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INVESTIGATION OF THE EFFECTS OF ADDITIVES USED IN REDUCING ASPHALT PRODUCTION TEMPERATURES

Süleyman Nurullah Adahi ŞAHIN[1*], Metin İPEK[1], Mehmet Barış GÖKÇEK[1]

Abstract

This study is related to evaluations of the performance and usability evaluations of existing and also newly produced Warm Mixed Asphalt (WMA) additives. Viscosity, softening point, and penetration tests were performed on bitumen with additives without changing the bitumen rate for the additives. For the asphalt concrete, Marshall Stability tests were performed. WMA additives are used to reduce asphalt production temperatures and, consequently, the temperature of the mixture significantly. According to the Marshall Stability test, it was determined that the WMA samples fulfilled values within the local standards. The Hot Mixed Asphalt (HMA) and Warm Mixed Asphalt (WMA) additives were compared as to additive costs and energy savings considering the reduced production temperatures. Additives have great potential to be used in adverse weather conditions and in many countries.

Address

[1] Department of Civil Engineering, Sakarya University of Applied Sciences, 540050, Sakarya, Turkey

* ***Corresponding author:*** adahisahin@subu.edu.tr

Key words

- Warm Mix Asphalt (WMA),
- Hot Mix Asphalt (HMA),
- Modified Bitumen,
- Viscosity,
- Additive,
- Energy Saving.

1 INTRODUCTION

Asphalt surface courses have thicknesses ranging from 20 to 30 mm, depending on various factors such as their design, construction, and maintenance (Morova et al., 2011). Local environmental conditions, the interaction of the materials in a pavement's composition, and the traffic load on the asphalt pavement should be known, as they play a very effective role in the future performance of asphalt concrete (Tosun, 2011). Hot Mix Asphalt (HMA) is made of aggregate that is dried at 145-160ºC and heated to approximately the same temperature, and the bitumen is turned into a viscous liquid. Approximately 95% of the mixture consists of aggregate and 5% bitumen. Owing to the additives used in Warm Mix Asphalt (WMA), the high temperatures in the production of traditional methods could be reduced. In this way, the applicability, workability, and paving of asphalt are easier and provide great advantages (Rahman et al., 2020).

Warm Mix Asphalt was first tested and performed in Europe in Germany and Norway from 1995 to 1999 (Ranken et al., 2019; Cheraghian et al., 2020). In 1996, scientists in Norway performed the first experiments using their new type of asphalt mix called Warm Asphalt Mix (WAM). As a result, they developed WAM Foam, one of the earliest examples of foam technology. In 1997, Hamburg became the first city to use a warm mix asphalt with a wax additive i.e., Sasobit, while an aliphatic hydrocarbon produced by Sasol Wax (Germany) by the Fischer-Tropsch method. The aliphatic hydrocarbon obtained by the Fischer-Tropsch method is defined as a long-chain aliphatic hydrocarbon because it contains more than 40 to 115 carbon atoms. In 1999, the first trials of WMA with foam asphalt and Aspha-min zeolite were conducted in Norway and Germany, respectively. A study conducted by the National Asphalt Pavement Association (NAPA) in 2002 introduced WMA technology to the USA (Cheraghian et al., 2020). Later, synthetic zeolite additive started to be used in WMA technology; the zeolite formation helped the foam to provide ease of movement and workability in the bitumen (Barthel et al., 2005). Many additives and forms have been produced or designed using this technique. WMA has been accepted in 45

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countries in America and Europe. It is currently gaining more interest as a new technology but is still trying to be actively implemented in many countries in recent years. It is estimated that most of the asphalt production facilities will be established for WMA in the future by large industrial enterprises (Kim et al., 2012).

The additives are of three types: organic, foam, and chemical additives, respectively (Seth, 2010). Additives that reduce the viscosity of the binder are used to ensure that the aggregate is completely covered and that the compactability of the mixture is at a low temperature. An average 20-40°C reduction in the mixing temperature can be achieved with organic additives. Besides, these additives modify the asphalt to increase its resistance to deformation (EAPA, 2016). These additives act as surfactants at the interface between the aggregates and bitumen. Typically, they regulate and reduce the frictional forces at the interfaces in a range of 85°C to 140°C. Thus, it is possible to mix the bitumen and aggregates at lower temperatures and to compact the prepared mixture. The chemical additives can reduce the mixing and compaction temperature by approximately 20°C (EAPA, 2016).

With the low mixing and compacting temperature achieved by using warm mix asphalt, smoke and odor emissions are reduced to their lowest levels, and a better working environment is provided for asphalt workers. In practice, there is a 50% reduction in the emission of fumes released with every 12°C decrease in temperature (Brandt and Groot, 1999). It is also known that energy consumption decreases by a maximum of 40%, which reduces the production temperature, and this reduction benefits the asphalt production as well as the WMA process (Ruhl and Lindemier, 2006). Although the WMA application seems to have an economic advantage in terms of fuel savings as it provides for pavement production at a lower energy cost, both the facility installation and the cost of the additives almost eliminate this advantage. However, considering its positive effects on the environment, it can be seen that it has more economic benefits over the long term. In countries where fuel is more expensive, WMA can be very economical (Aytekin, 2018). According to the data obtained by some researchers, the greenhouse gas emissions such as CO2, NO2, and SO2 are decreasing at the rate of energy savings achieved; this rate varies between 25% and 50%, depending on the process used. Besides, it was determined by experiments that there is a significant reduction of 30-50% in the output of multi-ring aromatic hydrocarbons (PAHs) with asphalt odor and fumes compared to the hot mix asphalt (FHWAPL, 2008). In a study conducted in Norway in 2011 to compare the applications of warm mix asphalt with hot mix asphalt, it was found that the exposure to bitumen fumes and vapor in warm mix asphalt was significantly lower. In this study in Norway, the working environment of 11 warm mix asphalt and hot mix asphalt trial sections the same day was evaluated. According to the results, with an average decrease of 29°C in the asphalt's temperature, there was a very significant decrease in asphalt fumes, ranging from 58-67% (Norwegian WMA project, 2012).

Issues involving foaming have been investigated in detail, and it has been found that it is beneficial to heat the aggregate for the foaming of the bitumen below 100°C (Kristjánsdóttir, 2007). Larsen et al. worked on WMA production to produce asphalt at temperatures lower than HMA to reduce the energy consumption, bad odors, and smoke emissions. The work specifically focused on foaming WMA (Larsen et al., 2004). Hurley and Prowel (2005) investigated the process of adding Sasobit wax to the mixture by a melting method in their study and reported that the air void contents were less than in other additives. They also examined the interaction with filler and other materials and stated that WMA was better than the traditional method. Johannesson et al. (2005) examined the differences between warm and hot mix applications in Iceland. The report includes some information about and comparisons of different types of pavements used in the country, according to the life cycle costs. In the feasibility study results, it was seen that warm mix asphalt is a less costly option than hot mix asphalt over the long term. Jamshidi et al. (2012), investigated the behaviour of WMA technologies containing Sasobit under load strain, and time factors. The findings obtained in the laboratory and field trials were evaluated. At the same time, the life cycle assessment, the energy-saving potential of the Sasobit mixture, and the potential for a reduction in greenhouse gas emissions were examined, and they achieved positive results. Zhao and Guo (2012), used a test tool to evaluate the workability of WMA with Sasobit. First, a feasibility study was performed with asphalt mortar; then the workability of the WMA was determined at different temperatures and frequencies and compared with the HMA. As a result, it was concluded that WMA with Sasobit reduces the mixture's temperature to close to 30°C and has better workability than HMA and a very similar performance to HMA. The study found that by subjecting the Evothem J1 additive to a Marshall stability test, the temperature of the additive used can reduce the mixture's temperature to 120°C. At the same time, when examining its effect on the humidity, it provides a decrease compared to HMA; its performance does not change or even increase (Mahida et al., 2015). In studies on MCM-41, which is a mesophore (small pore) silica material, Woszuk et al. (2018) revealed that it can be used as a WMA additive in terms of both environmental and economic benefits. At the same time, they showed that this additive, which reduces viscosity at low temperatures, is convenient in terms of its workability. Aktaş et al. (2018) applied viscosity tests to bitumen modified with Evothem M1 and Viatop plus C25 additives at different temperatures; they observed that these additives significantly lower the viscosity at low temperatures and demonstrated the differences in terms of their applicability and workability.

In Denmark, the National Competence Centre (NCC) produces warm mix asphalt with a foam bitumen technique using a patented foaming generator. They carried out a WMA application study on a highway under classic asphalt production conditions. Polymer-modified bituminous stone mastic asphalt was produced, and the production temperature was reduced by approximately 20°C with this technique (EAPA, 2016). The Asphalt Manufacturers Association in Norway started a new project in 2010 on low-temperature asphalt, i.e., "LTA-2011". Within the scope of this project, 11 trial sections were constructed with 6 different techniques; issues in terms of the asphalt workers' health and the quality of the asphalt were investigated, and the production temperature was reduced by approximately 30°C. A trial section was made using zeolite on an urban road section in Istanbul in 2012, and its performance was found to be equivalent to traditional asphalt (EAPA, 2016).

Belc et al. (202)1 investigated WMA additives such as chemical, synthetic zeolite, and organic additives at different

mixing temperatures and determined that there was no difference between HMA and WMA characteristics. However, organic additives significantly reduce the mixing temperature by almost 40°C. Ferotti et al. (2017) declared that the effect of chemical additives on bitumen is not significant but that modified bitumen could decrease the viscosity temperature, while increasing the rutting resistance and the elastic responses. A study that dealt with a laboratory investigation of the properties of WMA binders containing polyphosphoric acid showed that the additive increased viscosity (Liu et al., 2018). It was not discussed whether the additive used was organic or chemical. Jattak et al. (2021) used bottom ash to examine the performance of WMA and declared that using bottom ash with Evotherm 3G improved the indirect tensile strength of WMA.

Zhang et al. (2020), examined the water stability performance of WMA with a ZYF-1 additive at a low temperature and recommended a 4% dose. ZYF-1 also reduced the construction temperature of the asphalt mixture. Zhang et al. (2021) evaluated a surfactant additive foamed for modified asphalt and declared that it showed better workability and had a good low-temperature performance. It can be said that most of the studies regarding WMA and its performance show significant developments in terms of using low temperatures.

Within the scope of this study, the performance and usability evaluations of additives developed from existing and newly produced WMA additives have been made. Specifically, the additives in this study have been used for the first time. This study with the new additives proved that there is no need to change the bitumen ratio.

In Section 2, the bitumen and materials are given as detailed in Fig.1 and Tab.1. Section 3 is related to experimental methods such as viscosity, the softening point and penetration tests that were performed on the bitumen with the additives used in the study. Then, the Marshall Stability test was performed in line with the results obtained. In section 4, the bitumen viscosity of the WMA additives was examined according to the reference bitumen, and the difference in the mixing temperature was observed. The Marshall Stability test was used to measure the values of the WMA-added samples within the ranges specified by the local standards. In the last part, HMA and WMA are compared in terms of the additive costs and energy savings. Section 5 is the discussion and conclusion of the study.

2 MATERIALS

2.1 Bitumen and Additives

According to the Turkish national standards, the recommended bitumen grades for the province where the study was conducted were chosen as 4.2% and 4.8% with a 50/70 penetration for the binder and surface courses. The additives used in this study were determined as "A", which is an amidoamine derivative and polyamine used in the industry and with long-chain aliphatic hydrocarbon content "B". These two additives are still used in the road industry and are well-known products. Also, three other additives (a) with a hydrocarbon resin and synthetic-based mineral content named "HYR-901", (b) with atactic polypropylene and polyolefin content named "Lomot", and (c) elastomer rubber SEBS compound content named "PDL6020" are newly produced and used for the first time (Tab. 1 and Fig. 1).



Fig. 1.1. *A additive*



Fig 1.2. *B additive*



Fig 1.3. *HYR-901*



Fig 1.4. *Lomot*



Fig 1.5. *PDL6020*

Tab. 1 *Additives and their ingredients*

Additives	Ingredient
Base Bitumen	-
A Additive	Amidoamine derivative and polyamine
B Additive	Long-chain aliphatic hydrocarbon
HYR-901	Hydrocarbon resin and synthetic based mineral
PDL6020	Elastomer rubber i.e. SEBS compound
LOMOT	Atactic polypropylene and polyolefin

Except for additive A, all the additives were added to the bitumen at a rate of 3% by weight. These rates were preferred as a result of considering the suggestions of the manufacturers. Ipek and Sahin determined the most appropriate additive value to be 0.3% according to the bitumen ratio in their study with the A additive (Sahin and Ipek, 2018). For this reason, the additive dosage used in this study was chosen as 0.3% for the A additive. A and B are additives used in the industry. The other additives were produced for this study in a laboratory environment.

2.2 Aggregate

The aggregate properties and proportions used in the experiments are given in Tabs. 2 and 3. Tabs. 2 and 3 also contain the aggregate rates for the binder and surface courses specified in the national standard. The sieve analysis values for the binder layer are shown in Tab. 2 and in Tab. 3 for the surface course. The granulometry curves are shown in Figs. 2 and 3, respectively.

Tab. 2 *Binder layer gradation and specification limits*

Sieve Size mm (in, No)	% Passed	Specification Lower Limit	Specification Upper Limit
25 (1”)	100	100	100
19 (3/4”)	80	80	100
12,5 (1/2”)	65	58	80
9,5 (3/8”)	55	48	70
4,75 (No. 4)	40	30	52
2,00 (No. 10)	30	20	40
0,425 (No. 40)	15	8	22
0,180 (No. 80)	10	5	14
0,075 (No.200)	5	2	7

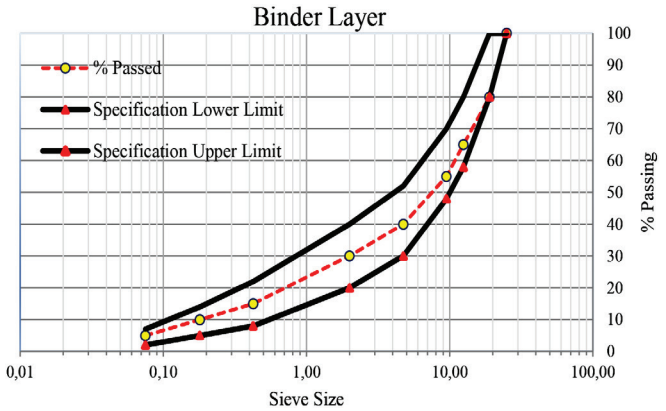


Fig. 2 *Grading curve of used asphalt concrete for pavement binder layer*

Tab. 3 *Surface course gradation and specification limits*

Sieve Size mm (in, No)	% Passed	Specification Lower Limit	Specification Upper Limit
19 (3/4")	100	100	100
12,5 (1/2")	90	88	100
9,5 (3/8")	74	72	90
4,75 (No .4)	45	42	52
2,00 (No. 10)	30	25	35
0,425 (No. 40)	15	10	20
0,180 (No. 80)	10	7	14
0,075 (No.200)	5	3	8

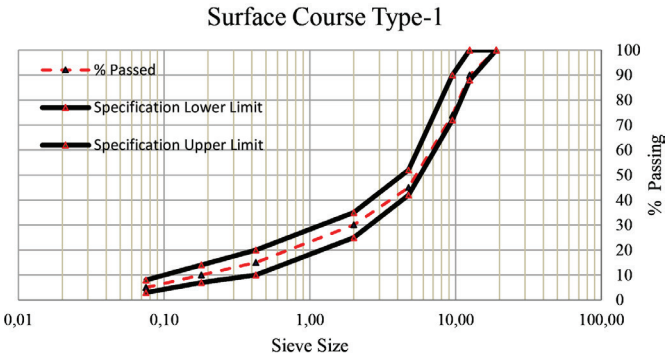


Fig. 3 *Grading curve of used asphalt concrete for pavement surface layer*

3 METHODS

Firstly, the bitumen experiments were carried out in the study. Subsequently, the experiments were conducted on asphalt concrete. The penetration test applied to the bitumen was carried out following the TS EN 1426, and ASTM D5 (2015) standards. The softening point test was carried out according to TS EN 1427 and the ASTM D36 (2015) standard measured the sensitivity of the bituminous binder to the temperature. The viscosity test was performed using a Brookfield Viscometer following the ASTM D4402 and TS EN 2031 standards.

The Marshall Stability test is applied only to WMA using aggregates with a certain penetration or viscosity grade that are 25 mm or less in diameter. The aggregate properties according to the relevant local standard and the type of layer are given in Section 2.2. The aggregates taken from a local province were provided as types of pavements according to the binder and surface course type 1A. In the preparation stage of the samples, the aggregates were initially dried until they reached a constant weight. The amounts of aggregates to be placed in the 1200g specimen was determined according to the mixture gradation. As seen in Section 2.1. the bitumen rate was determined to be 4.2% for the binder layer and 4.8% for the surface course. The experiments were performed by producing three samples for each layer and each additive for the WMA production. Following the TS EN 12697-34 standard, the performance analysis was conducted on the binder and surface courses by considering only the stability and flow values.

4 EXPERIMENTAL TEST RESULTS AND ENERGY-COST ESTIMATE

4.1 Bitumen Test Results

The test results were determined as 7.5 g for the 3% dosed B, HYR-901, PDL6020, and Lomot additives and 0.75 g for the 0.3% dosed A additives. The samples were prepared by mixing them at 180°C for 30 minutes. In addition to the softening point and penetration values of the bitumen, the viscosity values were checked at the temperatures specified in Tab. 4. The experimental results obtained are given in Tab. 4 and Figs. 4, 5, and 6.

Tab. 4 *Bitumen test results*

Additives	Softening Point °C	Penetration 25°C (0,1xmm)	Viscosity 110°C (Cp)	Viscosity 135°C (Cp)	Viscosity 150°C (Cp)
REF A additive	50 50	55 46	2450 2060	562 455	278 224
B additive	83	35	1870	370	188
HYR-901	47	81	1700	376	198
PDL6020	51	67	2120	550	260
LOMOT	52	60	2390	584	303

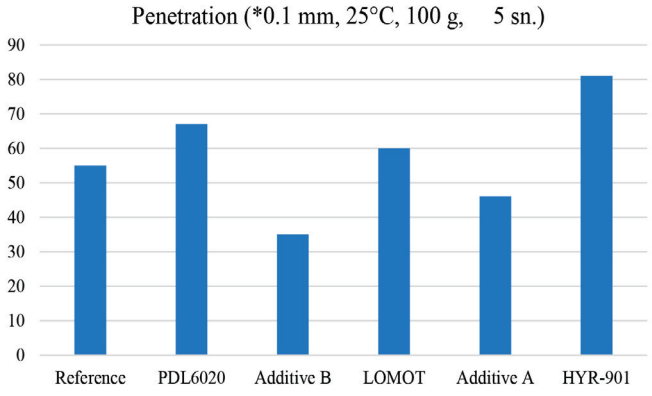


Fig.4 *Penetration test results*

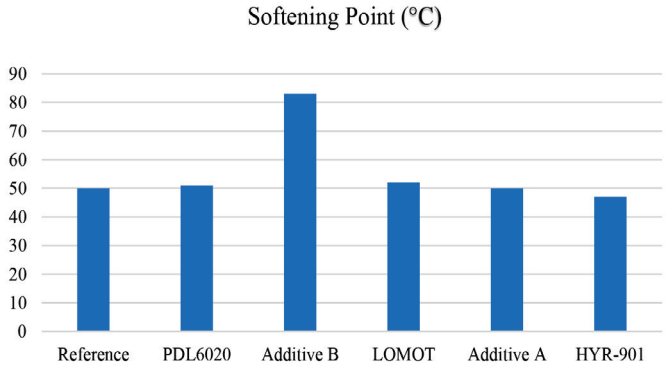


Fig. 5 *Softening point test results*

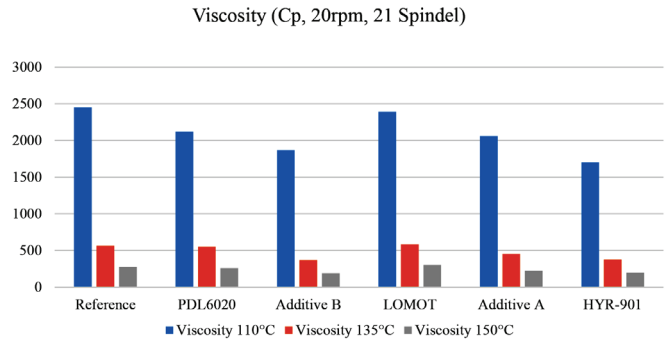


Fig. 6 *Viscosity test results*

The B additive increased the softening point by 66%, while HYR-901 decreased it by 6%; the other additives did not significantly change. As to the penetration values, HYR-901 increased by 47.27%, PDL6020 by 21.82%, and Lomot by 9.1%. The use of the B additive decreased the penetration value by 37.37% and the A additive by 17.37%.

All the additives decreased the viscosity values proportionally at 110°C. These rates were 30.16%: HYR-901, 23.67%: B contribution, 16.9%: A contribution, 13.47%: PDL6020, and 2.45%: Lomot, with the least impact, respectively. The PDL6020 reduced the viscosity value to 135°C with the 34.17% B additive, 33.1% HYR-901 and 19.04% A additive, but the other additives increased the Lomot by 3.91% and 9%.

At 150°C, the PDL6020 showed 6.5%, and almost similar value to the reference sample. The B additive with 32.38%, HYR-901 with 29.8%, and the A additive with 19.43% decreased the viscosity values.

It is predicted that the B, HYR-901, and A additives from the Warm Mix Asphalt additives will be quite economical and provide energy savings due to reducing the temperature and extending the manufacturing season. Additionally, it can be said in line with the values obtained that WMA will benefit in terms of its applicability and workability in the construction field. Based on this situation, the B and HYR-901 additives appear to be usable at a maximum of 135°C, while the A additive seems to be usable at a maximum of 140°C. For this reason, these three additives have been chosen in terms of the use of asphalt concrete in binder and surface courses. The reason for not using all the additives as mentioned before is that the other two additives were not appropriate for the further tests. For this reason and according to the standards, tests were not undertaken for those specimens.

4.2 Marshall Stability Test Results

The reference bitumen sample and aggregates were heated to 160°C and mixed in a heated mixer. The samples were prepared as three specimens, belonging to a group, and their averages were considered. The Marshall Stability test results of these prepared samples for the binder layer are given in Fig. 7 and Tab. 5.

Tab. 5 *Marshall stability test results binder layer*

Sample	Bitumen Rate (%)	Temperature	Marshall Stability (kN)	Flow (mm)
Reference	4,2	160˚C	9,62	7,65
A additive	4,2	140˚C	10,81	3,53
B additive	4,2	135˚C	11,99	3,83
HYR-901	4,2	135˚C	12,17	4,42

The Marshall Stability and flow values for the binder layer are shown in Fig. 7.a. and 7.b. The highest Marshall stability value was the HYR-901 added binder layer. The lowest expected flow value was shown by A added to the binder layer. As a result of the experiments, it was observed that the stability values of all the samples are above the local standard (TS EN 12697 – 34). However, the flow values of the reference sample were measured as 7.65 mm and were above the standard value of 4 mm.

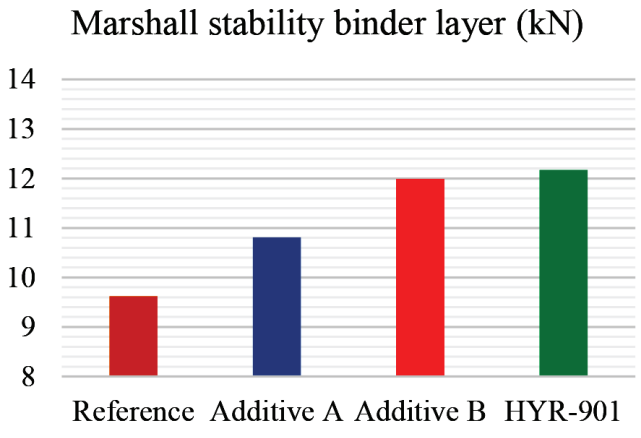


Fig. 7.a *Binder layer Marshall stability values*

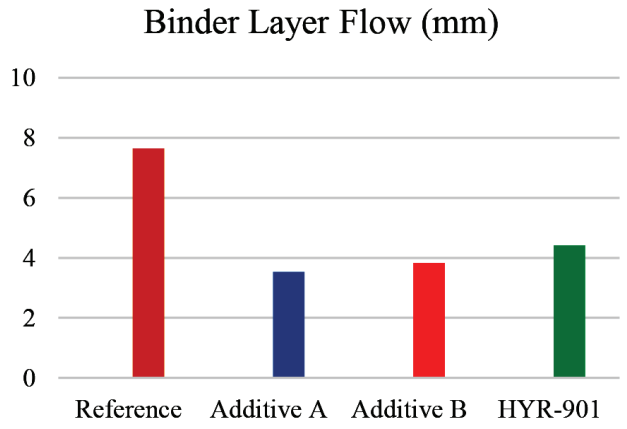


Fig. 7.b *Binder layer flow values*

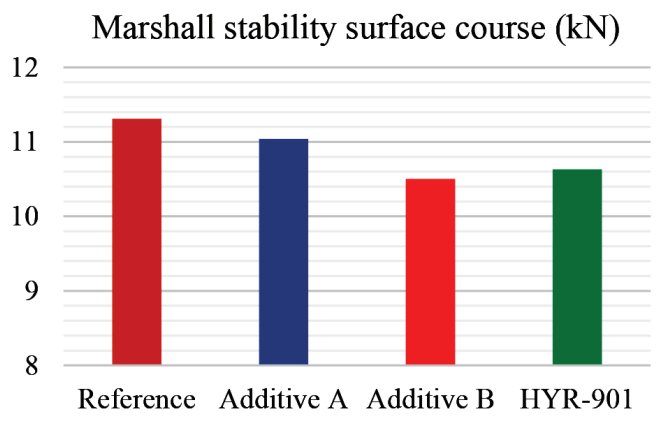


Fig. 8.a *Surface course Marshall stability values*

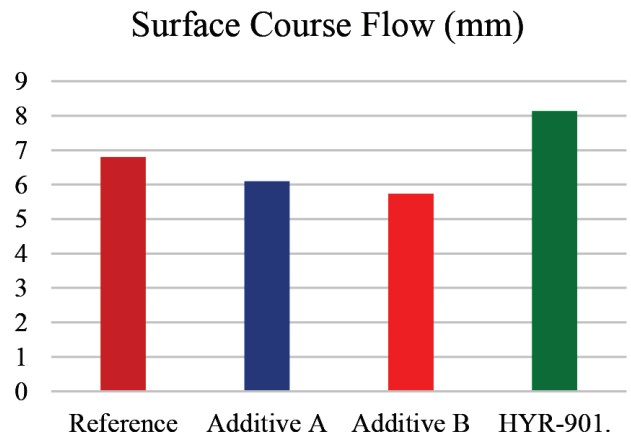


Fig. 8.b *Surface course flow values*

The average of the Marshall Stability and flow values for the surface course are shown in Figs. 8.a. and 8.b. and Tab. 6. The reference sample has the highest stability value. Additive A showed the best strength among the surface course asphalts produced with additives. In terms of the flow values, the surface course asphalt with the B additive showed the best performance.

Tab. 6 *Marshall stability test results surface course*

Sample	Bitumen Rate (%)	Temperature	Marshall Stability (kN)	Flow (mm)
Reference	4,8	160˚C	11,31	6,80
A additive	4,8	140˚C	11,04	6,10
B additive	4,8	135˚C	10,50	5,73
HYR-901	4,8	135˚C	10,63	8,13

According to the average values obtained as a result of the experiments, it was seen that the stability values of all the samples were above the local standards. However, the flow values of all the samples were outside the local standard. The additive B sample provided the closest flow value to the standard. Among the stability values, the reference sample showed the best performance. Nevertheless, they achieved the specified values in the additive samples. It is predicted that the samples with additives can be evaluated and used due to the low-temperature factor. Additive A gave the best results in terms of the stability value, and the B additive gave the best results in the flow values. The samples subjected to the experiment are shown in Fig. 9.a., and the appearance of the sample in the mixer that was not successfully mixed at 135°C is shown in Fig. 9.b.

4.3 Energy-cost estimate

As a result of the tests performed for the Binder and Surface courses, it has been shown that the asphalt concrete can be produced at low temperatures with additives. The 25°C decrease in Additive A obtained in the mixture temperature can make asphalt usable even when the weather is not rainy, by showing a positive effect in terms of its workability and operability, and by reducing bad gas and odor emissions. This could be particularly beneficial in terms of energy efficiency. The efficiency calculations were made with the information received from the ECO 4000 Benninghoven module plant manufacturer, as shown in Fig. 10 in the Asphalt Site. In addition to these efficiency calculations, the costs of the additives are also compared. The consumption data regarding the ECO 4000 Benninghoven are given in Tab. 7.



Fig. 9.a *Marshall Specimen*



Fig. 9.b *Not mixed specimen without additive*

Tab. 7 *Plant energy consumption (electricity) data for asphalt production*

Quantity and Temperature	Energy (Electricity) Expended	Energy Saving (for 25°C decrease)	Energy Expended as a Result of Savings
1 t Asphalt	2,5 - 3,5 kWh	%13,5	2,16- 3,02 kWh
160°C for 1 t Asphalt (Aggregate 952 - 958 kg)	74 kWh	%13,5	64 kWh
160°C for 1 t Asphalt (Bitumen 42 - 48kg)	74 kWh	%13,5	64 kWh



Fig. 10 *ECO 4000 Benninghoven module plant*

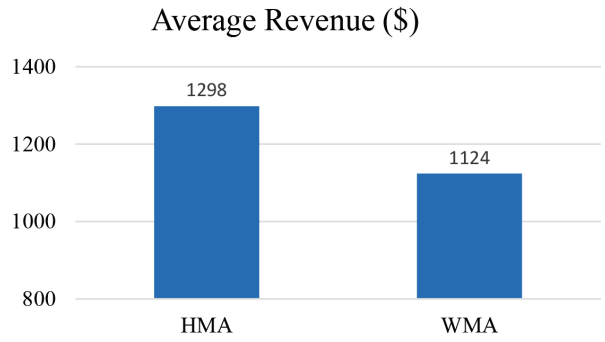


Fig. 11 *HMA and WMA energy cost comparison*

Tab. 8 *HMA and WMA energy costs*

Production Method	100 t/s Asphalt Cost	100 t/s Heating Cost (Aggregate)	100 t/ Heating Cost (Bitumen)
HMA	50,62 $/h	1191 $/h	56,2 $/h
WMA	43,76 $/h	1030,62 $/h	48,5 $/h

Tab. 9 *Binder layer additive costs*

Additives	Bitumen Amount (kg)	Additive Rate (%)	Additive Amount (kg)	Additive Unit Price ($)	Additive Cost ($)
A additive	4200	0,3	12,6	2,60	32,76
B additive	4200	3	126	3,71	467,46
HYR-901	4200	3	126	1,3	163,8

Tab. 10 *Surface course additive costs*

Additives	Bitumen Amount (kg)	Additive Rate (%)	Additive Amount (kg)	Additive Unit Price ($)	Additive Cost ($)
A additive	4800	0,3	14,4	2,60	37,44
B additive	4800	3	144	3,71	534,24
HYR-901	4800	3	144	1,3	187,2

The costs in the calculations are for May 2022. The energy consumed in heating the aggregates and bitumen for the production of 1 ton of asphalt, according to the data received, is approximately a 13.5% savings in energy provided by a 25°C decrease in the temperature. The energy unit cost was determined as 0.17 $/kWh, including tax. Based on this unit cost, calculations were made by taking into account the fact that the asphalt site produces an average of 100 tons/hour. These calculations again provide an average energy saving of 174$ per 100 tons during one hour of production as can be seen in Tab. 8 for the binder and surface course on average according to the production of HMA and WMA on an hourly basis. These values will provide savings even when considered annually. As can be seen in Fig. 11, the difference in average energy costs over the HMA and WMA is presented, and these values are calculated for over 100 tons per hour. The calculations were made taking into account the unit prices of the additives from the values obtained from the energy savings. The amount of bitumen required for 100 tons of asphalt production is 4200 kg for the binder layer and 4800 kg for the surface course. The required additive amounts and costs are given in Tab. 9 for the binder layer and Tab. 10 for the surface course.

In terms of energy savings, the hourly additive costs for 100 tons of asphalt were taken into consideration and given in Fig. 12. It was determined that the largest cost gain belongs to the A additive, depending on both the usage rate and the unit price. The B additive increases the cost considerably due to the unit cost.

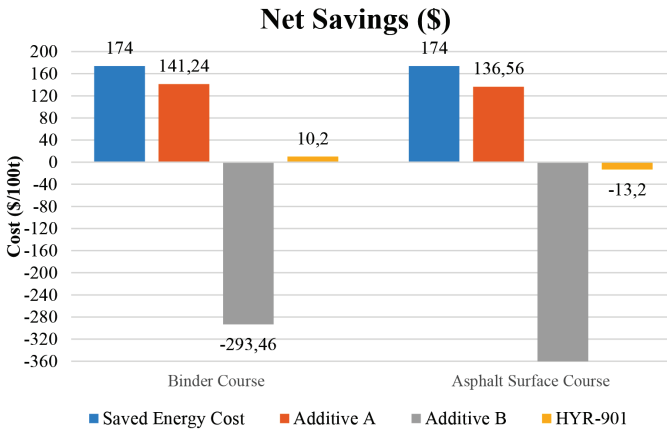


Fig. 12 *Energy savings and additive costs*

The savings value shown in blue in Fig. 12 should be evaluated as the amount gained from the asphalt production in the case of a 25°C decrease. Compared to the cost of the additives, although the B additive is the highest cost (Tab. 9), it provides fewer savings due to the high unit cost. The A additive provides the lowest cost since the contribution rate is low. However, when the A additive is used, the maximum temperature reduction is approximately 15°C, which increases the energy costs shown above, compared to 25°C. In this case, the HYR-901 is a highly preferable additive as it saves 10.2$ per hour for 100 tons of asphalt production for the binder layer, depending on the viscosity. Due to its ease of production, environmental impact, and cost, the HYR-901 can be a preferable addition to WMA technology.

5 DISCUSSION AND CONCLUSION

In this study, the performance evaluations of the WMA additives were made based on the specifications. These evaluations were tested on the binder and surface course, which is preferable more in terms of traditional asphalt use, and compared according to the Marshall Stability values after the use of the additive ratios.

In the laboratory, the experiments were performed by adding 50/70 penetration bitumen and a WMA with A, B, LOMOT, PDL6020, on HYR-901 additive. As a result of these experiments, additives that can provide low-temperature production in terms of viscosity were determined and preferred according to their suitability for asphalt concrete production. The additives and bitumen rates were used to prepare Marshall test specimens for A, B, and HYR-901, which include one new product and two known products for the surface course and binder layers. These specimens were compared with the reference sample to examine the performance values of the additives at low temperatures.

As a result of the modifications made with the 50/70 penetration bitumen WMA additives, it has been observed that each additive affects the properties of bitumen differently:

- Since the penetration value is inversely proportional to the viscosity, as the penetration increases, the bitumen softens; the higher the viscosity, the harder the bitumen. Since the viscosity of bitumen with very high softening points is also high, their production temperatures are also high. It was observed that the A and B additives decreased penetration, while the other additives (HYR-901, PDL6020, and Lomot) increased it. It was observed that the A additive did not change the softening point value; the PDL6020 and LOMOT increased it slightly, and the HYR-901 decreased this value a little. The B additive increased the softening point value by 65%.
- Since the performance of these additives was evaluated according to the bitumen ratio used, the efficiency required has been achieved without any change in the bitumen ratio. The fuel savings, energy efficiency, and increase in the workability of the mixture at low temperatures will reduce the harmful effects on the environment and will provide positive effects on the health of workers.
- The energy savings from the asphalt production are calculated as an average of 174 $/h. When the unit costs of the additives compared to this amount are examined, at a temperature difference of 25°C, the HYR-901 additive for the binder layer has a profit of 10.2$/h for 100 tons of asphalt production.
- The values obtained as a result of the viscosity tests show that the A and HYR-901 additives have better capacity for the reducing temperature. In particular, the HYR-901 additive might be used in cold climates. It was observed that the production temperatures of WMA prepared with these additives (A, B, and HYR-901) decreased by 20-30°C. This decrease in the mixture temperatures not only saves fuel but also means a reduction in harmful gas emissions in the production plant.

As a result of the Marshall tests performed on the surface course and binder layer, it has been seen that it can be very beneficial to use additive mixtures for the production of WMA in terms of strength and stability. Also, this study shows the new WMA additive products are very beneficial and performed well compared with the others. At this time, preferring WMA and similar technologies will be beneficial as they are economical and environmentally friendly.

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