Effect of binder thermal expansion on healing performance of asphalt mixtures

Breixo Gomez-Meijide[1], Siham Salih[1], Harith Ajam[1], Alvaro Garcia[1]
([1] Nottingham Transportation Engineering Centre [NTEC], Department of Civil Engineering, University of Nottingham, Nottingham NG7 2RD, UK
breixo.gomez.meijide@nottingham.ac.uk)

ABSTRACT

Most of our roads are made of asphalt mix, a complex-visco-elastoplastic material with self-healing properties. The flow of bitumen through cracks during the healing process is produced by a combination of different actions, such as capillary forces, gravity, hydrostatic pressure and energy dissipation. The aim of the present investigation was the study of how the thermal expansion of bitumen can also affect the healing performance of asphalt mixtures. In order to determine this, 5 types of bitumen with different coefficient of thermal expansion were used. Also two types of asphalt mix, dense and porous, were manufactured to respectively constrain and facilitate the flow of bitumen through internal pore network. Results indicated that bitumen with higher coefficient of thermal expansion produce higher healing levels but if the flow exceeds the capacity of the internal pore network, internal pressure can increase, which leads to decreases in healing performance and even damage in the material.

Keywords: asphalt, healing, thermal expansion, internal pore network

1. INTRODUCTION

Most of our roads are made of asphalt [1], a complex visco-elasto-plastic material with self-healing properties [2]. The flow of bitumen through cracks during the healing process is produced by a combination of different actions, such as capillary forces, gravity, hydrostatic pressure and energy dissipation [3]. The process can be artificially accelerated by increasing the temperature, as it reduces binder viscosity [2]. Different approaches to produce this, are the application of microwaves, electromagnetic induction or infrared radiation [4, 5].

In [6] it was observed that healing levels increase with increasing temperature in the mix. However, when the temperature is maintained high and steady, healing level reduces again. In addition, the maximum healing that can be obtained resulted higher for porous mixes than for dense mixes. These behaviours could not be predicted by the healing model proposed in [3], which led the authors to conclude that there should be, at least, another action contributing to healing phenomena not considered in the model. This, together with the fact that the coefficient of thermal expansion of bitumen is one order of magnitude greater for bitumen than for aggregates [7], led the authors to hypothesise that the differential thermal expansion of bitumen and aggregates could be a feasible explanation for the previously mentioned behaviour.

The aim of the present investigation is to study how the thermal expansion of bitumen affects the healing performance of asphalt mixtures.

2. MATERIALS AND METHODS

2.1 Materials

The present investigation was carried out with hot mix asphalt containing 2 different percentages of air voids: 5% and 21%. In order to obtain that, two different gradations were used (Figure 1). Also different bitumen contents were selected to keep the same amount of effective binder in the mix (4.7% and 3.3% respectively). Five types of bitumen were used in order to study how with different coefficient of thermal expansion. The aggregate was limestone for all the samples (Table 1).

The materials were heated at 160ºC, mixed and compacted into 306 × 306 x 50 mm^3 slabs and then cut into 150×60 x $50\,mm^3$ prismatic beams.

TABLE 1 Characteristics of the five types of bitumen used in this investigation

#	Country	Supplier	Pen grade	Needle pen.
1	Israel	Pazkar	40/60	49
2	Netherlands	Shell	70/100	70
3	Netherlands	Shell	50/70	46
4	Netherlands	Total	40/60	44
5	Netherlands	Total	70/100	73

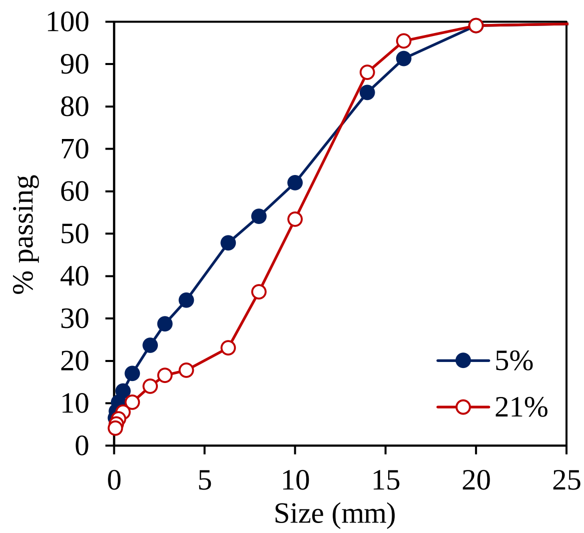

FIGURE 1 Gradation curves of mixes produced with different air voids contents

2.2 Thermal expansion test

The thermal expansion of the five types of bitumen was measured by using a Thermomechanical Analyser instrument (Q400 TMA), with temperature range of 10-50°C, heating rate of 10°C/min and measurement resolution of 0.02mm. In this case, in order to produce samples with good consistency, each binder was mixed with the same amount of limestone (50%-50%). The gradation was composed by 50% of 4-6 mm aggregate and 50% dust (<0.063 mm). The samples were then cut, moulded and polished to produce 25mm height and 10mm diameter cylindrical samples. Three samples were tested for each bitumen and the average were taken to determine the coefficient of thermal expansion.

2.3 Single crack healing test

The healing phenomenon occurring in a single crack was studied through a 3-steps test, as follows: First, the temperature of the samples was reduced to -20±2ºC to ensure the production the brittle cracks and subjected to strain-controlled 3-point bending with an increasing deformation rate of 50 mm/min. The ultimate force applied at the moment of break was measured and denoted as F_0. Then both halves were kept at 20±2ºC for 4 hours, put gently together again and subjected for different times (from 15 s to 240 s) to the action of electromagnetic induction heating generated by a 15x15 cm squared coil composed by three windings and placed at a distance of 1 cm above the samples. The current intensity was set to 80A. With it, a quasi-linear increase of temperature was produced in the samples at an average rate of 0.22ºC/s (standard deviation 0.03ºC/s), not existing significant correlation between such rates and the type of bitumen (R^2=0.152). Finally, the temperature of the samples was reduced again to -20±2ºC and the 3-point bending test was repeated obtaining a new ultimate load registered as F_f. The healing ratio (*HR*), which gives an idea about the percentage of initial strength that was recovered thanks to the healing process, was defined as follows:

$$HR(\%)=F_f/F_0 \tag{1}$$

For these tests, series of 16 samples were produced with every of the 5 types of bitumen described above. Within each series, each sample was subjected to a different heating time, from 15 to 240 s in intervals of 15 s. Thus, the correlation between heating energy and healing level could be obtained. The results were fitted by the model proposed by [3].

$$S(\tau)=\frac{C_1}{F_0}\cdot e^{-D\tau}\left(-1+e^{\frac{D\tau}{2}}\right)^2 \tag{2}$$

Where $S(\tau)$ is the healing ratio (%), F_0 is the initial 3-point bending strength of samples (kN), τ is the energy applied during the healing (K·s) and D and C_1 are parameters defined as:

$$D=\frac{\rho g r}{\beta} \tag{3}$$

$$C_1=8\frac{\sigma_u\cdot C}{L\cdot H} \tag{4}$$

Where ρ is the density (kg/m^3), g is the gravity (m^2/s), r is the width of the crack (m), β is a dimensionless parameter that takes into account possible sources of energy losses, σ_u is the maximum force resisted by the beam (N), L is the span of the beam (m), H is its height and C is a material constant with units (m^2). Furthermore, the D value is an indication of the healing rate, when its value increases, the healing happens faster.

2.4 Fatigue microcracks healing tests

The phenomenon of bitumen thermally expanding through the internal pore network was studied through three point fatigue tests, on two series of samples with different air voids contents: 5% and 21%, as described above. In this case, samples were subjected to dynamic cyclic loads under 3-point bending conditions at the 20 ± 1ºC. The loading wave oscillated between 0.15 kN and 2.5 kN at a frequency of 4 Hz. A resting period of 0.15 s was included between consecutive loading pulses. In order to avoid creep deformations, an elastic membrane was placed under the samples (Figure 2). The loading of each sample was stopped at a different number of cycles and the healing treatment was applied to all the samples. Then the extension of fatigue life was obtained for each sample:

$$HI = \frac{N_f - N_{0.5}}{N_{0.5}} \tag{5}$$

Where N_f is the total number of cycles resisted and $N_{0.5}$ is the number of cycles with probability of breaking the material equal to 0.5. This value was considered as a reference value for the fatigue life of the material and it was obtained by testing a series of 15 samples until breaking without applying any healing treatment and by fitting a Weibull statistical distribution.

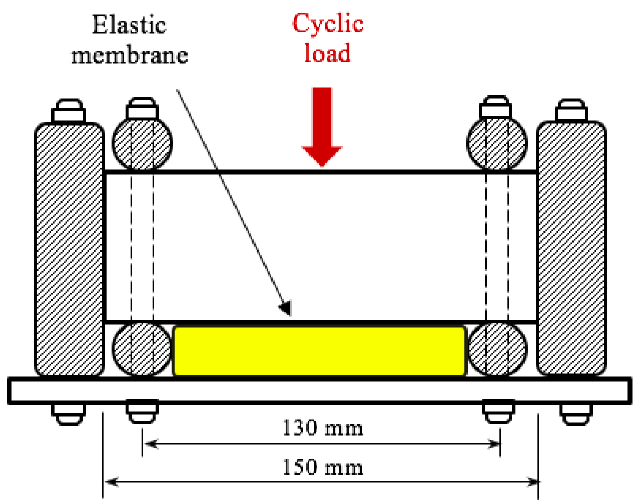

FIGURE 2 Setup of 3-point bending fatigue tests

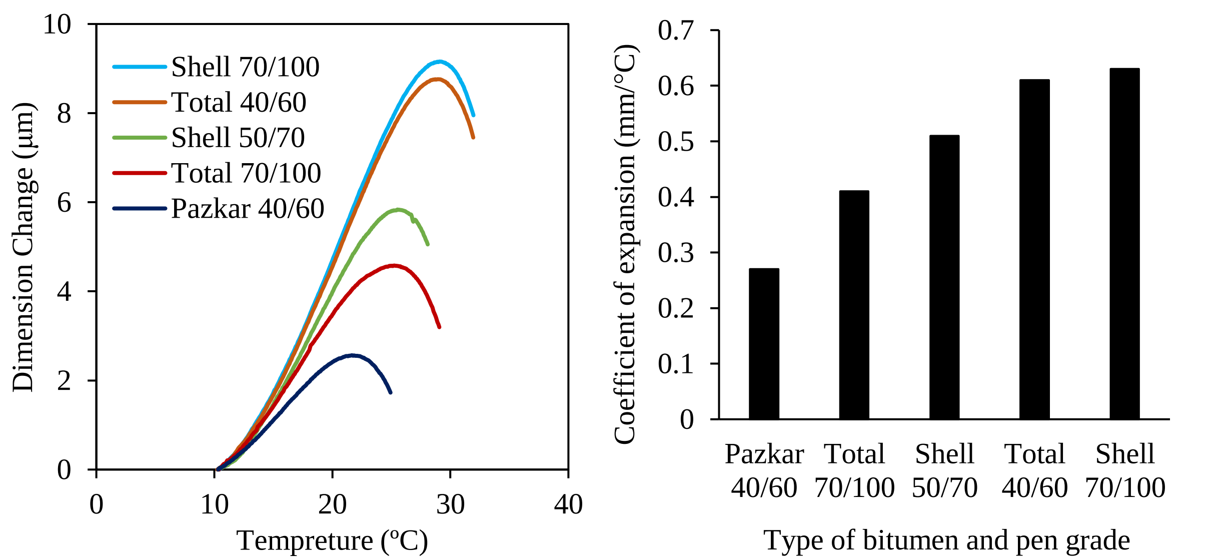

FIGURE 3 Results of thermal expansion tests: correlation between dimension change and temperature (left) and coefficients of thermal expansion (right)

3. RESULTS

3.1 Thermal expansion

Figure 3 shows the results of thermal expansion obtained for the five types of bitumen considered in this investigation. As can be seen, all of them present different coefficients of thermal expansion, from 0.27 to 0.63 mm/ºC. In addition, the obtained values do not depend on other properties, such as source or pen grade. This will be useful to isolate the effect of thermal expansion on healing performance, as explained in following sections.

3.2 Effect of bitumen thermal expansion on asphalt healing

The healing model explained in Eq. (2) to (4) was fitted to the experimental healing results obtained for each series of samples, manufactured with different types of bitumen (example in Figure 4 – left). In this Figure, it is also shown, as a reference value, the healing expected at 20ºC, (around 10%). In Figure 4 – right, it is shown the correlation between coefficient of thermal expansion of each bitumen and the healing ratio obtained for a healing energy of $4.35 \cdot 10^6$ K·s.

As can be seen, compared to healing at 20ºC, the healing performance after applying $4.35 \cdot 10^6$ K·s is significantly higher and tends to improve with the coefficient of thermal expansion for values between 0.27 and 0.51 mm/ºC. This means that as long as the thermal expansion of bitumen increases, it can fill a greater volume of crack and, as a consequence, the obtained healing increases.

However, after the value of 0.51 mm/ºC it is not clear that greater thermal expansion of bitumen involves better healing. All the opposite, the results seem to stabilise or even decrease slightly. In other words, thermal expansion can result detrimental once a certain value is exceeded.

Taking into account that these tests were produced on dense samples with 5% of air voids content, the Authors have hypothesised that a bitumen expanding too much could exceed the permeability of the internal pore network increasing the internal pressure and expanding the interstitial space between aggregates. If this is true, dense mixes with low air voids content would be more difficult to heal than porous asphalt, especially when microcraks (case of fatigue), instead of big cracks (this case) are produced. In order to observe it, fatigue-healing tests on samples of dense and porous asphalt were carried out as described in the following section.

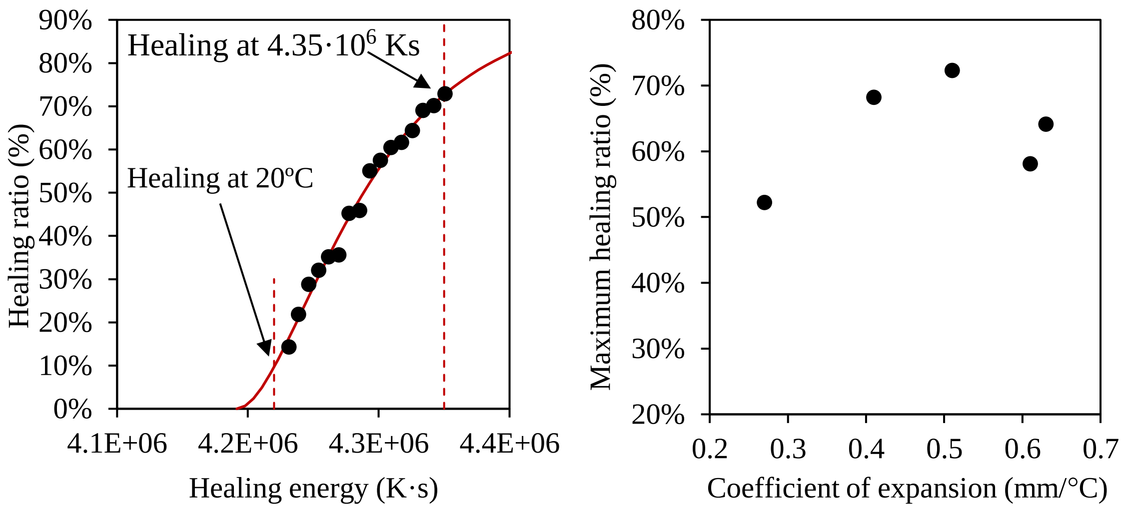

FIGURE 4. Example of fitting of healing model to test results for the case of samples TOTAL 70-100 (left) and maximum healing ratio for the five types of bitumen (right)

3.3 Internal pore microstructure and thermal expansion

In Figure 5-left it can be seen, for dense mixes (5% air voids content) the healing index, or extension of fatigue life, when the healing treatment is applied at different number of loading cycles. The results follow a bell-shaped relationship, which indicates that there is an optimum number of cycles (around 3500 cycles) to apply the healing treatment and obtain the maximum fatigue life extension.

The bell-shaped relationship also indicates that if the treatment is applied too early, the healing is not significant as there is a reduced amount of cracks that actually need to be healed. On the contrary, if the treatment is applied too late, the cracks are so big that the effectiveness of the process decreases again.

In Figure 5-right, they are shown the homologous results obtained for the case of porous mixes (21% air voids content). As can be seen, the obtained healing follows also a bell-shaped trend but, in this case, with the optimum value placed in significantly lower number of cycles and higher healing index. As a consequence, the healing must be applied earlier within the service life of the road, but the life extension that can be produced is greater. Hence, the maximum healing obtained is close to 180% while for dense mixes remained lower than 50%.

In addition, it must be highlighted that results for dense mixes are not only lower than for porous mixes, but also negative when the healing is not applied close to the optimum moment. In other words, the samples get damaged instead of healed. This fact, only happening in dense mixes, where the flow capacity of interior pore network is reduced, supports the hypothesis introduced in previous section.

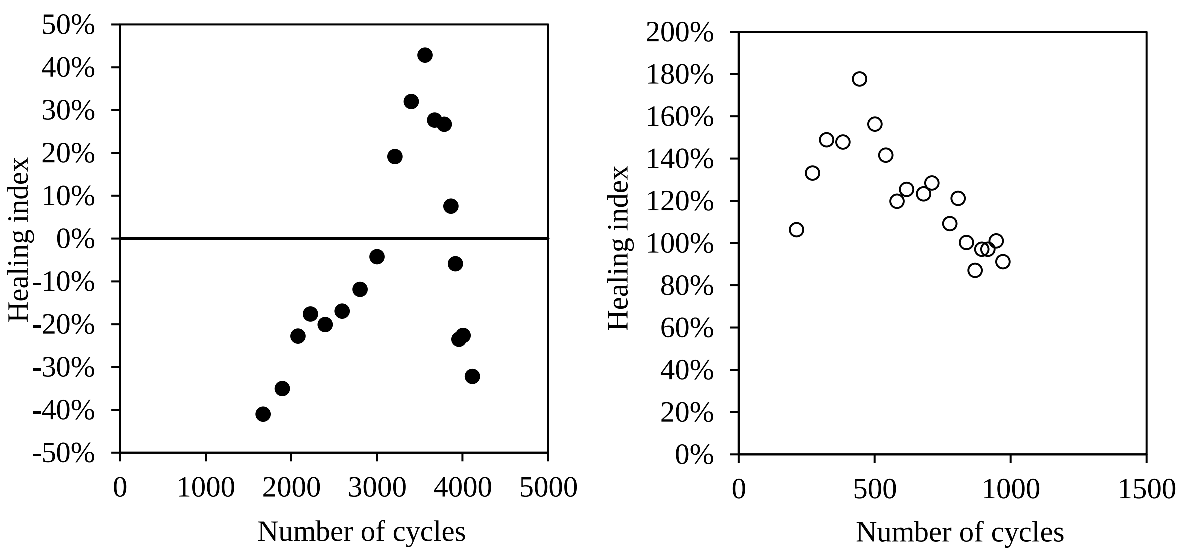

FIGURE 5. Healing index obtained for dense mixes (left) and porous mixes (right) by applying the healing treatment at different number of cycles

4. CONCLUSIONS

The main two conclusions of the present investigation are:

1. The healing performance of asphalt mixes improves with the coefficient of thermal expansion of the binder until a certain value is reached. Higher thermal expansions

do not produce any further improvement. On the contrary, they can even produce reductions in healing capacity.

2. The flow capacity of internal pore structure affects significantly the behaviour of the mix. When the air voids content is low, reduced and even negative results can be obtained. In other words, the material gets damaged instead of healed.

Considering both previous conclusions, the Authors believe that, when the flow of expanding bitumen exceeds the capacity of pore network, an increasing internal pressure is produced. This might happen because two reasons: (a) because an excessive thermal expansion of bitumen or (b) because an insufficient flow capacity of pore network. If the effect is strong enough, it can produce the damage of the material, reducing service life of roads instead of enlarging it.

1. REFERENCES

[1] National Cooperative Highway Research Program (NCHRP) (2001). Rehabilitation Strategies for Highway Pavements. NCHRP Web Document 35 (Project C1-38): Contractor's Final Report. 152pp.

[2] P. Ayar, F. Moreno-Navarro, M.C. Rubio-Gamez, The healing capability of asphalt pavements: a state of the art review, Journal of Cleaner Production 113 (2016) 28-40

[3] Garcia, A., Bueno, M., Norambuena-Contreras, J., Partl, M. N., Induction healing of dense asphalt concrete, Construction and Building Materials 49 (2013) 1-7.

[4] J. Norambuena-Contreras, A. Garcia, Self-healing of asphalt mixture by microwave and induction heating, Materials & Design 106 (2016) 404-414

[5] Ajam H, Lastra-González P, Gómez-Meijide B, Airey G, García A. Self-healing of dense asphalt concrete by two different approaches: electromagnetic induction and infrared radiation. Journal of Testing and Evaluation 45 (2017) 8pp. https://doi.org/10.1520/JTE20160612. ISSN 0090-3973.

[6] Gómez-Meijide B, Ajam H, Lastra-Gonzalez P, Garcia A. Effect of air voids content on asphalt self-healing via induction and infrared heating. Construction and Building Materials 126 (2016) 957-966

[7] Read, J., Whiteoak, D., The shell bitumen handbook, Thomas Telford, 2003.