Construction and Building Materials 171 (2018) 577–587

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mining materials to generate magnetically-triggered induction healing of bitumen on smart road pavements

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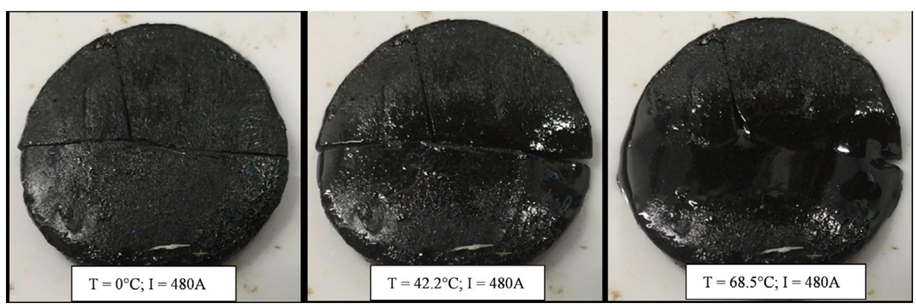
HIGHLIGHTS

- Magnetite powder can be added to asphalt mixes as filler replacement.
- Microstructure and thermal characteristics of magnetite-bitumen were investigated.
- Induction heating of magnetite-bitumen composite mastic was evaluated.
- Up to 50 °C per second induction heating rate was achieved.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 November 2017
Received in revised form 20 March 2018
Accepted 21 March 2018

Keywords:
Bitumen
Magnetite
Mining material
Healing
Induction heating
Asphalt

ABSTRACT

Around the globe, maintenance costs to repair asphalt roads during their service life often exceed the available budget of road authorities and municipalities. In this research, a novel approach is presented to generate engineered healing capabilities in iron ore particles (magnetite)-bitumen composites through induction heating. This approach is expected to contribute in decreasing the amount of maintenance needs on road pavements.

A comprehensive experimental campaign was conducted to evaluate the possible use of mining material as healing promoter for road pavement systems, reducing maintenance needs during the road service life hence saving agency and user costs. Two different types of magnetite were mixed with bitumen according to three different filler/bitumen ratios. Rheology of bitumen was firstly evaluated to characterise its viscoelastic response at different temperature, then induction heating principles were applied to generate an alternative magnetic field to rapidly heat bitumen-magnetite samples, melt the surrounding bitumen and heal the crack. Experimental measurements also included optical, calorimetric and chemical evaluation of the samples.

Results showed that the temperature of the composite samples increased under the alternative magnetic field, reaching high temperature values in a very small amount of time. The heating rate (up to 50 °C/s) depended on the intensity of the electric current in the induction heating machine and on filler/bitumen ratio, among others.

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https://doi.org/10.1016/j.conbuildmat.2018.03.160
0950-0618/

1. Introduction

Road pavement materials, during the service life, are exposed to traffic loads, atmospheric agents and bitumen aging phenomena, which lead to pavement cracking. The initial formation of micro cracks rapidly grows and propagates causing irreversible damage that could possibly evolve and generate potholes and other distresses; maintenance is thus required to tackle cracking at its initial stage and increase safety for road users. In order to extend the service life of pavements and avoid excessive use of raw materials for maintenance and reconstruction activities, cracks have to be controlled and fixed as soon as they appear. In previous research studies [1,2,3], embedded capsules were studied to promote self-healing of road asphalt materials; a common drawback is that the process is not repeatable and once the capsules are broken and the rejuvenator agent (mostly oil based) has flown out, the healing effect quickly finishes. Similarly, capsules could be broken during mixing and paving operations and can soften the mix at early age.

Bitumen is a self-healing material [4] and is able to self-repair the cracks during periods of time at high temperatures (from 30 °C to 70 °C, depending on the type of binder) and with limited traffic loads [5]. This property could be used to enhance healing phenomena in bituminous mixtures. At temperatures between 30 and 70 °C [6] the binder reduces its viscosity, starts flowing, and fills up the cracks.

Many studies [7,8,9]; were carried out to fix the micro-cracks by reducing the viscosity of bitumen through externally-triggered induction heating methods. To exploit this methodology, electrically conductive susceptible particles were added to the bitumen [10]. When an alternative magnetic field is applied to the bitumen containing ferrous embedded particles, eddy currents are generated in the sample and the material is heated through Joule effect [11]. Many studies demonstrated how the electrical conductivity of the asphalt is proportional to the ferrous fibres/filler content [12,13]. Garcia et al. [10] showed the existence of the optimum content of conductive steel fibres that leads to the maximum value of conductivity; above a specific percolation threshold, adding more fibres did not increase the conductivity significantly.

Other tests were carried out using conductive fillers; Shaopeng et al. [14] found that adding 12.7% of graphite powder as a filler into the bitumen matrix decreased the resistivity of bitumen-based composites from 10^{12} Ωm to 10^{3} Ωm. However, better results were obtained by mixing a small amount of carbon fibres with graphite; fibres provided in fact a bridging effect between conductive clusters of filler and form continuous conductive path through the material.

However, an excess of fibre could form clusters which lead to a localized overheating of bitumen and cause bitumen aging [15]. Adding more graphite increased the induction heating potential but reduced the rheological properties of the bitumen.

Vast deposits of magnetite are located in Australia, New Zealand, North Europe and America. In particular, Australian magnetite is primarily used for iron and steel production purposes; however, research is trying to replace steel based materials with plastics, composites and other light weight products. Hence finding suitable avenue for magnetite use is one of the possible strategies to keep using an abundant natural resource and reduce landfill. Magnetite is widely extracted also in India and China where the magnetite tailings are accumulated and stockpiled in huge tailing ponds, which required great land occupation. Furthermore, the tailing ponds could cause pollution, which leads to health risks and environmental danger [16]. Magnetite is widely used as iron ore due to its high iron content and also employed in coal washing processes [17]. Wang et al. [18] added magnetite aggregates in the mix design to heat up the asphalt mixture using microwaves and potentially de-icing road pavements. In addition, magnetite has excellent mechanical properties such as high compressive strength and low wear value [19].

Iron oxide particles have also been widely studied in medical research as a possible treatment to heal cancer [20] due to its excellent magnetic properties [21,22]. The ferromagnetic particles are able to generate a localized heat (hyperthermia) in presence of an alternative magnetic field [23]. This phenomenon has also been used to produce a localised heat in synthetic materials [24]. Magnetic nanoparticles were embedded into stimuli-responsive polymer for repairing purposes [25].

Magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) nanoparticles were added to the bitumen as healing-promoter additives [26]. Due to their size (<100 nm) these nanoparticles have high specific surface area and are able to increase the temperature in the bitumen if well dispersed. The results showed a linear relationship between the application time of the alternative magnetic field applied to the sample, and the surface temperature of the sample. In the same study this technique was successfully applied to repair micro-cracks by melting the bitumen surrounding the crack. Downsides however included the handling of nanoparticles, which needed to be pre-treated with oleic acid, sealed and sonicated in ultrasonic bath to avoid clustering; the long pre-treatment of nanoparticles (more than 24 h) could possibly limit the use of this technology at larger scale.

The present research uses small amounts of magnetite powder, directly coming from mining operations with no additional preliminary treatment, as trigger material for engineered induction heating of magnetite-bitumen composites. Due to the use of magnetite powder in its current form, this research overcomes common disadvantages of nanoparticles processing and handling operations in the asphalt plant. In addition, a common drawback of induction heating in pavement mixes is related to the slow heating rate; magnetite fillers in the studied form can greatly enhance the induction heating rate of bituminous mastics up to 50 °C per second on 1-mm thick samples. This value could even be improved if reduced thickness and/or greater electrical power are used, thus showing promising results on asphalt samples too.

2. Materials and experimental plan

This research study aimed to use magnetite from mining operations as filler material (size below 75 μm and one of the commonly used aggregate gradations in road construction practices) to trigger healing capabilities of bitumen in the presence of electric currents. The bituminous mastic (i.e. filler plus bitumen) was obtained by mixing bitumen and magnetite at different proportions. Morphological, optical, rheological, chemical and mechanical analyses were conducted on small cylindrical samples (25 mm in diameter).

The experimental plan is shown in Fig. 1.

Two types of magnetite were used as filler material according to AASHTO standard M17 [27] (Table 1); magnetite was mixed with two different types of bitumen – C170 and C320 – classified in accordance with AS2008 [28] (Table 2).

2.1. Bitumen

Bitumen rheology was firstly tested using frequency sweep tests [29] with a dynamic shear rheometer (DSR TA HR3) in strain-controlled mode. Six different temperatures (5, 20, 35, 50, 65, 80 °C) were analysed. During each test, the frequency was increased from 0.1 Hz to 30 Hz. Results obtained from the tests are isothermal curves of the complex shear modulus and phase angle. Master curves were constructed at reference temperature of 20 °C applying the time-temperature superposition principle (Fig. 2). Christensen and Anderson model [30] was used in the analysis with the shift factor being calculated from Arrhenius equation [31].

C170 and C320 are both standard types of bitumen in Australia with C320 being adopted on higher traffic volume roads than C170. As expected, master curves at T_{ref} = 20 °C showed greater stiffness for C320 bitumen over the entire frequency domain and lower phase angle at different testing temperatures compared to C170 bitumen.