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Effects of Synthetic Wax and Surface-Active Additive on the Ageing Process of Foamed Bitumen Binder

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Abstract. One of the main priorities of present industrial activities is to reduce associated emissions, fulfilling the requirements to preserve the natural environment. Also, the road construction industry undertakes efforts to develop technologies permitting more sustainable production of asphalt mixtures, e.g. by utilizing reduced production and paving temperatures. The most effective technology in this respect is the half-warm mix asphalt technique (HWMA) with foamed bitumen, enabling the production temperature to be decreased to as low as 90°C - 110°C depending on the type of mixture, which is approximately 60°C lower than the production temperature of traditional hot mix asphalt (HMA). The present study evaluated a 50/70 asphalt binder foamed with water, intended to produce asphalt concrete. In order to ensure the most favorable characteristics of the foamed binder, i.e. maximum expansion ratio (ER) and half-life (HL), Fisher Tropsch synthetic wax was used in the amounts of 1.0, 1.5, 2.0 and 2.5% and a surfactant in the amount 0.2, 0.4 and 0.6% in relation to asphalt by weight before foaming. The utilization of the additives significantly improved the foaming characteristics of the investigated binder. Due to the fact that the asphalt binder is subject to aging, which affects the properties of the produced asphalt mixture and the durability of the asphalt pavement, the binders were subjected to short-term (RTFOT). The effects of the additives on the basic characteristics of the binders were evaluated after aging. The tests included penetration, softening point, and Frass breaking point. Statistical analysis of test results was performed using the ANOVA test. Certain compositions of the foamed asphalt binder were identified, which were characterized by more favorable properties than the reference asphalt binder. This permitted to conclude that it is possible to produce an asphalt mixture with high quality parameters using low-temperature technology with water-foamed asphalt.

Keywords: Foamed asphalt binder; asphalt ageing process; synthetic wax; surface active additives

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INTRODUCTION

In response to environmental alterations and climate warming, efforts are being pursued to decrease the energy consumption of manufacturing processes, thereby reducing CO^2 emissions. The principle of closed-cycle material utilisation is also being pursued in closed loops. As a result, there is a reduction or even significant elimination of the issue of industrial waste produced at different stages of the production process. The global road construction industry is also getting involved in these activities. From the outset of the 21st century, technologies have been introduced with the intent of recycling already utilised road materials from past highway structures, which are re-acquired during their refurbishment or renovation process. Primarily, this encompasses the cold in-place recycling (CIR) technology where the asphalt rubble and stone debris from the underlying layers of the pavement structure, produced during road refurbishment, are utilised [1,2]. It is being recycled to make new construction layer material. The outcome of this technology also involves reducing the energy consumption necessary for the procurement of stone materials in the rock processing procedure by substituting them with debris.

The advent of the 21st century also marked the development of technologies that lower the production temperature of mineral-asphalt mixtures intended for the upper layers of pavement structures. Traditional mineral-asphalt blends are considered some of the most energy-consuming road materials. Their production temperature ranges from160ºC to 185ºC, depending on the type of asphalt used. As a result of such high production temperatures for traditional mineral-asphalt mixtures, large quantities of greenhouse gases, especially CO_2, are released, which contribute considerably to climate change. Two technologies have been developed to reduce the production asphalt temperatures: Worm Mix Asphalt (WMA) [3-6] and Half Warm Mix Asphalt (HWMA) [7]. The use of WMA technology has been demonstrated to reduce energy requirements by approximately 15% compared to the production temperature of conventional asphalt mixes. The temperature at which MMA is produced is reduced from 165ºC to 140ºC to be the result of the use of asphalt viscosity-reducing additives, including synthetic wax [8,9], chemicals [10,11] and zeolite in the asphalt mixture production process [12,13]. The reduction in process temperatures has been demonstrated to result in a 20% reduction in CO_2 emissions and a comparable reduction in emissions of other greenhouse gases when compared with the production of traditional asphalt mixes. An even more environmentally friendly technology is the HWMA process, which allows the production of water-foamed asphalt within a temperature range of 110°C to 90°C using scratching. Substantial reduction in temperature achieves the further beneficial environmental impact. The evolution of water-foamed asphalt technology has been observed on a global scale since the beginning of the 21th century, with the publication of Jenkis' research results in 2000 [14]. Following the addition of water, the binder assumes the form of a foam, exhibiting two key parameters: the maximum expansion (ER) and the half-life of the bitumen foam (HL) [14,15]. The form above enables the binder to surround the mineral material and asphalt waste optimally, thereby ensuring the high quality of the resulting material. This quality is further enhanced by the binder itself [16, 17]. Consequently, during the initial phase of its implementation, this technology was solely employed in the context of road rehabilitation to produce a recycled mineral-asphalt mix for the pavement structure' s lower layers during cold deep recycling [18]. Nevertheless, the contemporary challenges of environmental protection and the decarbonisation of industrial production have led to a broader interest in this technology for the production of mineral and asphalt mixtures for the upper layers of structures, thus replacing traditional mixtures produced at very high temperatures [19]. To address this challenge, research is being conducted to identify the most effective additives for foamed asphalt. These additives may include synthetic waxes [20, 21], chemicals [22], or surfactants [23], which are added to the binder before foaming.

The implementation of temperature-reduced asphalt mixtures is of significant importance in terms of environmental impact and ensuring the highest possible quality standards. Applying a lower production temperature slows down the ageing process of asphalt, an organic material. Two distinct stages of this phenomenon can be identified: technological ageing, which occurs due to the effects of high temperatures on the binder, and operational ageing, caused by the impact of solar radiation, precipitation and wind on the asphalt pavement. A variety of techniques were employed at an early stage to reduce the rate of ageing of the asphalt and, thus, the asphalt mix. One method employed was the use of hydrated lime in the asphalt mix, as evidenced by references [24-26]. Alternatively, various chemical compounds were employed to slow down the process. The most beneficial effect is achieved by lowering the temperature of the asphalt mixture production, which slows the rate of carbonisation of the bitumen. Laboratory studies are conducted to investigate the effects of various additives on the ageing of bitumen. This is achieved through the use of the RTFOT methodology.

Therefore, determination of the impact of additives is necessary, such as synthetic wax or a surface-active agent, on the technological ageing of foamed bitumen, particularly in relation to the foaming process.

MATERIALS AND RESEARCH PROGRAM

Tested Materials

Asphalt 50/70 is the most commonly used bitumen for the upper layers of pavement structures in Poland and across Europe. The basic properties are given in the Table 1.

TABLE 1. The basic properties of 50/70 bitumen.

Property	Test Method	Unit of Measurement	Result	
			Average Value	Standard Deviation
Penetration at 25°C	EN 1426	0.1 mm	65.9	0.78
Softening point $T_{R\&B}$	EN 1427	°C	50.4	0.15
Frass breaking point	EN 12593	°C	-15.1	0.81
High critical temperature	EN 14770			
Before RTFOT	EN 12607-1	°C	68.5	0.69
After RTFOT		°C	69.3	0.65

Conversely, the surface-active agent SAA and the synthetic wax F-T_{LC}, which have a reduced carbon footprint compared to those previously used in road practice, were employed as additives to the 50/70 bitumen used before foaming. The material was introduced into road practice in 2023 as a solution that meets the current high environmental requirements. The properties of the synthetic wax F-T_{LC} are shown in Table 2. F-T_{LC} synthetic wax is available in the form of white granules with a grain size of 3 mm (Figure 1). The properties of the surface-active agent SSA are presented in the Table 3.

TABLE 2. Characteristics of the synthetic wax F-T [27]

Properties	Unit of Measurement	Value
Color	-	white, yellowish
Flash point	ºC	285
Freezing temperature	ºC	95
Density at 25 ºC	Mg/m^3	0.9
Viscosity at 135 ^{C}	Belt	12
Molecular weight	g/mol	approx. 1000

FIGURE 1. Synthetic wax F-T_{LC} was added before foaming to bitumen 50/70 (fot. M.M. Iwański).

TABLE 3. The characteristics properties for the surface-active agent SAA [28].

Property	Unit of Measurement	Value
Appearance	-	Brown viscous liquid
Density at 20°C	Mg/m^3	0.88-0.98
Viscosity at 20°C	mP	3000
Freezing point	°C	<0
Flashpoint (open flame)	°C	>218

The surface-active SAA agent, which is employed as an additive to the 50/70 bitumen before foaming, is presented in a liquid form with an oily brown consistency (Figure 2).

A crucial factor influencing the quality of the tests applied is the homogeneity of binder on which the tests were performed. Therefore, the proper preparation of laboratory samples was significant in order to meet this condition. To a sample of adhesive with a mass of 1000 g, synthetic wax F-T_{LC} was added. The process of mixing the binder with an additive involved heating the binder to a temperature 100°C higher than its softening temperature and mixing it in a blender at this temperature using a stirrer rotating at speeds of 150 revolutions/min for 30s, and then at a speed of 600 revolutions/min for 270s. To obtain analytical samples for testing, the procedure was followed in accordance with EN 12594 standard. Then a macroscopic assessment of the obtained binder samples was performed. When a lack of uniform colour of the binder was observed or the presence of distinct types of spots on the surface of the analytical sample indicating improper dissolution of the synthetic wax $F\text{-}T_{LC}$ such samples were not used in the studies. In a comparable way, the procedure was followed to apply the SSA to bitumen 50/70.

FIGURE 2. A representation of a surface-active SAA agent.

Experimental Program

The process of testing the effect of the synthetic wax $F\text{-}T_{LC}$ and the surface-active agent SAA on the ageing process of the 50/70 asphalt was conducted in three stages.

The initial stage of the process involved foaming the 50/70 bitumen with additives (synthetic wax and SAA) that were incorporated into the binder before foaming. The study aimed to ascertain the fundamental characteristics of asphalt foaming.

- maximum expansion ER [15],
- half-life of asphalt foam HL [15].

The foaming test of asphalt 50/70 with SAA was conducted using the conditions specified in [14, 15].

- the asphalt temperature is 155°C,
- the temperature of water is 20°C,
- the water flow is 100 g/s,
- the foaming time of asphalt is 5 s,
- the air pressure is 500 kPa, and
- the water pressure is 600 kPa.

During the foaming process, the foaming water content (FWC) of 1.5%, 2.0%, 2.5% and 3.0% was added to the hot 50/70 bitumen.

The bitumen foaming was conducted using a WLB-10S laboratory apparatus (Figure 3), which was equipped with a foaming chamber.

FIGURE 3. The WLB-10S asphalt foaming unit is characterised by the foaming properties of bitumen (fot. M.M. Iwański)

The binder obtained after water foaming and characterised by optimum foaming parameters was then subjected to RTFOT technological ageing using specialised equipment in accordance with the requirements of EN 12607-1 (Figure 4).

FIGURE 4. RTFOT asphalt ageing test apparatus (fot. M.M. Iwański)

The final stage of the study involved the determination of the following parameters of bitumen 50/70 with synthetic wax and surface-active agent SAA following the ageing process:
- penetration at 25°C temperature (Pen, EN 1426:2015-08),
- softening temperature ($T_{R\&B}$, EN 1427:2015-08),
- Fraass breaking point temperature (T_{Fraass}, EN 12593:2015-08).

Each study was conducted on nine samples based on the recommendations outlined in [26, 27]. The results were subjected to statistical analysis to ascertain their reliability, employing the variance analysis technique (ANOVA).

RESULTS AND DISCUSSION

The foaming parameters obtained during the testing of bitumen 50/70 with synthetic wax F-T and surface-active agent SAA as a function of the amount of water dosed were employed to ascertain the foaming characteristics. Figure 5 shows the foaming characteristics of the 50/70 bitumen.

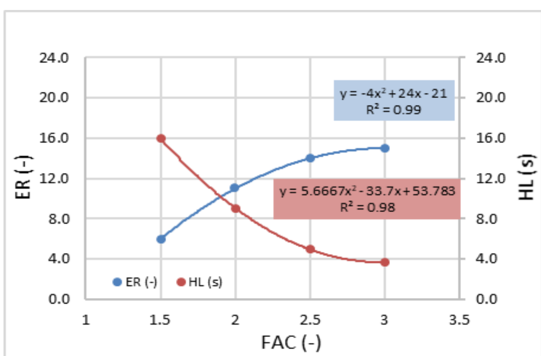

FIGURE 5. The following characteristics of foamed bitumen 50/70 are presented for consideration

The foamed bitumen 50/70 characteristics, illustrated in Figure 4, indicate that the maximum ER expansion is ten, and the HL half-life is 9 s at a water content of FWC—2.0 %.

The synthetic wax impact on the foaming characteristics of the 50/70 bitumen was then evaluated (Figure 6).

A study of the foaming characteristics of bitumen 50/70 revealed that the addition of synthetic wax F-T_{LC} to the binder prior to foaming significantly increased both the maximum ER expansion and the half-life of the HL bitumen foam.

The subsequent stage of this study was the assessment of the impact of the surface-active agent SAA on analysed foaming characteristics of the 50/70 bitumen (Figure 7).

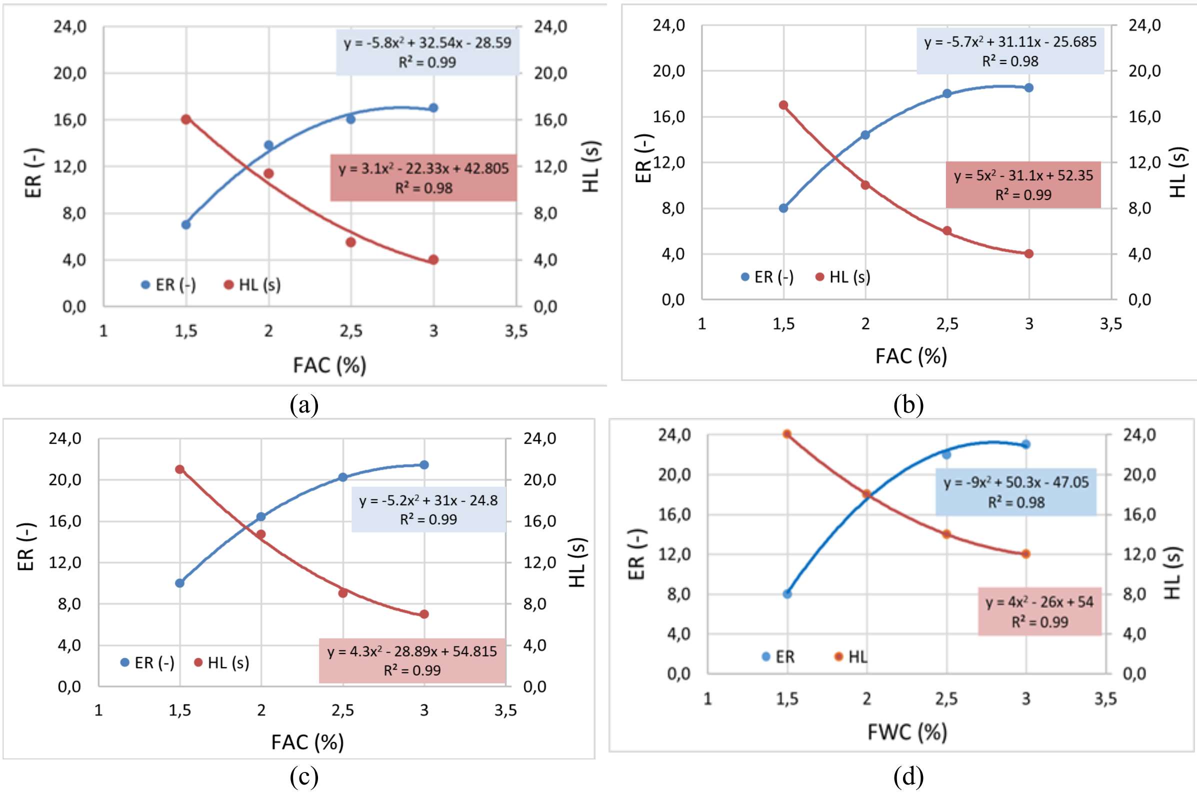

FIGURE 6. The water-foaming characteristics of bitumen 50/70 were investigated with the addition of synthetic wax at 1.0% (a), 1.5% (b), 2.0% (c) and 2.5% (d).

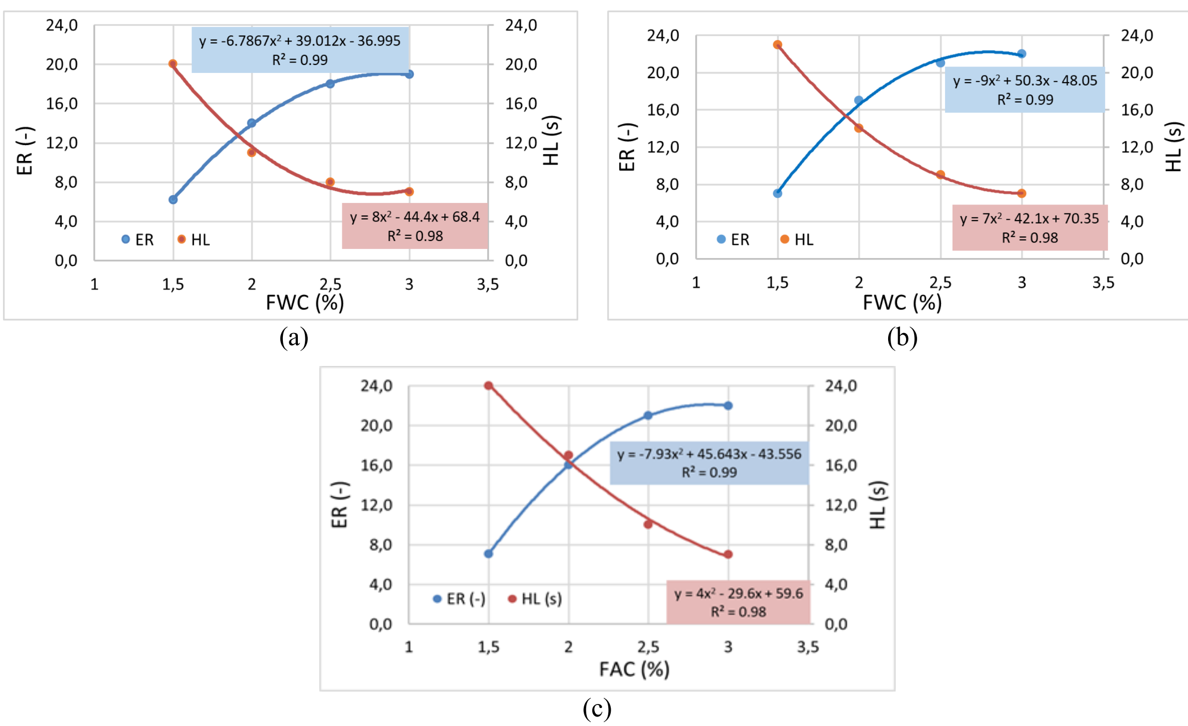

FIGURE 7. The water-foaming characteristics of asphalt 50/70 were investigated with the addition of the surfactant SAA at 0.2% (a), 0.4% (b) and 0.6% (c).

The incorporation of the surface-active agent SAA into the 50/70 bitumen before foaming has a pronounced impact on the maximum ER expansion and the half-life of the HL bitumen foam - an increase in the compactness of SAA results in an enhancement of the binder's foaming characteristics. At a compactness of 6.0% SAA, these characteristics are approximately double those of the control asphalt 50/70.

The ageing of the foamed bitumen obtained at the recommended FWC foam water contents was then carried out using the RTFOT methodology. The impact of process ageing on penetration at 25°C (Pen) of tested binders is illustrated in Figure 8.

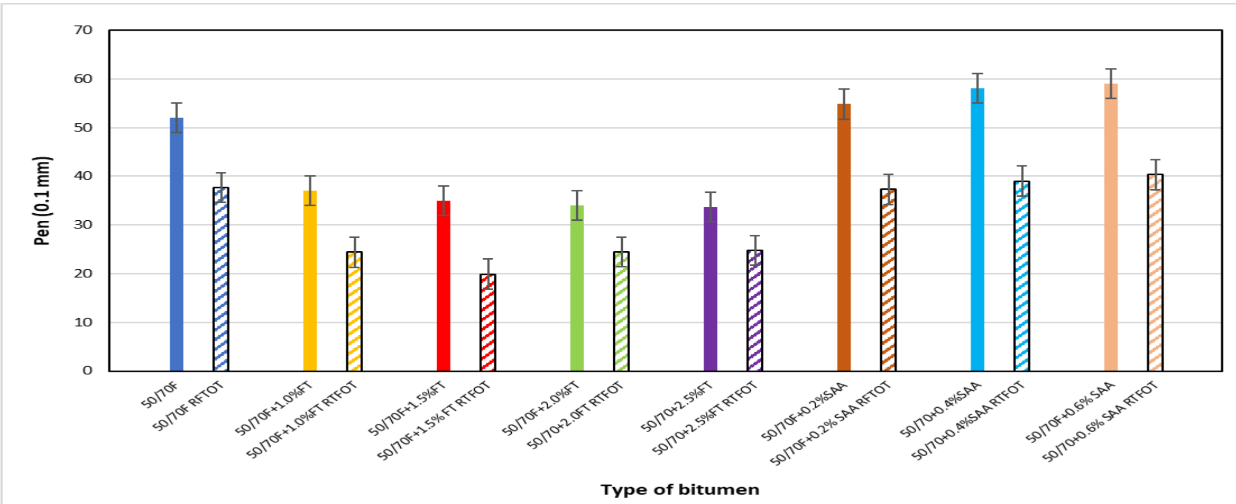

FIGURE 8. This study examines the penetration characteristics of 50/70 foamed bitumen with synthetic wax and SAA at 25 before and after RFTOT ageing.

The utilisation of the synthetic wax additive F-T_{LC} has the consequence of reducing the penetration of the foamed bitumen 50/70. In contrast, a different trend is observed with the use of the SAA additive. As the binder penetration increases, so too does the penetration of the foam. Even at an SAA content of 0.2% by weight of bitumen, the penetration is higher than that of the control 50/70 bitumen after foaming. The behaviour of the tested binders observed after RTFOT ageing is analogous to that observed during the initial testing phase. Consequently, by incorporating both additives into the 50/70 bitumen before foaming, the penetration of the foamed binder can be precisely calibrated to meet specific requirements. At the same time, the intensity of ageing can be effectively modulated.

Figure 9 illustrates the effect of technological ageing on the softening temperature ($T_{R\&B}$) of the tested binders.

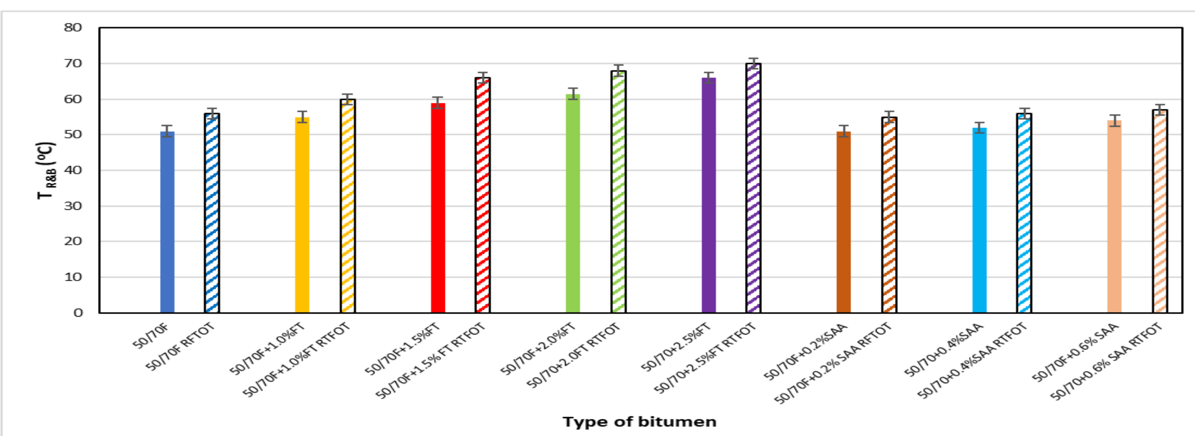

FIGURE 9. $T_{R\&B}$ softening point characteristics of 50/70 foamed bitumen with synthetic wax and SAA before and after RFTOT ageing

Synthetic wax F-T_{LC} has a notable impact on the enhancement of the softening temperature ($T_{R\&B}$) of foamed bitumen 50/70, which is accompanied by a reduction in penetration at 25ºC. A comparable phenomenon is observed with the utilisation of SAA, yet the softening temperature increment is notably minimal, even when employing an additive comprising 0.6% by weight of 50/70 asphalt. The softening temperature of the tested binders is observed to increase with time, a phenomenon that can be attributed to the effects of technological ageing. The growth trend is retained when 50/70 bitumen is combined with synthetic wax and SAA before foaming.

Figure 10 illustrates the impact of technological ageing on the Frass temperature (T_{Frass}) of the tested binders.

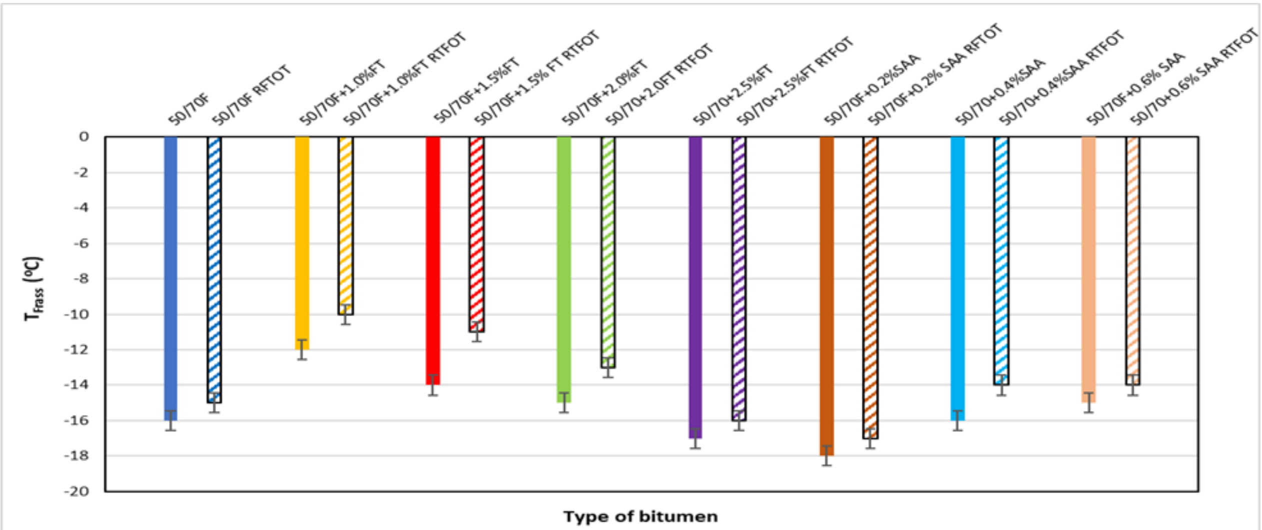

FIGURE 10. Frass temperature characteristics (TFrass) of 50/70 foamed bitumen with synthetic wax and SAA before and after RFTOT ageing

Incorporating the synthetic wax additive F-T_{LC} at a concentration of 1.0% reduces Frass temperature. Conversely, an augmented concentration of the substance in question engenders an intensification of the characteristics under analysis. At a density of 2.0% synthetic wax, the Frass temperature is demonstrably higher than that of the control bitumen 50/70 following the foaming process. Conversely, the use of SAA additive is associated with an upward trend in the temperature of the frass, which is observed at a compactness of 0.2% SAA in 50/70 bitumen. Following the RTFOT technological ageing process, the tested binders exhibited behaviour analogous to that observed before the ageing process. The observed trend in the variation of the Frass temperature of the analysed binders remains consistent when the foamed bitumen 50/70 additive is used.

CONCLUSION

The results of the studies conducted on the impact of the incorporation of synthetic waxes F-T and SAA on the foaming of bitumen 50/70 before and after RTFOT technological ageing have led to the following conclusions:

- Synthetic wax F-T_{LC} has been demonstrated to exert a more pronounced influence on the enhancement of the ER expansion rate and HL half-life of 50/70 foamed bitumen. In contrast, the SAA additive plays a comparatively minor role in the binder foaming process compared to synthetic wax,
- The incorporation of the synthetic wax additive has a pronounced impact on penetration at 25°C, softening point and the temperature of the 50/70 foamed bitumen. The observed effect of the synthetic wax is likely due to its role in stiffening the binder. In contrast, the addition of SAA has a less intensive impact on the analysed characteristics of foamed bitumen. In particular, its effect on the softening temperature and the Frass after foaming of the binder are more favourable than those of synthetic wax,
- The application of RTFOT technology results in a reduction in the analysed characteristics of the 50/70 bitumen tested after foaming. The synthetic wax impact and SAA additive on the penetration, softening point and flash point of the 50/70 bitumen remains consistent with that observed before ageing.
- The analysis of the effects of synthetic wax F-T_{LC} and SAA on the analysed properties of bitumen 50/70 before and after foaming has led to the conclusion that the foaming characteristics of the binder can be modelled

appropriately and their properties after RTFOT technological ageing can be influenced by the use of both additives together in a certain compactness.

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