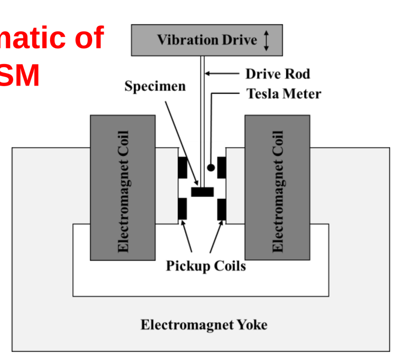
pavement materials

- Asphalt concrete (AC-13 and SMA-13)
- Portland cement concrete (PCC)

Test of magnetic properties

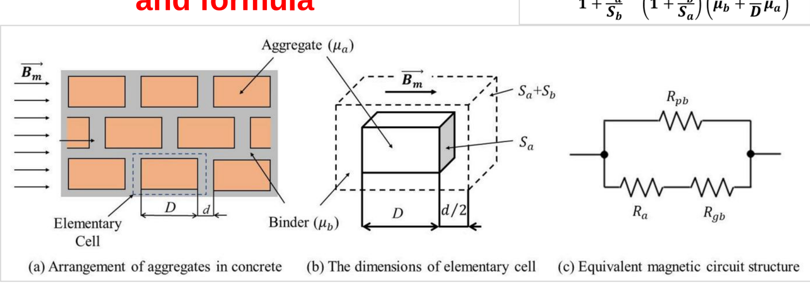
- Relative permeability of raw materials tested by VSM
- **Effective relative permeability** of pavement materials calculated through **equivalent magnetic circuit model**

Schematic of VSM

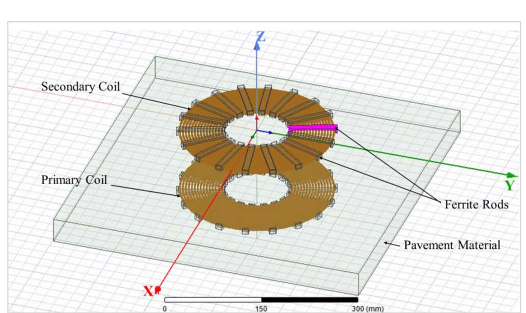


Equivalent magnetic circuit model and formula

$$\mu_e = \frac{\mu_b}{1+\frac{S_a}{S_b}} + \frac{\left(1+\frac{d}{D}\right)\mu_a\mu_b}{\left(1+\frac{S_b}{S_a}\right)\left(\mu_b+\frac{d}{D}\mu_a\right)}$$



3D Finite element model and Mathematical model



FEM of resonant induction coupling process to obtain L_1, L_2, and M

Calculation formulas of power and efficiency

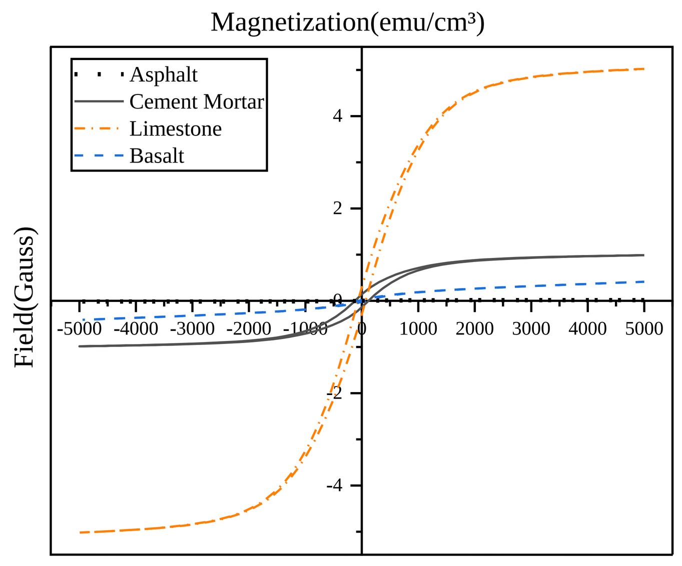
$$\begin{bmatrix}U_s\\0\end{bmatrix} = \begin{bmatrix}Z_1 & -j\omega M\\ -j\omega M & Z_2\end{bmatrix}\begin{bmatrix}I_1\\I_2\end{bmatrix} \qquad \omega = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}$$

$$P_L = I_2^2R_L = \frac{\omega^2M^2U_S^2R_L}{\left((R_1+j\left(\omega L_1-\frac{1}{\omega C_1}\right))(R_2+j\left(\omega L_2-\frac{1}{\omega C_2}\right)+R_L)+\omega^2M^2\right)^2}$$

$$\eta = \frac{R_L}{R_2+j\left(\omega L_2-\frac{1}{\omega C_2}\right)+R_L} \times \frac{\omega^2M^2}{(R_1+j\left(\omega L_1-\frac{1}{\omega C_1}\right))(R_2+j\left(\omega L_2-\frac{1}{\omega C_2}\right)+R_L)+\omega^2M^2}$$

Results and discussion

Magnetic properties of pavement materials



Hysteresis loop of raw materials.

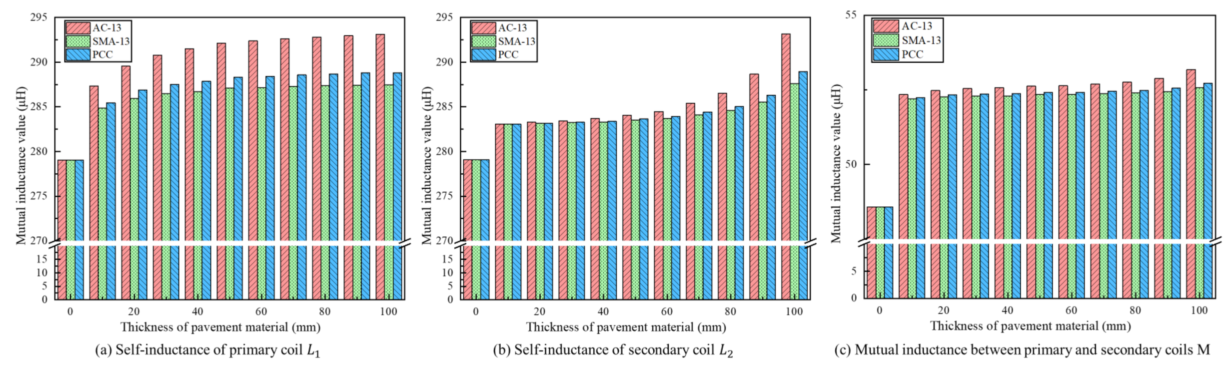
Relative effective permeability of different types of pavement materials

Gradation type	AC-13	SMA-13	PCC
μ_e	1.04864	1.02120	1.02774

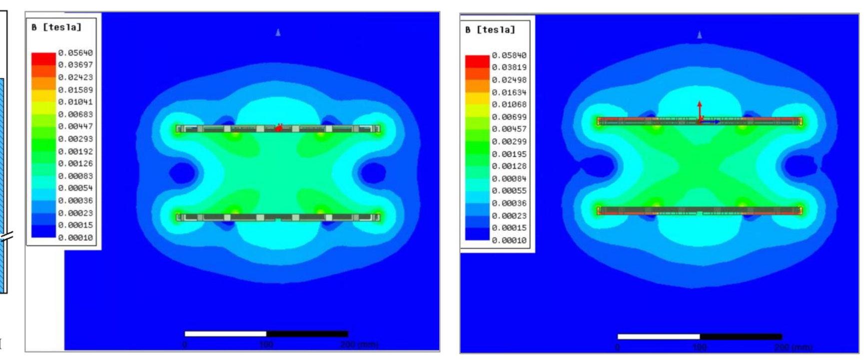
- Among the raw materials, limestone had the highest permeability, followed by cement, basalt was the third, and asphalt had the lowest permeability, which was almost negligible.
- The effective relative permeability of different pavement materials was: **AC-13>PCC>SMA-13**.

Influence of pavement materials on resonant induction coupling

- L_1, L_2, and M increased with the pavement materials inserted because of the increase of magnetic field intensity.
- **L_1: convex shape, L_2: concave shape, M: first convex, and then concave.**



L_1, L_2 and M at different thicknesses of pavement materials.



Cloud images of magnetic field. (a) AC-0cm. (b) AC-100mm.

Establishment of tuning model

- The thickness factor t_f and material factor a_P^L ... were constructed according to change rate curves of L_1, L_2, and M.
- The tuning formula of resonant induction coupling process was proposed to restore the resonant state.

Tuning formula of WPT

$$t_f = {}^{T}/_{TD}$$

$$L_{1c} = \left(a_{PM}^{L_1}{t_f}^3 + b_{PM}^{L_1}{t_f}^2 + c_{PM}^{L_1}t_f + d_{PM}^{L_1}\right)L_1$$

$$L_{2c} = \left(a_{PM}^{L_2}{t_f}^3 + b_{PM}^{L_2}{t_f}^2 + c_{PM}^{L_2}t_f + d_{PM}^{L_2}\right)L_2$$

$$M_c = \left(a_{PM}^{M}{t_f}^3 + b_{PM}^{M}{t_f}^2 + c_{PM}^{M}t_f + d_{PM}^{M}\right)M$$

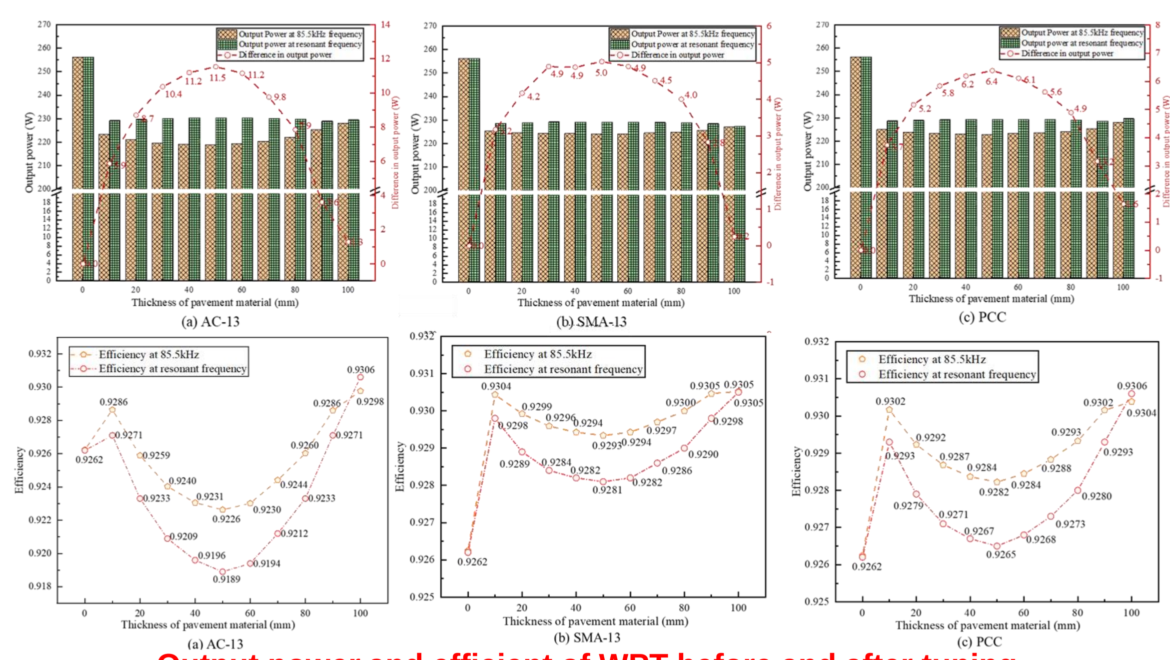
$$\omega_c = \frac{2}{\sqrt{L_{1c}+n^2L_{2c}} \times \sqrt{C_1 + {}^{C_2}/_{n^2}}}$$

$$P_{Lc} = {I_{2c}}^2R_L = \frac{4(1+\frac{C_2}{C_1})(\frac{L_{1c}+L_{2c}}{L_1})\omega^2{M_c}^2U_sR_L}{((1+\frac{C_2}{C_1})(\frac{L_{1c}+L_{2c}}{L_1})R_1(R_2+R_L)+4\omega^2{M_c}^2)^2}$$

$$\eta_c = \frac{R_L}{R_2+R_L} \times \frac{4\omega^2{M_c}^2}{(1+\frac{C_2}{C_1})(\frac{L_{1c}+L_{2c}}{L_1})R_1(R_2+R_L)+4\omega^2{M_c}^2}$$

Verification of tuning model

- After tuning, the output power increased and the efficiency decreased, but the reduction was only about 0.2%.
- The minimum efficiency under the three materials still met the requirements of the specifications.



Output power and efficient of WPT before and after tuning.

Conclusions

- L_1, L_2, and M increased with the pavement thickness and the power loss caused by material type was: AC-13>PCC>SMA-13.
- The loss of power and efficiency can be compensated by adjusting the frequency of the high-frequency voltage supply. The formula for tuning the resonant frequency of the power supply and for calculating the power and efficiency after tuning were given.
- After tuning, the corresponding output power of different kinds of pavement materials from high to low was: AC-13 > PCC > SMA-13. The efficiency of the system before and after tuning was more than 90%, which met the requirements of the specification.
- The tuning model proposed is effective.

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