Factors Affecting the Reachable Healing Level of Induced Self-Healing of Mastic Beams

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ABSTRACT

Asphalt is known to recover certain losses, due to periodic loading and ageing, of its functionality over time. This phenomenon of self-healing is mainly attributed to the component bitumen and is affected by the bitumen properties, asphalt composition and other factors like rest periods, degree of damage, temperature and moisture. Widely established is that higher temperatures and longer periods without loading have a positive influence on healing. Increasing filler content and increasing degree of damage result in a prolonged healing period to achieve the same healing level.

This study investigated the correlation and limits on the reachable healing level. Therefore, asphalt mastic beams manufactured with varying bitumen types were healed. The main healing method was by convection heating, additional induction heating was used. The asphalt mastic beams were healed under different defined conditions.

It was indicated that an increasing density lead to a decrease in average healing level. Though ranging in the variation of the healing level, it was consistently observed to be independent of the healing method used. A major influence has the mould used. Beams healing inside polytetrafluorethylene (PTFE) moulds reached a 90% healing level of 0.72 for temperatures of 80 °C, 100 °C and 120 °C. Healing in silicone moulds resulted in an average healing level of 0.94. The significant increase in healing level is attributed to the additional pressure due to geometry of the silicone moulds. Higher bitumen content caused a healing level increase, which is attributed to the liquid like state of the high bitumen content beams after healing at 100 °C. A repetitive healing at 120 °C showed that bitumen was drained at the joints of the moulds resulting in a mass loss and hence caused a decrease in healing level with each repetition.

Keywords: induced self-healing, healing level, mastic beams, induction heating, convection heating

1. INTRODUCTION

Bituminous constructions, like asphalt roads, last longer compared to prediction based on laboratory testing. Incorporated in an empirical correction factor, a part of the prolonged lifetime is due to the material ability to recover lost or diminished properties with time [1]. The amount of property recovered depends on the duration with diminished or without loading, the degree of introduced damage, damage type, bulk and interface properties of the bituminous material [2-5]. In general the recovery rate increases with increasing temperature, limited by thermal degradation of bitumen and stability of the construction.

Concerning asphalt, the main application of bitumen mixed with aggregates and additives at times [6], self-healing is associated with the disappearance of cracks [7] or the reduction in the number of cracks respectively reduction of crack sizes [8]. Observation during healing processes indicates that crack closing is due to the flow of bitumen. This flow can be driven by gravity [9, 10] and/or capillary force [11]. During the healing process, simultaneously a reduction in amount of air voids was observed [8], showing that healing as flow process does not differentiate between air voids due to damage and air voids due to mixture design and asphalting. The flow characteristics and thus the self-healing ability is influenced by the bitumen type and bitumen content, added additives, type of mineral filler, pressure and temperature, which is the most influential factor [3-5, 12, 13].

If the temperature is above a critical temperature for flowing, which is associated for non-modified bitumen to be either the glass transition temperature [14] or the temperature marking the transition from a non-Newtonian to a Newtonian liquid [8], it would be expected that damage without material loss is healed to its original state given enough time. However, rarely a complete recovery of macro cracks can be observed, partly due to changes in the material (for example void distribution and ageing). Observation of gap closing in bitumen showed that a bigger gap width needed more time to close [15]. And from the healing of fatigue damage by induction heating only cracks to a certain width could be healed [8].

The aim of this study is to investigate the factors limiting healing of macro cracks in bituminous mastic beams. Two different heating methods were used to induce healing. The main method used in this study was convective heating and the second method was induction heating. Further affecting factors investigated besides heating methods included temperature, mould material and geometry, bitumen content and bitumen type and heating cycles.

2. MATERIALS AND METHODS

Five different bitumen were used in this study, with the main focus on bitumen T73, and general properties are provided in Table 1. Further, to produce bituminous mastic beams, sand of a maximum grading of 2.8 mm and a density of 2.363 $g\cdot cm^{-3}$ and steel grid with a linear gradation from 1 mm to 0.25 mm and a density of 7.52 $g\cdot cm^{-3}$ was used. All components were heated to 180 °C and mixed together in proportion of 15wt% bitumen, 11wt% steel grid and 74wt% sand. Beams in dimensions of 3 x 3 x 10 cm^3 with a predetermined breaking point were manufactured from the mixture by compacting manually into the moulds. After cooling to ambient temperatures, the beams were separated from the moulds and stored in a freezer at -17 °C. This low temperature ensured a brittle fracture during the three-point breaking and prevent healing during the storage duration after the heat treatment. Furthermore, beams with varying amount, from 5wt% to 28wt%, of bitumen T73 were manufactured.

TABLE 1 Bitumen properties

Properties	P49	S46	S70	T44	T73
Needle penetration [dmm]	49	46	70	44	73
Density [g·cm^{-3}]	1.025	1.034	1.020	1.026	1.020
Surface energy [mJ·m^{-2}]	25.5	24.5	24.7	23.2	24.5
Viscosity at 100 °C [Pa·s]	3.93	2.87	2.00	3.90	2.36
Saturate fraction [wt%]	19.1	20.7	22.1	16.9	18.6
Aromatic fraction [wt%]	42.3	40.3	42.1	46.3	48.3
Resin fraction [wt%]	22.0	22.4	22.1	24.1	24.2
Asphaltene fraction [wt%]	16.6	16.7	13.7	12.7	8.9

A macro crack (complete fracture) was achieved by breaking the beams at low temperature, below -15 °C, under three-point breaking in force controlled condition with 10 N·s^{-1}. After the macro crack was induced, the beams rested for at least 16 hours at ambient temperature.

Two different moulds were used for healing. The first one was the manufacturing mould consisting of polytetrafluorethylene (PTFE). The second one was a two-piece silicone mould with dimension approximately 1 mm smaller compared to the original moulds.

The beams broken and moulded were heated by convection (main method used in this study) and induction. For convection heating a Hot Box oven (Gallenkamp) was used. For bitumen T73, temperatures of 60 °C, 80 °C, 100 °C and 120 °C were used for both mould types and additional 40 °C was used for the silicone moulds only. Duration of the samples in the oven was adjusted to the temperature and mould type. The remaining four bitumen types were only heated to 100 °C using the silicon moulds. A 6 kW induction heating generator (Ambrell Company) at a frequency of 348 kHz was used for induction heating and the current intensities were 50 A, 80 A, 100 A, 200 A and 300 A for bitumen T73 and exclusive 300 A for the other bitumen types embedded in the silicone moulds. A three-winding flat squared coil was used and beams inside the silicone moulds were placed approximately 20 mm below the coil. For both heating methods, the average surface temperature was measured by an infrared camera (micro-epsilon, TIM 160, UFPA, 160x120 pixels).

After heating the beams were stored in the freezer and retested by three-point breaking. The healing level was defined as the ratio of the breaking force after healing to initial breaking force.

3. RESULTS AND DISCUSSIONS

Figure 1 shows the healing levels reached by beams manufactured with bitumen T73 for both heating methods. A significant variation was observed for healing in PTFE moulds. The variation decreased with increasing heating temperature. Healing in silicone moulds showed less variation, yet the same trend in a variation decrease with increase in heating temperature was observed. The significant difference of approximately 0.31 healing level between PTFE and silicone moulds is attributed to a slight deformation for silicone mould healed beams. This deformation is caused by the negative beam geometry of the mould and happened during the first 5 minutes of heating. The 90th percentile calculated for PTFE moulds serves as an upper healing limit for these moulds. Further, the healing level increased with increasing heating temperature, which was attributed to an increasing contribution of thermal expansion and lower viscosity. This trend was more dominant for PTFE moulds, as the expansion in silicone moulds might have a smaller contribution to pressure compare to the pressure of the mould causing the deformation.

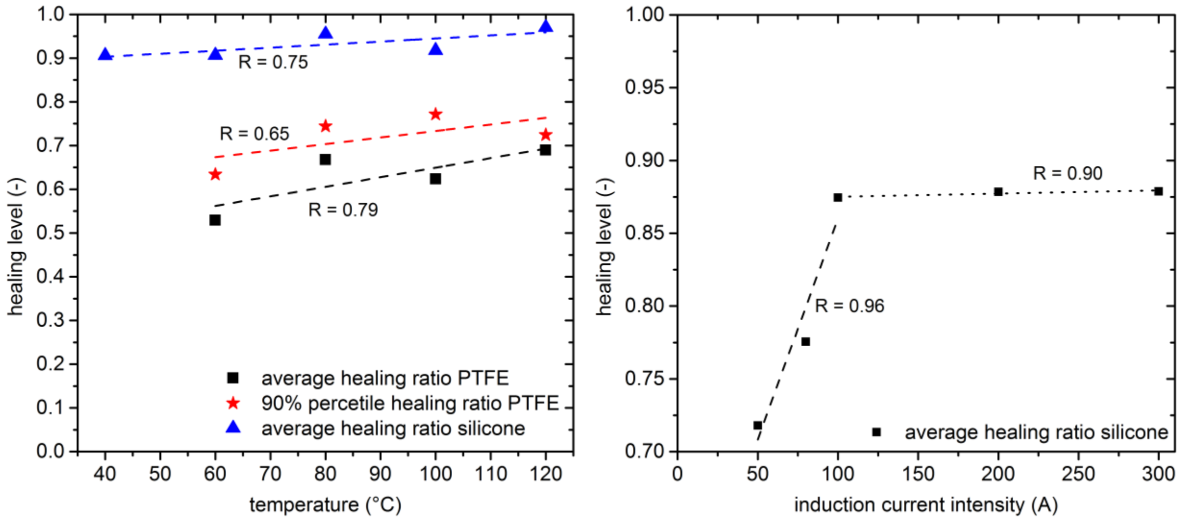

FIGURE 1 Healing level of fractured beams, produced with bitumen T73, healed by convection heating within PTFE and silicone moulds (left) and induction heating within silicone moulds (right). The change in induction heating is accentuated by two linear regressions.

A direct comparison between induction and convection heating was not possible. For convection heating the surface temperature of the beams remained constant after reaching the oven temperature. In contrast the surface temperature of induction heating increased nearly linearly without reaching an equilibrium state. However, healing levels increased until an average surface temperature between approximately 50 °C and 80 °C was reached and remained constant within variations afterwards. The observation of the constant healing level was limited by thermochemical changes. These changes were indicated by fumes arising of the beams, which induced a manually stop in heating. The average healing level reached increased with increasing current intensity until 100 A was reached. A steady reachable healing level above 100 A was related to the self-regulation of the induction generator, which resulted in a cut-off at approximately 110 A.

A significant influence on the reachable constant healing level had the amount of bitumen, studied on bitumen T73 in various content to manufacture beams. The left figure in Figure 2 shows the distinct trend of increasing constant healing level with increasing bitumen content. As the bitumen content increases, the beams became more molten. Beams with bitumen content of 28wt% showed significant deformation at room temperature after 6 hours without geometric support. Hence, due to the promoted viscous behaviour of the mixture, the crack interface is more likely to disappear respectively the gap between the crack surfaces closes faster. Further, the initial crack was more seldom through aggregates as bitumen content increased. Healing of cracks in bitumen heal faster and complete compared to cracks, which includes fracture surfaces running through aggregates. A healing level above one was achieved as a permanent change in dimension was easier attainable with increasing bitumen content due to the geometry of the silicone moulds used.

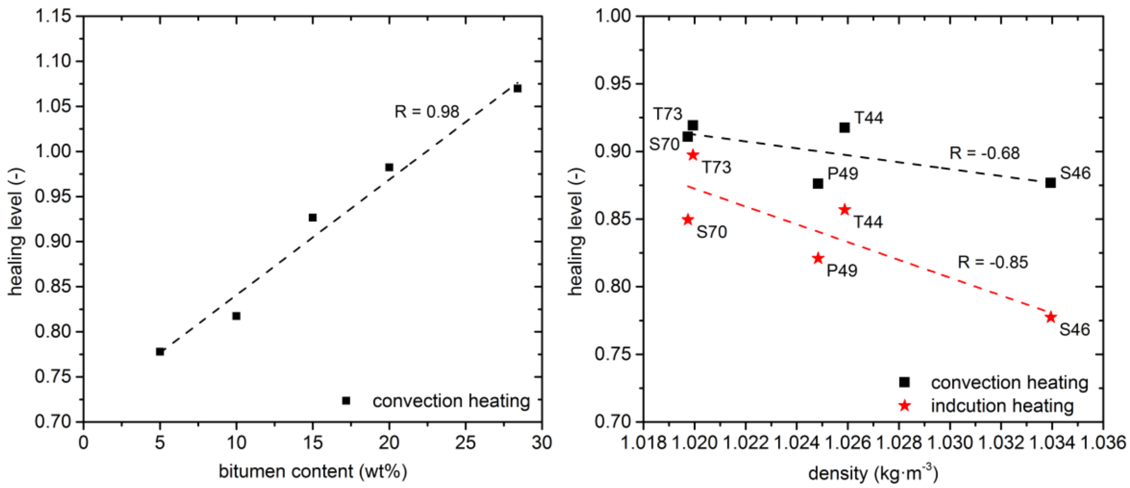

FIGURE 2 Increase in average reached constant healing level, induced by convection heating, with increasing bitumen content of bitumen T73 (left). And average healing levels reached of the five bitumen types used, heated by convection heating at 100 °C and induction heating with 300 A plotted against density (right).

Even though not directly comparable, beams healed in silicon moulds by convection heating reached a higher healing level as healed by induction heating. Furthermore, this was observed for different bitumen types used, which manufactured beams were healed in silicone moulds by convection heating at 100 °C and induction heating with a set current intensity to 300 A, shown in Figure 2 right. Correlation analysis revealed that the average healing level reached correlates negative with density, shown in Figure 2 right. A lesser correlation was found for viscosity. Bitumen obtained from the same producer, differing in grades, revealed that relatively softer bitumen has a lower viscosity and lower density compared to harder bitumen and reached a higher healing level. No significant correlations with the bitumen fractions were found.

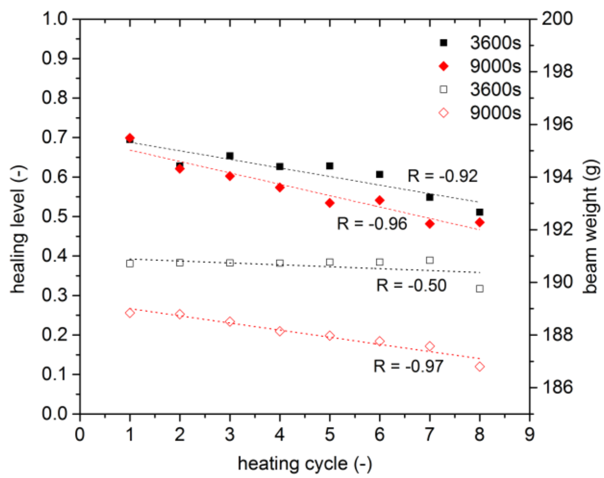

FIGURE 3 Decrease in healing level (full symbols) and decrease in the weight of the beams (empty symbols) with repeated heating cycle of 3600 s and 9000 s of convection heating treatment per cycle.

The repeated healing of beams manufactured with bitumen T73 in PTFE moulds at 120 °C showed a decrease in healing level with each repetition, shown in Figure 3. The weight loss due to breaking and healing was recorded and the weight of the beam decreases with each healing cycle. One part of the weight loss was assigned to the loss of particle during the brittle fracturing of the beams. A loss of bigger particles, above approximately 0.1 g, entailed that parts of the fracture surfaces were not in contact during heating and an air void was observable in the crack after re-breaking the beam. The other part was due to the draining of bitumen into the joints of the PTFE mould, which slightly open during the heating due to expansion and a gap remains. Therefore, draining mainly occurred at the ends of the beam and caused a visible loss of material in the interface of beam and mould.

5. CONCLUSIONS

This study investigated factors affecting the reachable healing level of asphalt mastic beams, which were broken by three-point testing and healing was induced by convection and induction heating. A main influence on the healing level was due to the supporting conditions (moulds) during the heating phase. Using PTFE mould, which were used for production, resulted in a lower healing level compared to silicone moulds, which added a slight pressure from two sides to assure fitting, which resulted in a deformation. For both mould types an increase in healing level with increasing heating temperature was found. The authors assumed that this increase is caused by thermal expansion and decreased viscosity. Thermal expansion contributes to an internal pressure, and allows the fracture interface to be pressed together, causing a better interconnection. Decreasing viscosity allows an easier deformation of the beams for crack closing, faster flow of material into the crack and interfacial crosslinking via diffusion. Similar results were achieved by induction heating. The reachable healing increased with increasing induction current intensity until a self-regulation of current intensity capped further increases at 110 A The constant healing level observed was short, as induction heating takes seconds to minutes and the heating phase was stopped after thermal degradation occurred, indicated by fumes.

The amount of bitumen to produce the asphalt mastic beams had a significant influence. Increasing weight per cent led to an increase in healing level. This dependency on bitumen content is attributed to molten state of the beams, which causes a faster deformation at ambient room temperature and due to the tendency that the initial crack was rarely through aggregates with increasing content of bitumen.

Repeating convection heating cycle showed that a part of the material was lost through the joints in the moulds. Hence, beam weight and healing level dropped with each cycle. The decline in healing level was higher for longer heating durations.

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