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Influence of rheological and physical bitumen properties on heat-induced self-healing of asphalt mastic beams

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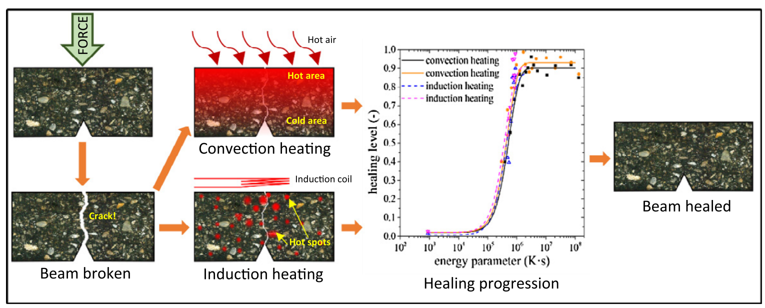
HIGHLIGHTS

- The minimal healing temperature for mastic beams is between 8 °C and 20 °C.
- Induction heating is significantly faster compared to convection heating.
- Localised high temperatures during induction heating cause thermal degradation.
- The standard bitumen type can be exchanged without affecting healing performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Asphaltic materials have self-healing properties due to the capacity of bitumen, a viscoelastic liquid with a temperature- and time-dependent viscosity, to flow and/or drain into cracks. Different types of bitumen have different adhesive and rheological properties depending on the refining process, chemical composition, and origin of the bitumen. In addition, other factors that affect the self-healing capacity are the resting period between traffic loads, filler content and ambient temperatures. To further investigate the influencing factors for asphalt self-healing for macro cracks, the authors have selected five types of bitumen, which are commonly used in road constructions, from different sources. The self-healing was assessed by manufacturing asphalt mastic beams and breaking these beams. Healing was induced by either convection or induction heating. The rheological and compositional properties of bitumen were correlated to the healing characteristics of the beams tested. Interestingly, the physical, rheological and chemical properties of bitumen did not influence healing properties, as the thermal expansion coefficient, surface energy and density of the bitumen used were similar. Hence, healing became similar as the influence of viscosity became minor compared to other driving forces.

1. Introduction

Asphalt mixture is the most commonly used road material in the world [1]. It consists of mineral aggregates with size ranging from a few microns to 2–3 cm, and bitumen, which is an adhesive viscoelastic liquid with temperature-dependent viscosity [2]. Bitumen is obtained from the refining process of petroleum and its properties vary depending on its source, refining and post-treatment processes. To produce asphalt mixture, aggregates and bitumen are mixed at approximately 180 °C until the aggregates are properly coated. Afterwards, the mixture is mechanically compacted to reach maximum packing of the aggregates at approximately 140 °C. As a consequence of the compaction process and aggregate gradation, air voids may remain in the compacted mixture, which may affect the durability of the road [2]. In addition,

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asphalt mixture is a self-healing material. When a crack appears, bitumen can drain into and fill it, restoring mechanical properties [3].

Damage in asphalt roads, that may appear as cracks and corrugations like rutting, potholes, bleeding and ravelling, is caused by the progressive oxidation of bitumen, traffic loads and environmental temperature changes [2]. Self-healing of permanent deformations, such as rutting, loss of aggregates or granular base defects, is not possible and this therefore limits asphalt self-healing to certain types of cracks. The closure of cracks is driven by the capillary flow of bitumen that is caused by surface energy [3] and gravity [4]. Therefore, the main factors affecting the flow of bitumen are the location of cracks within the pavement, temperature, pressure, and the resting period between successive loads [5]. Furthermore, the mineral type of filler, bitumen content, and additives that affect the flow behaviour of bitumen may have a substantial impact on the self-healing properties of asphalt mixtures [6].

It has previously been reported that temperature is the most influential factor in asphalt self-healing [7]. The reason is that the viscosity of bitumen reduces at higher temperatures and self-healing happens only above a certain temperature threshold [3]. The threshold temperature has been previously correlated with the glass transition temperature of bitumen [8] and with the transition from non-Newtonian to Newtonian flow behaviour [9].

Moreover, it is widely acknowledged that the fractional and chemical composition of bitumen influences its rheological behaviour [10]. Ageing causes changes in the fractional distribution of bitumen that are associated with an increase in compounds with higher molecular weight, such as resins and asphaltenes. Due to these changes, the viscosity of bitumen increases [10] and its self-healing capacity reduces [11]. A further relation between the chemical composition and self-healing is based on the methylene to methyl ratio or aliphatic chain length [12], which enhances the healing potential by reducing the viscosity of bitumen at constant temperature [13].

To trigger and enhance the self-healing of asphalt, the viscosity of bitumen has to be reduced [14]. For this purpose, electrically conductive particles [15] or capsules containing rejuvenators [16], i.e. bitumen solvents, can be incorporated into asphalt mixture. Commonly used electrically conductive materials are steel wool or steel grit that can be heated using induction energy [15]. On the other hand, capsules containing bitumen solvents in the asphalt mixture can release their content when damage reaches a critical level [17].

In previous studies, only a small number of bitumen properties affecting healing were investigated. Hence, this study correlates several chemical, rheological and physical properties of different types of bitumen to the healing capacity of asphalt mastic beams manufactured from these types of bitumen. Five different types of bitumen, of various sources and pen grades (though within the range of bitumen commonly used in road applications), were used. Properties investigated include Fourier Transformed Infrared Spectroscopy (FTIR), saturates, aromatics, resins and asphaltenes (SARA) analysis, and wax content as chemical properties. The rheological properties studied were viscosity, viscoelasticity, and flow behaviour index. Further, the thermal expansion of bitumen was included as a physical property besides density and surface energy.

2. Materials and testing methods

2.1. Materials

In this study, five different types of bitumen, namely A49, B46, C70, D44 and E73 (the number represents the penetration depth measured), were used. The bitumen types studied are commonly used for road constructions in Israel and the Netherlands and have been obtained from three different suppliers to these countries. Table 1 provides an overview of the bitumen properties measured.

A mastic mixture was produced by using a continuous dense gradation of sand with a maximum particle size of 4 mm and a density of 2363 kg·m^{-3}, steel grit of uniform gradation size between 0.5 mm and 2 mm and a density of 7520 kg·m^{-3} (to allow heating by electromagnetic induction), and bitumen. The content of the mixture was 74 wt% sand, 11 wt% steel grit, and 15 wt% bitumen.

Mixing and compaction with a spatula of bitumen and aggregates were carried manually out at 180 °C, to produce beams with dimensions of 3 × 3 × 10 cm^3 (Fig. 1). The manufacturing moulds had a triangular notch at the midpoint of the cast (running parallel

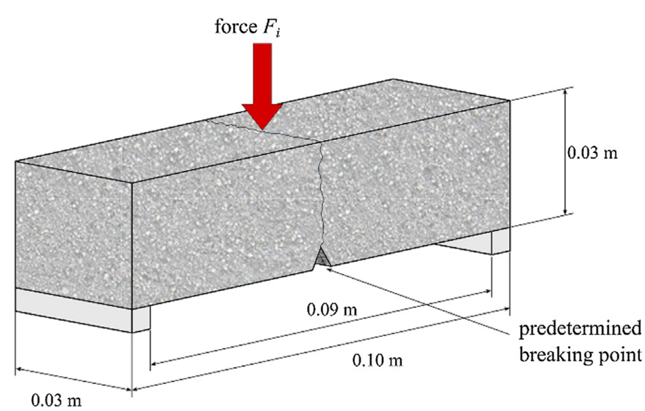

Fig. 1. Mastic beam dimensions and 3-point breaking test set up. The point force was vertically aligned with the predetermined breaking point in the middle of the underside of the mastic beam.

Table 1
Bitumen properties.

	Bitumen type				
	A49	B46	C70	D44	E73
Surface energy [mJ·m^{-2}]	25.5	24.5	24.7	23.2	24.5
Density at 25 °C [kg·m^{-3}]	1025	1034	1020	1026	1020
Volumetric thermal expansion coefficient [10^{-4} K^{-1}]	6.12	6.64	6.69	6.14	6.30
Viscosity at 100 °C [Pa s]	3.93	2.87	2.00	3.90	2.36
Newtonian transition temperature [°C]	45	44	37	39	31
Saturate content [%]	4.9 ± 02	4.7 ± 0.2	5.3 ± 0.2	4.9 ± 0.2	4.1 ± 0.2
Aromatic content [%]	41.8 ± 1.4	43.2 ± 1.5	43.3 ± 1.8	43.3 1.8	51.1 ± 2.1
Resin content [%]	35.6 ± 1.3	35.9 ± 1.3	37.7 ± 2.0	36.1 ± 1.5	33.1 1.6
Asphaltene content [%]	15.8 ± 0.4	15.8 ± 0.6	13.7 ± 0.3	15.5 ± 0.6	11.0 ± 0.4
Wax content [%]	0.5	1.7	3.6	2.2	0.9
MMHC [–]	2.203	2.214	2.197	2.203	2.203