Materials and Design 84 (2015) 100–109

Contents lists available at ScienceDirect

Materials and Design

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

Development of mechanomutable asphalt binders for the construction of smart pavements

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ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form 19 March 2015
Accepted 16 June 2015
Available online 25 June 2015

Keywords:
Bitumen
Asphalt
Smart
Pavement
Mechanomutable binder
Magnetic particles

ABSTRACT

A new generation of asphalt binders with mecanomutable properties has been developed, with the aim of obtaining smart materials able to adapt their mechanical performance to the real changing load conditions that occur during their service life. These materials are composed of a bituminous matrix that has been modified with magnetic particles that are able to change the mechanical behavior of the binder when they are activated by a magnetic field. This study examines the main variables that govern the mechanical behavior of these materials. The mechanomutable performance of different binders has been demonstrated under various concentrations of magnetic particles. In particular, these binders could increase their stiffness and perform elastically when they are activated by a magnetic field (even at high temperatures), which, once removed, enables the initial properties of the binders to be recovered. The changes induced in the properties of the binder depend on the amount of magnetic particles, the intensity of the magnetic field, and the type of bituminous matrix. The findings open up the possibility of a wide field of applications for its implementation in smart infrastructures, with special interest in the construction, rehabilitation, and maintenance of asphalt pavements.

1. Introduction

Recent years have seen the development of a significant body of research aimed at obtaining smart materials for their use in civil engineering. Given that many structures are exposed to different types of load and climatic conditions that can change during their service life, it is of particular importance to use smart materials that can change their properties to provide the best possible response to each situation.

Road networks represent one particular area of concern, given their central importance in the development of societies across the world. In particular, it is necessary that roads are maintained to an adequate standard in order to ensure quality of service. Thus, a research field of particular interest is one that is aimed at developing new materials adaptable to different traffic loads and weather conditions, thereby extending the road service life while providing a safer wearing surface.

Asphalt pavements consist mainly of a mineral skeleton composed of aggregates, which are agglomerated by a bituminous binder. Because of the importance of the binder in the mechanical behavior of these infrastructures, modified bitumens are being developed to provide pavements that are sufficiently rigid at high temperatures to reduce the appearance of plastic deformations, and flexible enough at low temperatures to avoid the formation of cracks [1]. The modifiers used to improve the mechanical behavior of these binders are polymers such as thermoplastics, elastomers, and elastomer thermoplastics [2–4], which reduce their thermal susceptibility and increase their elastic recovery. Nevertheless, in spite of the fact that these bitumens can improve the performance of asphalt pavements, it is still necessary to develop new binders that can withstand severe climates (which combine low and high temperature periods) and traffic conditions (high loads combined with slow speeds).

In relation to this issue, it is also worth noting that recent years have seen an increase in the demands placed on roads and highways. The appearance of smart materials, which are capable of reducing the consumption of natural resources and pollutant emissions while increasing the energy efficiency or interaction with the user to provide valuable information, have changed the conception of these infrastructures. Consequently, recent research in pavement engineering has focused on the development of new asphalt materials that are able to self-heal [5,6], and are less contaminant and more efficient [7–9]. In this respect, new systems are being developed which can transform energy from the pavements into electricity [10–12], offer information about the state of the road [13] or guide the vehicle [14,15].

Accordingly, this research focuses on the development of smart bituminous materials, or mechanomutable binders, that can be applied in asphalt pavements. These binders are able to adapt their mechanical response according to the particular stresses to which they are exposed. Under high loads and temperatures, they should behave in a more rigid manner (reducing the appearance of plastic deformations and

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http://dx.doi.org/10.1016/j.matdes.2015.06.098
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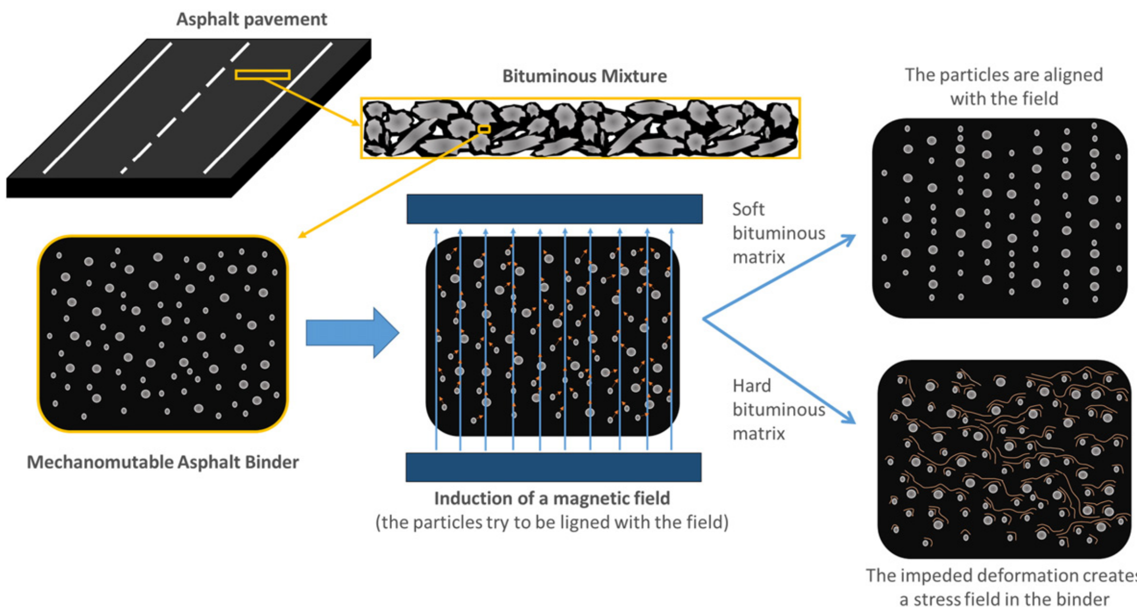

Fig. 1. Sketch of the phenomena appearing in the mechanomutable binders when activated by a magnetic field.

the effects caused by the stresses transmitted by the traffic). At low temperatures, or in the absence of loads, they should perform more flexibly (dissipating the stresses caused by thermal shrinkage or adapting its shape without cracking under the presence of possible settlements of the soil foundation).

These binders are composed of a bituminous matrix that has been modified with magnetic particles that are homogeneously dispersed on it. These particles are activated when a magnetic field is near to them, and they try to move inside the bituminous matrix (each particle attempting to be aligned with the magnetic field). However, as the bituminous matrix restricts their movement, an impeded deformation appears in the proximity of each particle, thereby inducing a stress in the binder. As the particles are homogeneously dispersed in all of the binder, these impeded deformations cause a stress field in the binder matrix that can increase its stiffness. When the magnetic field is removed, the mechanomutable binder relaxes the stresses and its initial rheological properties are restored.

The use of magnetizable particles is commonplace in various technological developments, such as magnetorheological (MR) fluids. In these materials, the application of a magnetic field produces an increase in the apparent viscosity of the suspension [16,17], and a modification of their rheological behavior from Newtonian to viscoelastic, with a yield stress or elastic modulus up to 100 kPa [18]. These changes occur in a few ms and are removed reversibly when the magnetic field is switched off [19, 20]. This rheological ability to control the structure is due to well-defined particle chain structures formed by the alignment of the magnetic movements of the particles in the direction of the field [21]. The strength of the magnetorheological effect is directly related to the amount, size distribution, shape, density, and intensity of the magnetic field applied [21–23]. The dispersed phase can be either a ferri or ferromagnetic material, including iron, magnetite, or other ferrites [24–26] typically in the micrometer size range [27]. The carrier usually takes the form of different kinds of oils (silicone oils), but the non-magnetic characteristic of the carrier determines to a large extent the nature of the MR material, the most representative examples being fluids, though MR gels, MR foams, and MR elastomers can also be used [28]. Since their discovery in the 1940's [29,30], the application of MR materials has forged its way into several branches of technological development, including industrial areas such as aerospace [31], biomedical prostheses [32], drug vehicle design [33], and mechanical engineering with shock absorbers and seismic insulators [34–36]. In the particular field of architecture [37], the creation of light and resistant materials that provide damping is a continuous need. There are currently a number of structural control systems based on the integration of MR materials confined in dampers [24].

The binders developed in this study are based on similar concepts, but in this case a bituminous matrix that impedes the movement of the particles is used, generating a stress field in the material that modifies its rheological properties (increasing modulus and decreasing the phase angle) (Fig. 1). Nevertheless, if the bituminous matrix is soft enough (composed of a high penetration bitumen), the intensity of magnetic field is high enough, or the temperature is elevated, the

Table 1
Properties of the bituminous matrix tested.

Type of bituminous matrix	B 20/30	B 50/70	B 70/85
Penetration at 25 °C (mm, EN 1426 [38])	22	65	81
Softening point (°C, EN 1427 [39])	64.8	51.8	46.4
Fraass fragility (°C, EN 12593 [40])	−1	−8	−10
Flash point (°C, ISO 2592 [41])	>245	>230	>230

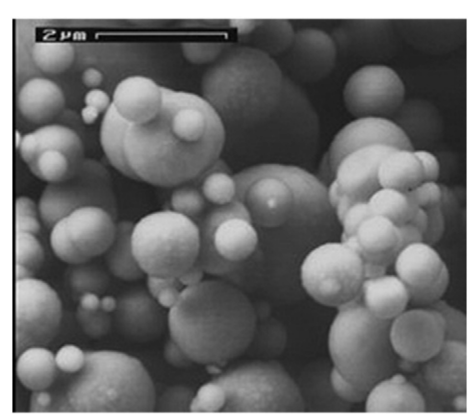

Fig. 2. Scanning electron microscopy pictures of iron particles used in the manufacture of the mechanomutable binders. Bar lengths: 2 μm.