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Advanced evaluation of asphalt mortar for induction healing purposes

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HIGHLIGHTS

- Application of advanced tools enables the implementation of induction technology for healing in asphalt mixes.
- Induction heating and healing potential of asphalt mortar using different inductive particles types is studied.
- An optimization framework for the design of induction healed asphalt mortars is proposed.
- The increase of inductive particles contributes to the electro-thermo-mechanical performance improvement and the healing potential of asphalt mixes.

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ABSTRACT

Induction heating technique is an innovative asphalt pavement maintenance method that is applied to inductive asphalt concrete mixes in order to prevent the formation of macro-cracks by increasing locally the temperature of asphalt. The development of asphalt mixes with improved electrical and thermal properties is crucial in terms of producing induction healed mixes. This paper studies the induction healing capacity of asphalt mixes without aggregates as the part of asphalt concrete where inductive particles are dispersed notably contributing to the final response of asphalt pavements. Special attention was given to the characterization of inductive asphalt mixes using experimental techniques and numerical methods. The research reported in this paper is divided into two parts. In the first part, the impact of iron powder as filler-sized inductive particle on the rheological performance of asphalt-filler systems was studied. The mechanical response, the induction heating and healing capacity of asphalt mortar by adding iron powder and steel fibers was evaluated as well. In the second part, the utilization of advanced finite-element analyses for the assessment of the induction heating potential of inductive asphalt mortar with steel fibers are presented. The influential factors of induction mechanism in asphalt mixes are also described. The experimental and numerical findings of this research provided an optimization method for the design of induction healed asphalt concrete mixes and the development of necessary equipment that will enable the implementation of induction technology for healing of asphalt concrete mixes.

1. Introduction

Asphalt concrete mixes are the most common types of pavement surface materials applied in transportation infrastructure and consist of asphalt binder, aggregate particles and air voids. These mixes are temperature-dependent materials with a self-healing capability because they can restore stiffness and strength [1–5]. Nowadays, it is known that asphalt concrete mixes should be considered as mixes of mortar-coated aggregates rather than binder-coated aggregates in terms of developing asphalt pavements with enhanced durability. In 2014, the European asphalt industry (EU27) produced about 280 million tonnes of asphalt and invested about €80 billion per year in pavement construction resulting increased energy consumption and CO_2 emissions during various asphalt production, construction and maintenance processes [6]. The importance of reducing CO_2 emissions by developing new, last longer asphalt mixes and to enhance road safety by providing high quality road network is crucial for fulfilling the European objective for sustainable development. Within this framework, the necessity of solving construction and rehabilitation issues of pavement structures has led industry to focus on development of alternative novel state-of-the-art techniques. Regarding asphalt pavement maintenance, among others [7,8] healing of asphalt micro-cracks using the induction technique has been approved as a very promising method to prolong the service life of asphalt pavements [9–13].

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The induction heating technique has been used as a maintenance technique for asphalt pavements in order to speed up the healing process of asphalt. Field trials are available and a very exciting example is the Dutch motorway A58 near Vlissingen [14]. This technique requires new mixes with inductive particles in order to make them suitable for induction heating. Specifically, when an alternating electric current is applied to an induction coil, a time-variable magnetic field is generated around the coil. According to Faraday's law, this magnetic field induces currents (eddy currents) in inductive particles within the mix and they are heated up based on the principles of Joule's law. The generated heat in particles increases locally the temperature of asphalt mix around the stone aggregates, rather than heating them. Through the temperature rise the bitumen is melting the micro-cracks are closed and the mechanical properties are recovered [4]. This mechanism of healing asphalt mixes with the assistance of electro-magnetic induction is known as induction healing.

Previous research indicated that asphalt mixes with inductive particles, such as steel fibers, can be heated in a very short time by using the induction technology [9–17]. However, the distribution of steel fibers within mixes appears to have a direct relation with the volumetric and mechanical properties of asphalt mixes [18–21]. Also, it was observed that the characteristics of steel fibers – diameter and length – are affected by the mixing and compaction processes [16]. Especially, the longer steel fibers easily produce clusters inside the asphalt mixes, causing inhomogeneity and reducing the mechanical response [15,16]. Apart from the performance degradation, the large amounts of fiber-type particles cause a significant increase of costs [28]. For this reason and in order to resolve the problems resulted by the fiber-type particles, inductive asphalt concrete mixes can be produced by adding other types of inductive components.

In particular, the effective properties of asphalt mixes vary considerably according to the type and the characteristics of inductive particles. Higher electrical or thermal conductivity of particles results in higher effective conductivities of the asphalt concrete mixes. These particles are normally divided into categories according to their size and shape as: filler-sized (e.g., graphite, carbon black) [11,32–36], stone-sized (e.g., steel slag) [31] and fiber particles (e.g., steel and carbon fibers) [11,36,37]. Among all the fillers used in inductive asphalt mixes, carbon black and graphite powder are the most often investigated because of their excellent associated compatibility with asphalt binder imparting in parallel easy mixing. However, no extended research has focused on other types of filler-sized inductive particles and for this reason is presumed very important to develop inductive mixes with well dispersed inductive components to provide sufficient isotropic material properties to mixes for induction applications.

Additionally, more data is still required to clarify the role and the significance of the various parameters on the asphalt induction heating phenomenon. Induction heating is a complex phenomenon that combines the electromagnetic and heat transfer theory and has a strong relationship with the electro-thermal properties of materials [22–24]. Furthermore, it is known that the efficiency of the induction heating depends on the coupling between the size of the inductive particles and the operational characteristics of the induction coil (frequency, power, shape of the induction coil, etc.). Thus, the experimental and the numerical analysis of electro-thermo-mechanical properties of asphalt mixes is becoming very important in terms of determining the most crucial material parameters for obtaining enhanced durability simultaneously with high induction heating rate.

This paper is divided into two investigation approaches; the experimental and the numerical. Since asphalt mortar is the crucial part of asphalt concrete that suffers more damage and contains the particles for induction heating, an experimental approach was developed for the sufficient characterization of structural and non-structural performance of induction heated mortars. The current numerical study provides us this efficient tool to conduct analysis of induction heating predicting in parallel the heating time needed in order to heal micro-cracks inside the asphalt mixes.

2. Experimental approach

During the induction heating, the asphaltic part around the stone aggregates with the inductive particles is heated locally resulting durability improvement of the bonding characteristics between asphalt constituents. In this study focus was given on conducting in-depth analyses of the interaction between the inductive particles with the other asphalt constituents. Also the evaluation of structural and non-structural performance of asphalt mastics (binder and filler-sized particles) and mortars (binder, filler-sized particles and sand) was ascertained crucial.

Iron powder was selected as filler-sized particle and its interaction with the other components was studied on asphalt mastic level. For a certain asphalt binder, asphalt mastics with different volumetric properties were developed and characterized following an experimental protocol designed for this purpose. It is well recognized that the performance of asphalt mastic is associated with reinforcement of filler-sized particles in asphalt mastic [38–40]. The particle size of filler, the loading time, temperature and the interaction of fillers within the binder matrix are the most influential factors for the stiffening of mastics. Rheological and micro-morphological analyses were carried out quantifying thus the stiffening potential of iron powder with different contents. The electro-thermal properties were assessed within an effort to obtain the optimal combination of fillers in this study.

After the completion of mastic characterization, sand and steel fibers were added in asphalt-filler systems in order to prepare the inductive asphalt mortars. The effect of different volumes of fibers and powder on the electrical conductivity of mortar was evaluated by using the same experimental technique with the mastic level of analysis. Once the optimal inductive particles combination was obtained, the thermal conductivity of inductive asphalt mortars was studied. Due to the fact that the improved macroscopic response of asphalt pavements has a direct link with the durability of asphalt mixes, the mechanical performance of asphalt mortars were investigated as well. Although the reinforcing impact of steel fibers on mechanical properties of asphalt mixes has been studied extensively, still limited research was done to evaluate the performance of asphalt mortars with different inductive particles. At the end of the experimental analysis of this paper, the induction heating and healing capacity of inductive asphalt mortars were examined.

2.1. Material and preparation

Firstly, the selected mineral fillers and the iron powder as filler-sized inductive particle were analyzed. A scanning electron microscope (SEM), BET (Brunuer, Emmett and Teller theory) and a Ultrapycnometer have been utilized in order to determine shape, specific surface area and density, respectively. Fig. 1 shows the SEM images of the filler-sized particles; weak limestone (WL) filler, produced limestone (PL) filler and iron powder (IP). It can be seen that the angular shape and the size of filler limestone – WL and PL – is similar compared with iron powder (IP) where it has slightly smaller size and smoother surface texture than the minerals.

In order to investigate the impact of iron powder as filler-sized particle within the asphalt mastic, two asphalt-filler preparation processes were used. The first one was by adding iron powder with replacing an equivalent volumetric amount of mineral fillers and