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Iron-based particles for the magnetically-triggered crack healing of bituminous materials

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HIGHLIGHTS

- Iron-based particles can be used as local heat sources for effective crack healing.
- For iron metallic particles, heating reaches a maximum at a critical particle size.
- For iron oxide particles, heating is caused by the reorientation of magnetic dipoles.
- Particle sizes smaller than 1 mm prevent the formation of high temperature gradients.

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ABSTRACT

Bituminous road pavements may suffer from cracking over the years due to repeated stresses. In this study, we compare the effect of different sizes and chemical compositions of magnetically-responsive iron-based particles used as additives to heat up road pavements and thus to close cracks. By applying an alternating magnetic field (AMF), we found that there is an optimal size depending on the particle electrical conductivity at which the temperature on the surface of asphalt samples is the highest. Even when particles are well-distributed after mixing, we found that asphalt samples containing larger particles display inhomogeneous heating during the exposure to the AMF. The mechanical recovery of samples during a double torsion test before and after the exposure to the AMF confirmed the healing capability of asphalt materials containing iron-based particles. Based on these results we provide guidelines for the design of magnetically-responsive asphalts for road pavements of enhanced durability.

1. Introduction

Cracks in road pavements are the consequence of long-time exposure to repeated traffic loads and environmental conditions such as water, temperature changes or UV light from the sun that may affect directly on the pavement surface. They can also arise from irregular compaction during their manufacturing. Ultimately, road pavements need to be replaced, a costly and energy intensive procedure. For instance, Switzerland invested 1.6 billion of Swiss Francs in road maintenance only in 2015 [1]. Additionally, millions of tons of CO_2 emissions were generated from road replacement works [2]. Therefore, solutions that could repair cracks before they compromise the mechanical integrity of asphalts would extend the lifetime of the roads significantly.

Road pavements in Europe are in 90% of the cases made of bituminous materials, particularly asphalt [3]. Asphalt consists of a glue, called mastic and made of a bituminous binder and stone filler (<0.063 mm) that holds together the structurally-active large mineral aggregates (>0.063 mm) giving the stiffness to the material. The bituminous binder, usually bitumen from crude oil distillation, is a mixture of long chain hydrocarbons with varying molecular weight [4] and exhibits the main characteristics of a thermoplastic polymer such as a glass transition temperature and a melting temperature.

Existing practical techniques for repairing road pavements usually focus on the cracks that are visible on the road surface. These surface defects represent the final stage of road damaging. When the cracks become as large as few millimetres in width, road workers usually clean the cracks with high-pressure hot air, fill them up

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with a hot sealing compound and finally sprinkle fine sand to temporarily solve the problem. Nevertheless, the cracks will quickly come back as this approach does not repair the numerous microcracks, invisible on the surface with the naked eye and possibly also located much deeper within the pavement. These microcracks generally initiate within the mastic (cohesive cracking) or at the interface between the binder and the mineral aggregate like sand or gravels (adhesive cracking). If not repaired, they will eventually propagate again, merge with neighbouring microcracks and form large cracks. Asphalt can heal the microcracks by itself when exposed to heat [5]. In this case, healing is understood as the partial or total recovery of the mechanical properties of the material.

Studies showed that during melting of the binder, capillary flow could fill up the microcracks, eventually extending the lifetime of the material [6]. These results opened the doors to many investigations with the common goal of locally and momentarily decreasing the viscosity of the binder to enable flow for re-filling the microcracks.

One approach for inducing binder flow consists of releasing active chemicals from microcapsules previously incorporated into the bitumen, as first shown in polymer composites [7–10]. By encapsulating organic oil extenders or rejuvenating agents, numerous studies showed that microcracks could be closed in-depth upon capsule breaking. Upon release, the oil solubilizes bitumen resulting in the decrease of the binder viscosity. However, this technique is difficult to implement at a larger-scale for multiple reasons. Encapsulating techniques can be used only once, since the content is irreversibly and fully released as soon as the capsule is broken. In addition, the active material that is released by the capsules is not the same as the original binder. Due to the lower viscosity of the released chemical, the healed material is typically softer than the original bitumen. Finally, it is very challenging to design capsules that endure the harsh conditions during the mixing of asphalt but at the same time remain still weak enough to rupture as a crack propagates during use of the material.

The other method to reduce locally and momentarily on demand the viscosity of the binder is through heating. Magnetic fields achieve that purpose remotely, rapidly and in-depth, and thus represent a promising alternative [6,11–15]. The principle consists in exposing the damaged bituminous material containing pre-embedded magnetic-sensitive additives to alternating magnetic fields [16]. Steel wool fibres were used in some studies and alternating magnetic fields with frequencies in the range from kHz to MHz were applied. However, clusters of fibres may be formed during the mixing process [17]. The inhomogeneity in the fibres spatial distribution can be a major issue during heating, as local temperature gradients around the fibre clusters could damage the surrounding binder.

In contrast, particulate-shaped additives could potentially circumvent this problem and offer a more effective alternative for uniform magnetic heating. Particles exhibiting shape and size close to the mineral aggregates and sand are expected to be homogeneously distributed in the material after mixing, while offering the same magnetically-assisted heating mechanism enabled by fibres. Although the adhesion between particles and bitumen has not been evaluated in this study, we expect the naturally occurring oxide layer on the surface of the metallic particles to improve its bonding to the bituminous phase.

With the overall goal to design more durable road pavements, we exploit the thermal response of commercially available iron-based particles pre-embedded in asphalt to activate crack healing using an external magnetic field. The working principle of the proposed magnetically-assisted crack healing mechanism at large-scale is outlined in Fig. 1. A large pancake-like coil fixed on a truck

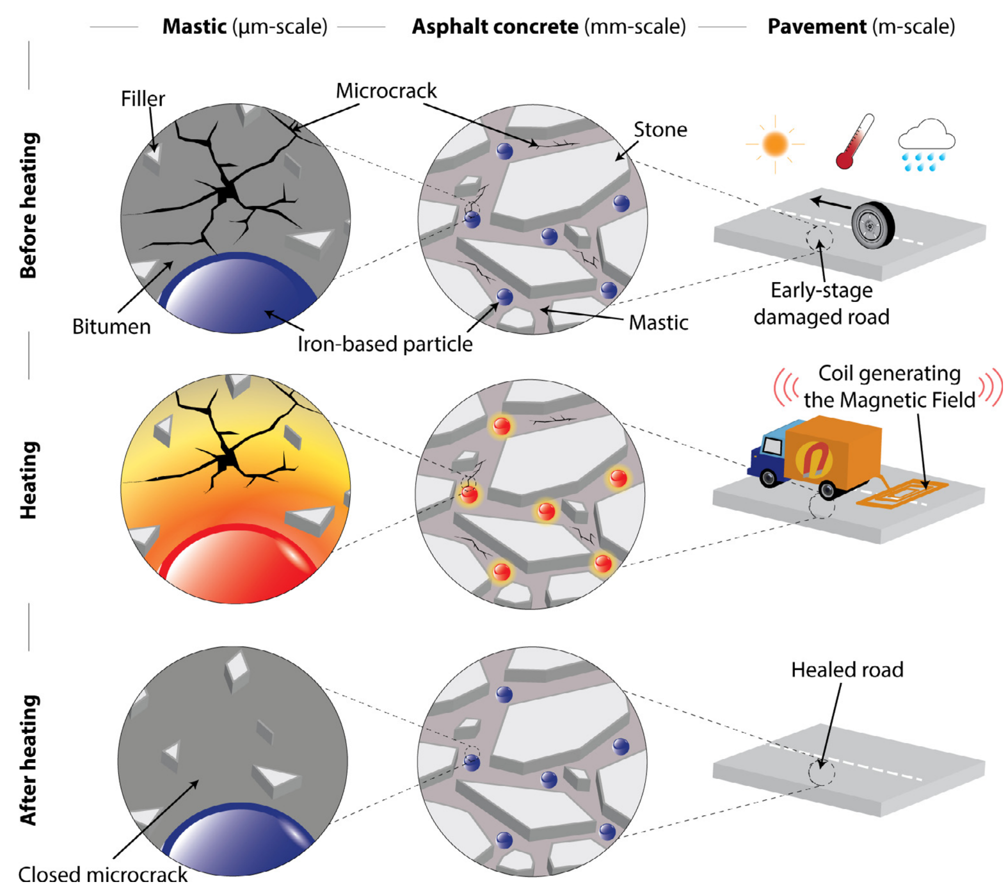

Fig. 1. Schematics illustrating the proposed crack healing method for bituminous materials using pre-embedded iron-based particles.