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Study of the impact of adhesion promoters on the properties of road bitumens

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Abstract:
The influence of cationic adhesion promoters of the amine type on the properties of petroleum road bitumens is studied in the article. The impact of the selected adhesion promoters on standard quality indicators of bitumen, such as penetration, softening point, and penetration index, is evaluated. The effect of the promoters on bitumen adhesion is assessed using the bottle rolling method and the glass surface adhesion method. The thermal stability of the promoters was determined by evaluating the reduction in bitumen adhesion after short-term ageing. The influence of adhesion promoters on the bitumen contact angle is also investigated. The following set of indicators is proposed for the evaluation of the effectiveness and thermal stability of adhesion promoters.

Keywords:
adhesion, adhesion promoter, bitumen, thermal stability, ageing

1. Introduction

In most countries, asphalt concrete is the predominant material for highway pavement construction. The physical and mechanical properties of asphalt concrete pavements, as well as their durability, are substantially influenced by the quality of bituminous binders. These binders bond the mineral aggregates into a continuous monolithic structure. Throughout the operational lifespan of the asphalt pavement, the bituminous binder must satisfy several critical performance criteria. Adhesion to the surface of aggregates must stay as strong as possible. It is important to note that resistance to traffic loads and temperature fluctuations is also provided by bitumen's cohesive and rheological properties. Ageing resistance must be high enough to exhibit minimal degradation in bitumen properties over time when subjected to mechanical and environmental factors, as well as internal physical-chemical processes.

The strength of the bond between bitumen and the surface of aggregates depends on the adhesive capability of the binder and the chemical-mineralogical composition of the aggregates [1,2]. Bitumen is a relatively inert material that contains a small amount of active, predominantly anionic, substances. In road construction globally, aggregates of acidic igneous origin, characterized by a high silicon dioxide content (e.g., granites, diorites, andesites, quartzites), are widely used. Silicon oxides form anion-active centers on the surface of the mineral material, making it a predominantly negatively charged [3,4]. The presence of negative charges on the surfaces of both the bitumen and the mineral material on both the bitumen and mineral surfaces precludes electrostatic attraction or direct chemical interaction. Consequently, adhesion is primarily achieved through physical adsorption, wherein lighter bitumen fractions are absorbed into the micropores and fissures of the mineral particles. However, this mechanism of physical adsorption alone is insufficient to provide a strong binder-aggregate bond. As a result, water, which wets the acidic rocks better than bitumen, displaces the bitumen film from the aggregate surface. Subsequently, under the action of vehicle tires, unbound mineral particles are displaced from the pavement structure, which initiates a process of pavement surface degradation, including peeling, formation of potholes, and other structural defects. A strong bitumen-aggregate bond can therefore be achieved by enhancing the adhesive activity of the binder.

Since the 1950s, the primary strategy for improving the adhesive properties of road bituminous binders has been the use of adhesion promoters [2,5–7]. During the 1950s, the main functions of adhesion promoters were established [8], namely: to enable bitumen to coat moist mineral aggregates and to enhance the water resistance of asphalt. As a result, the key requirements for adhesion promoters were formulated [7]. These include: ensuring strong adhesion between bitumen and the surface of aggregates; not adversely affecting the bitumen properties; being effective at low dosage rates; and cost-effectiveness, avoiding significant increases in the overall cost of asphalt pavement

The initial adhesion promoters that became widespread in European road industries were primary fatty amines [7], which were used to increase active adhesion. Over time, a diverse array of adhesion promoters has been developed and implemented across global road industries, accompanied by the proposal of numerous methods for assessing bitumen adhesion to aggregates [1,7,9–11]. These promoters are classified based on their mechanism of action (cationic, anionic, nonionic, and amphoteric), chemical composition (amine-based, polyphosphoric acid-based, and phosphate-containing compounds, organosilanes, etc.), and their functional impact on bitumen (plasticizing, structuring, or destructuring) [1].

Currently, cationic promoters based on amine- or phosphorus-containing compounds are predominantly employed in the road construction industry of most countries [7,9–11]. These promoters impart a positive surface charge to the bitumen, thereby facilitating electrostatic attraction with the typically negatively charged aggregate surfaces. Additionally, chemical interactions occur within the interfacial zone between the surface-active cationic compounds present in the bitumen and the active sites of the aggregates. These interactions lead to the formation of water-insoluble compounds at the phase boundary (e.g., silicate-amines, carbonate-amines, silicate-phosphates). This ensures a strong and durable bond between the modified bitumen and the aggregate surface. Prominent examples of amine-based adhesive promoters include Wetfix BE [9], Rediset WMX [11], Cecabase [11].

Organosilane-based adhesion promoters are currently gaining traction in the industry due to their significant efficacy in enhancing bitumen adhesion and aggregate wettability, even at remarkably low concentrations (0.01% of bitumen mass) [11]. Another contemporary focus is the development of environmentally sustainable bitumen adhesion modifiers derived from biological sources – rapeseed oil [12–14], bio-oil [15], fish oil ethyl ester [16].

The choice of an adhesion promoter is typically governed by several factors: the effectiveness in improving the binder's adhesion to aggregate surfaces; the thermal stability of the promoter; its mechanism of interaction with the binder; processing characteristics (physical state and optimal mixing temperature); sanitary and hygienic properties (odor, hazard classification); and cost-effectiveness. Considering the fact that the adhesion efficiency of most promoters is relatively comparable, the efficiency-to-cost ratio becomes a particularly important criterion. This highlights the relevance of developing cost-effective adhesion promoters that match the performance of commonly used alternatives. Furthermore, the effectiveness of an adhesion promoter is influenced by the structural–rheological type of bitumen [17] and the mineralogical composition of the aggregates. Therefore, modern adhesion promoters should be customized for bitumen binders of varying chemical compositions.

Additionally, adhesion promoters, depending on the type and composition of the surfactant agent, can exert diverse effects on bitumen, including destructuring, structuring, plasticizing (leading to a decline in quality indicators across a wide temperature range), or inhibiting oxidative aging of bitumen. Consequently, it is imperative to assess not only the efficacy of promoters but also their impact on the standard quality parameters of bitumen

The objective of this research is to evaluate the influence of the novel adhesive promoter Dinodor A1 on the properties of pavement bitumen. To achieve this goal the study involves: experimental determination of standard quality indicators (penetration, softening point) for road petroleum bitumen with different concentrations of the adhesive promoter Dinodor A1; quantification of the influence of the new promoter on the adhesive properties of bitumen, using multiple assessment methods; evaluation of the thermal stability of the Dinodor A1 additive after aging of bitumen by the RTFOT method. The effectiveness of the use of the adhesive promoter Dinodor A1 is assessed by comparing its influence on the properties of bitumen in comparison with the influence of the adhesive promoter Wetfix BE, which is widely used in European countries. The novelty of the work is the application of a proposed set of indicators to evaluate the effectiveness of Dinodor A1 adhesive promoter.

2. Experimental

2.1. Materials

Two adhesive promoters were taken as objects of research in the work – Dinodor A1 (a novel promoter produced in Ukraine) and Wetfix BE (a widely known promoter in the world, produced in Sweden). Both are cationic amine-type promoters, which are in a liquid state at a temperature of + 25 °C. Their properties are presented in Table 1.

The initial materials for the modification were two petroleum road bitumens (B1 and B2) 70/100 grade, produced by the Polish company PKN Orlen, made from different crude at the various refineries. The bitumens are characterized by similar penetration values at a temperature of 25 °C (71 × 0.1 mm and 76 × 0.1 mm, respectively) and softening point (45.8 °C and 47.6 °C, respectively), but differ significantly in adhesion characteristics.

Table 1. The characteristics of adhesion promoters. Source: own study

Physical properties	Adhesion promoter	
	Dinodor A1	Wetfix BE
Acid value (mg KOH/g)	< 10	< 10
Amine value (mg KOH/g)	246-285	246-285
Appearance at 25°C	liquid	liquid
Flash point (°C)	> 180	> 218
Pour point (°C)	< -22	< -20
Density at 20°C (g/cm^3)	0.92	0.98

The modification was performed by mixing for 15 min in a laboratory mixer, road bitumen at a temperature of 150 ... 155 °C with an adhesive promoter. The concentration of the adhesive promoter used in the research was 0.3 and 0.5 wt. % of the amount of bitumen (by weight), which is based on the manufacturer's recommendations.

2.2. Methods

Standard quality indicators of binders (penetration at 25 °C, softening point, and penetration index) were evaluated according to the specifications outlined in EN 12591 [18].

The adhesive properties of binders were determined:

- by the rolling bottle test, according to the requirements of EN 12697-11 [19],
- by the method of determining adhesion to glass (the method is standardized in Ukraine).

When determining adhesion by the bottle rolling test, granite crushed stone fractioned to 5 - 10 mm was used as the aggregate. The aggregates were previously washed of dust and dirt and dried to a constant mass. The aggregates preheated to 150 °C were mixed with bitumen heated to the same temperature, ensuring uniform particle coating. The resultant aggregate-bitumen mixture was kept at ambient temperature for 18–24 hours before testing. The experimental procedure involved subjecting the binder-treated aggregates to mechanical agitation in distilled water for a duration of 6 hours.

The adhesion of bitumen to the glass surface was tested according to a method standardized in Ukraine. The essence of the method is to determine the ability of bitumen binder, applied as a uniform 200 μm layer onto a medical glass slide (76 × 25 mm), to resist the peeling effect of water [20]. The glass slides are first thoroughly cleaned under running water, then boiled in distilled water for 30 minutes. The clean glass slide is dried in a drying cabinet at temperatures ranging from 105 to 125 °C. The prepared glass slide is placed on a special device that provides uniform heating of the glass to a temperature of 150 °C for 1–3 min. A measured quantity of bitumen was applied to the heated glass surface and evenly distributed. The prepared samples were maintained in a horizontal orientation within a drying cabinet at a temperature of 85 °C above the binder's softening point for 5 minutes to facilitate uniform bitumen distribution. The core of the test involved exposing these samples to distilled water at 85 °C. Changes in the bitumen-covered area were periodically monitored and quantified using a webcam and associated analytical software (Fig. 1). Binder adhesion was obtained as the percentage of the glass surface remaining coated with bitumen post-exposure. For each bitumen sample, five replicate glass slides were tested, and the final adhesion value was calculated as the arithmetic mean.

The influence of adhesive promoters on the wettability of the substrate by bitumen was quantitatively assessed by measuring contact angles. This evaluation employed a methodology analogous to the Sessile Drop Method. A medical glass slide was used as a substrate. Three drops of bitumen binder, heated to a temperature 80 °C above its softening point, were carefully applied to the prepared surface of the glass slide. These drops were then allowed to cool to ambient temperature. After this, the glass slide was placed for 30 min in a drying oven preheated to the process temperature (temperatures of 90 °C, 110 °C, and 130 °C were used). The samples prepared in this way, after cooling to ambient temperature, were used to measure the contact angle of bitumen binders.

The thermal stability of adhesive promoters was determined by the decrease in adhesion after laboratory aging of bituminous binders using the RTFOT method [21].

The efficiency of the adhesion promoters studied is evaluated using the following characteristics:

- adhesiveness increase index (A_i) (Eq. 1):

$$A_i = \frac{A - A_0}{A} \cdot 100, \tag{1}$$

where A is the adhesion value of the bitumen with the adhesion promoter (%) and A_0 is the adhesion value without the adhesion promoter (%);

- thermal stability index (A_{ts}) (Eq. 2):

$$A_{ts} = \frac{A_{before} - A_{after}}{A_{before}} \cdot 100, \tag{2}$$

where A_{before} is the adhesion value before aging (%) and A_{after} is the adhesion value after aging (%);

- index of the adhesion reduction rate during the test (A_R) (Eq. 3):

$$A_i = \frac{A_{2.5} - A_{10}}{10 - 2.5}, \tag{3}$$

where $A_{2.5}$ is the adhesion value after 2.5 minutes of exposure in distilled water at 85 °C (%) and A_{10} is the adhesion value after 10 minutes of exposure under the same conditions (%).

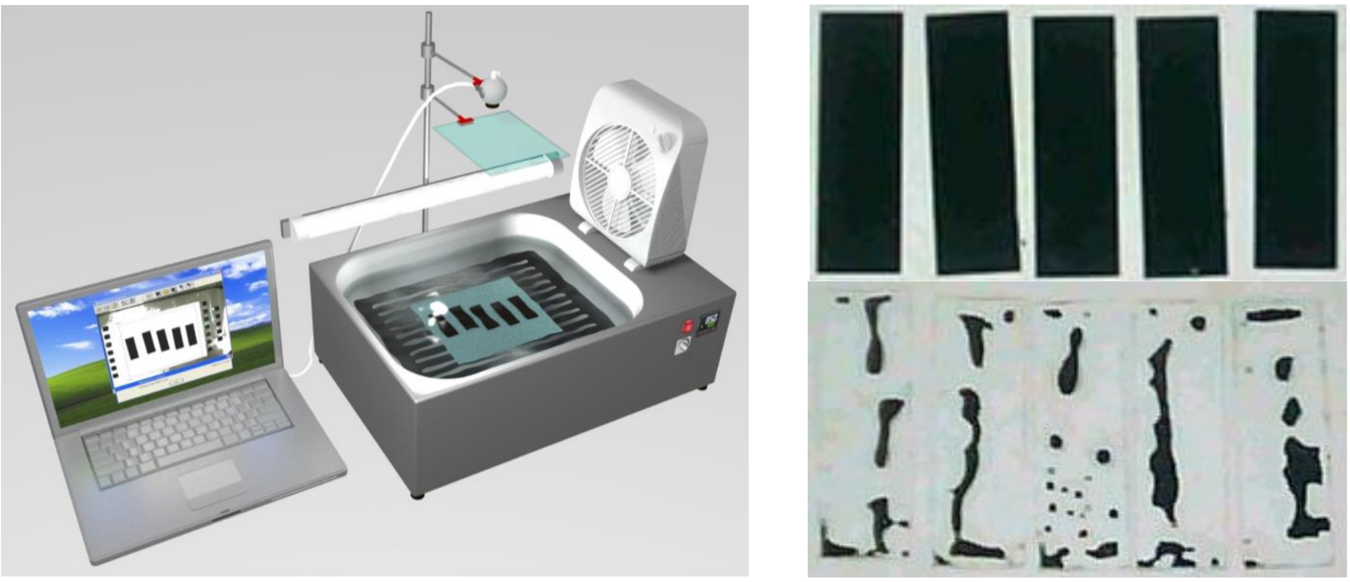

Fig. 1. Appearance of the equipment for determining the adhesion of bitumen to the glass surface, and a typical appearance of the samples before (top) and after (bottom) testing. Source: own study

The determination of the rate of bitumen peeling during the test was quantified by analyzing the temporal evolution of the glass surface area coated by the binder. Previous experimental data [22], indicate that this evolution can be modeled using a polynomial equation. For all bitumen binders tested, an increase in test duration resulted in a slowing decrease in the bitumen-covered area, eventually reaching a plateau where further increases in test time yielded negligible changes. Critically, the initial rate of decrease in the bitumen-covered area was found to be contingent upon both the inherent structural and rheological characteristics of the bitumen and the specific properties of the adhesive promoter.

3. Results and discussion

3.1. The influence of adhesive promoters on the standard properties of bitumens

Analysis of the experimental results (Table 2) reveals that the efficacy of a specific adhesive promoter can exhibit significant variability across different bitumen types. The softening point emerged as the least sensitive parameter, demonstrating minimal alteration irrespective of the adhesive promoter's concentration. Specifically, the maximum observed deviation in softening point between the original and modified bitumens across all tested samples was 0.7 °C, a variation well within acceptable experimental error margins. Similarly, no regular patterns of changes in the softening point with the increase in concentration of adhesion promoter were found. This observation suggests that the studied promoters do not plasticize the bitumen at temperatures close to the softening point.

In contrast, the impact of the adhesive promoter was clearly discernible in the penetration measurements. The modification of base bitumens B1 and B2 with the adhesive promoter Dinodor A1 resulted in a pronounced plasticizing effect at 25 °C, which intensified proportionally with increasing promoter concentration. For binders made on bitumen B1, with 0.3 wt. % of the promoter, penetration at a temperature of 25 °C increases from 71×0.1 mm to 88×0.1 mm, and with 0.5 wt. % of the promoter to 92×0.1 mm. The increase in penetration is almost 30 %. Similarly, 0.3 wt. % of the promoter Dinodor A1 in bitumen B2, increases the penetration of the binder from 76×0.1 mm to 82×0.1 mm, and 0.5 wt. % of Dinodor A1, respectively, to 84×0.1 mm, i.e., an approximate 10 % increment.

The observed enhancement in penetration, coupled with the negligible changes in softening point, indicates a reduction in the temperature susceptibility of the bitumen. This phenomenon directly influences the penetration index, a trend that was more clearly evidenced in the results obtained for bitumen B1.

The observed difference in the change of penetration between two bitumens may appear due to the presence in the composition of bitumen B1 of a substance that provides an unusually high value of adhesion to glass for unmodified petroleum road bitumen, which is 40.4 %. This hypothesis is further supported by the comparatively lower plasticization of bitumen B2 (adhesion to glass for original B2 is 20.8 % only) by the same promoter Dinodor A1.

In contrast, for the Wetfix BE adhesive promoter, regardless of its concentration and the original bitumen, the penetration value at a temperature of 25 °C varies within ± 2×0.1 mm, which is within the permissible error for this quality indicator according to the requirements of EN 1426.

A significant amount of information is provided by the analysis of changes in the properties of bitumens with adhesive promoters after aging by the RTFOT method. Regarding the softening point, which almost did not change with the promoters, the Dinodor A1 promoter exhibited minimal influence on the aging of both bitumens. The maximum difference in softening point change caused by the promoter is 0.4 °C only. The Wetfix BE promoter displayed a mild inhibitory effect on the aging, reducing the changes in softening point for bitumen B1 by 0.6 °C and for bitumen B2 by 1.0 °C on average.

The inhibitory effect of the Wetfix BE promoter is also confirmed by the increase in the residual penetration of the modified bitumen compared to the original. For bitumen B1, the residual penetration increases by 4.4 % on average, for bitumen B2 by 5.0 % on average.

However, it should be noted that the observed inhibition of bitumen aging processes occurs due to the thermal destruction of the adhesive promoter itself, which is noticeable by the decrease in its efficiency. Across all bitumens modified with the studied adhesive promoters, a general decrease in adhesion indicators is observed after aging by the RTFOT method. Indirect evidence of the promoter being involved in the bitumen aging process as an inhibitor is also the slowing of aging processes with an increase in the promoter concentration, obtained in almost all cases.

The assessment of aging via residual penetration of bitumens with the Dinodor A1 promoter is complicated by the plasticizing effect of the promoter, which has the most influence on penetration values. It can be noted that the noticeable decrease in residual penetration most likely occurs not due to the aging of bitumen with the promoter, but due to the partial cancellation of the plasticizing effect of the promoter due to its thermal destruction during the process of treatment of the bitumen at high temperature in the RTFOT test.

Table 2. Bitumen binder properties. Source: own study

Quality indicators	Bitumen B1					Bitumen B2				
	original	modified, wt. %				original	modified, wt. %			
		Dinodor A1		Wetfix BE			Dinodor A1		Wetfix BE	
		0.3	0.5	0.3	0.5		0.3	0.5	0.3	0.5
Penetration at 25°C (0.1 mm)	71	88	92	71	73	76	82	84	76	78
Softening point (°C)	45.8	45.1	45.3	45.6	45.8	47.6	47.8	46.5	48.2	47.5
Penetration index	-1.51	-1.15	-0.96	-1.57	-1.44	-0.81	-0.54	-0.85	-0.64	-0.77
Adhesion to glass at 85 °C (%)	40.4	97.5	98.1	94.2	98.3	20.8	90.8	97.2	95.2	96.8
Resistance to hardening (RTFOT, 163 °C, 85 min)										
Residual penetration (%)	78.9	65.9	68.5	83.1	83.6	69.7	64.6	66.7	73.7	75.6
Changes in softening point (°C)	3.3	3.5	3.5	2.8	2.6	4.2	4.1	3.8	3.0	3.3
Penetration index	-1.17	-1.22	-0.97	-1.23	-1.15	-0.61	-0.61	-0.87	-0.64	-0.32
Adhesion to glass at 85 °C (%)	41.9	94.6	95.7	92.6	96.7	19.2	61.4	84.4	86.0	93.1

3.2. The effect of adhesion promoters on the adhesion of binders

The main purpose of the adhesion promoter is to increase the adhesion of bituminous binders. The adhesion promoters investigated in this study consistently increase adhesion to the glass surface, achieving values exceeding 90 % across all original bitumen types and promoter concentrations (Table 1). The difference between the adhesion values of bituminous binders modified with 0.3 and 0.5 wt. % of the considered promoters did not surpass 7.5 %. This difference falls below the adhesion convergence value specified by the Ukrainian standardized method for adhesion assessment. If we do not take into account the thermal destruction of promoters, a concentration of each promoter in the amount of 0.3 wt. % is sufficient to ensure an increase in the adhesion of petroleum road bitumens to a value of 90 % or more.

The results of adhesion evaluation by the bottle rolling test are presented in Table 3, and the appearance of stone materials after testing is presented in Fig. 2.

Table 3. Rolling bottle test results. Source: own study

Quality indicator	Bitumen					
		original	modified, wt. %			
			Dinodor A1		Wetfix BE	
			0.3	0.5	0.3	0.5
Adhesion by the bottle rolling method after 6 hours of testing (%)	B1	25	30	75	35	90
	B2	25	25	70	30	85

The rolling bottle test imposes more stringent conditions compared to the adhesion to glass surface test due to the simultaneous action of water-induced peeling and mechanical friction. Consequently, binders modified with 0.3 wt. % concentrations of the Dinodor A1 and Wetfix BE promoters exhibited adhesion values comparable to those of the original bitumen. However, increasing the promoter concentration to 0.5 wt. % led to a rapid increase in adhesion values, significantly surpassing the Ukrainian road industry's standard requirement of 60 %. Notably, for the Wetfix BE promoter, adhesion values were 15 higher than those achieved with the Dinodor A1 promoter.

During asphalt production, the elevated temperatures required for mixing initiate aging processes in the bitumen. This implies that the moisture resistance of the final asphalt is dictated by the aged binder. If adhesive promoters in bitumen undergo substantial thermal degradation during the asphalt mixing process, they may be ineffective in the asphalt pavement.

The capacity of amine-type promoters to retain their properties after heating is evaluated using the method of adhesion of the binder to a glass plate (Table 2, Fig. 2). The thermal stability of the promoter was found to be significantly influenced by the characteristics of the original bitumen (Figs 3-4).

In bitumen B1, both promoters demonstrated sustained effectiveness throughout the aging process in modified bitumen. The observed reduction in adhesion did not exceed 2.9 % irrespective of the concentrations of both promoters. In contrast, bitumen B2 (Fig. 3) exhibited a more pronounced decrease in the effectiveness of both promoters during aging, particularly at lower concentrations. Specifically, for 0.3 wt. % of the Dinodor A1 promoter, after aging by the RTFOT method, the adhesion to the glass surface decreased by 35.1 %, and when the promoter concentration increased to 0.5 wt. %, the adhesion after aging decreased by 13.1 %. For the Wetfix BE promoter, at a concentration of 0.3 wt. %, after aging by the RTFOT method, the adhesion decreased by 9.7 %, and when the Wetfix BE promoter concentration increased to 0.5 wt. %, the adhesion to the glass surface after aging decreased by only 3.8 %.

Table 4 presents the efficiency characteristics of the adhesive promoters used in the study. The rate of bitumen peeling during the test was determined based on the dependence of the glass surface area covered with the binder on the test time, presented in Fig. 5.

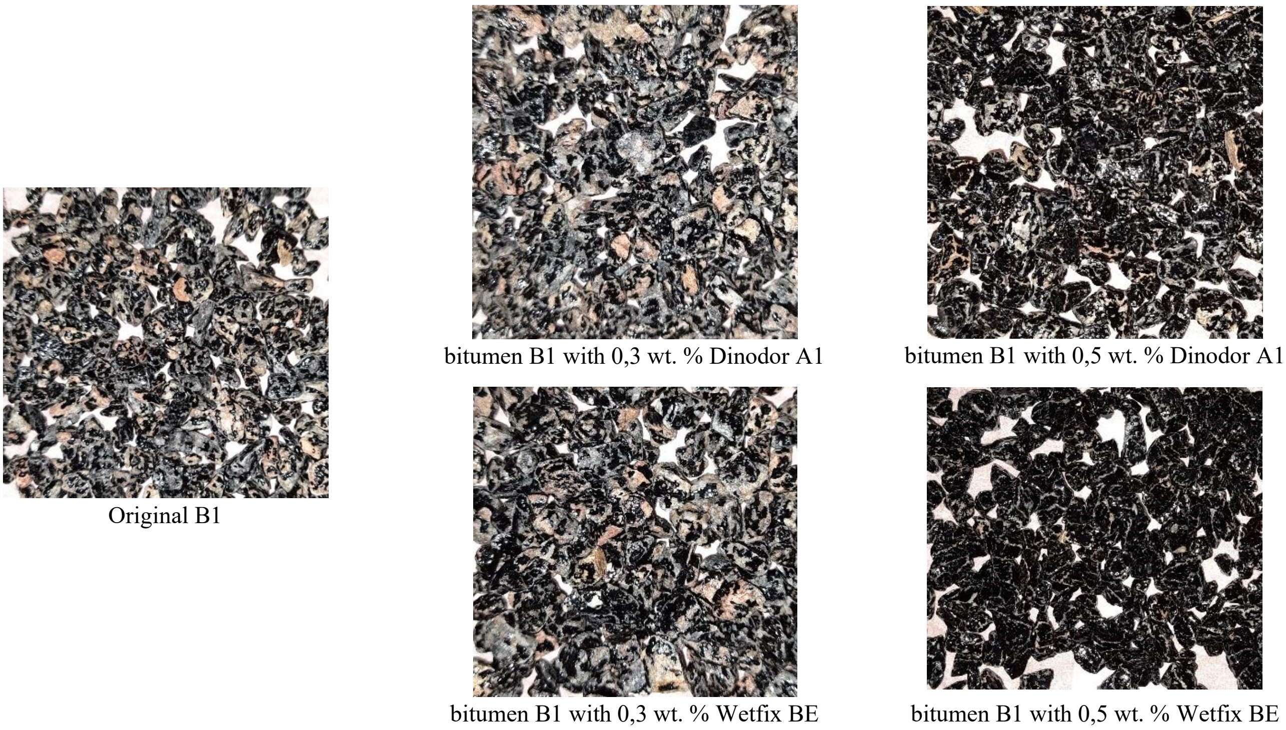

Fig. 2. Appearance of samples after bottle rolling test. Source: own study

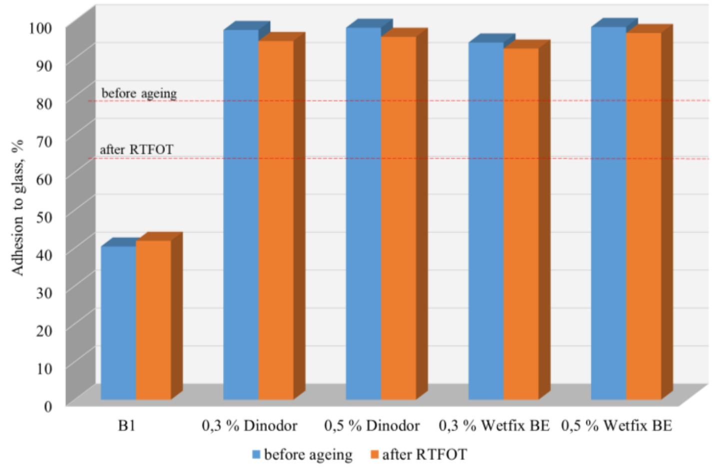

Fig. 3. Adhesion of binders made on the original bitumen B1 (the dotted lines represent the level of the minimum values, normalized by the Ukrainian standards). Source: own study

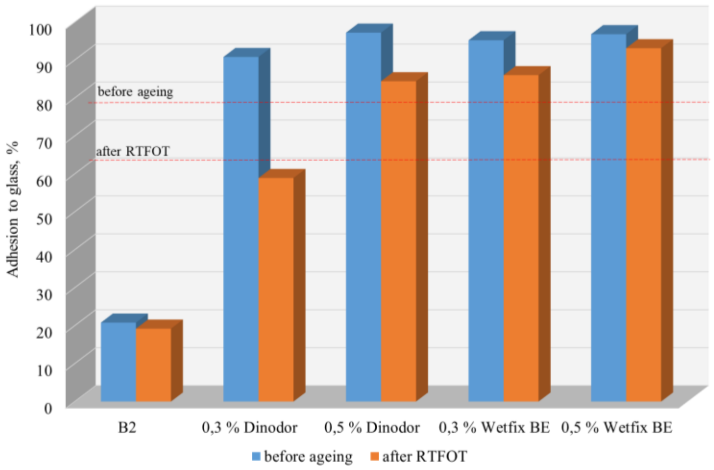

Fig. 4. Adhesion of binders made on the original bitumen B2 (the dotted lines represent the level of the minimum values, normalized by the Ukrainian standards). Source: own study

Table 4. Characteristic of the adhesion promoter's efficiency. Source: own study

Original bitumen	Adhesion promoter	Concentration, wt. %	Index values			
			adhesiveness increase, %	thermal stability, % (after aging)	Adhesion reduction rate	
					before aging	after aging
B1	Dinodor A1	0.3	58.6	3.0	0.05	0.08
		0.5	58.8	2.4	0.09	0.17
	Wetfix BE	0.3	57.1	1.7	0.05	0.16
		0.5	58.9	1.6	0.05	0.07
B2	Dinodor A1	0.3	77.1	35.1	0.09	1.52
		0.5	78.6	13.2	0.08	0.39
	Wetfix BE	0.3	78.2	9.7	0.01	0.43
		0.5	78.5	3.8	0.13	0.29

According to the formulas for determining these indicators, the effectiveness of the adhesion promoter is higher when: the value of the index of increasing adhesion ability is higher; the value of the thermal destruction index is lower; the value of the index of decreasing adhesion rate is lower.

Based on these criteria, the following conclusions can be drawn:

- the amine-type adhesive promoters studied, irrespective of their concentration or the specific bitumen used, effectively increase binder adhesion to a relatively high level. However, the degree to which adhesion is preserved after aging varies significantly among these promoters;
- a higher concentration of the adhesion promoter generally contributes to a better preservation of the modified bitumen's adhesive properties during the aging process;
- the original bitumen plays a critical role in the thermal degradation of promoters during the aging process. Therefore, the recommended concentration of an adhesive promoter should be determined with consideration for its thermal decomposition characteristics within a specific bitumen during aging.

- the indicator of increasing adhesion capacity provides limited information as it evaluates bitumen-promoter adhesion without accounting for the promoter's thermal stability within the bitumen. To accurately assess the effectiveness of an adhesive promoter concerning pavement durability, the thermal destruction index is the more appropriate metric. This index can be determined both by direct determination of adhesion and by the indicator of bitumen peeling rate during testing of bitumens aged by the RTFOT method.

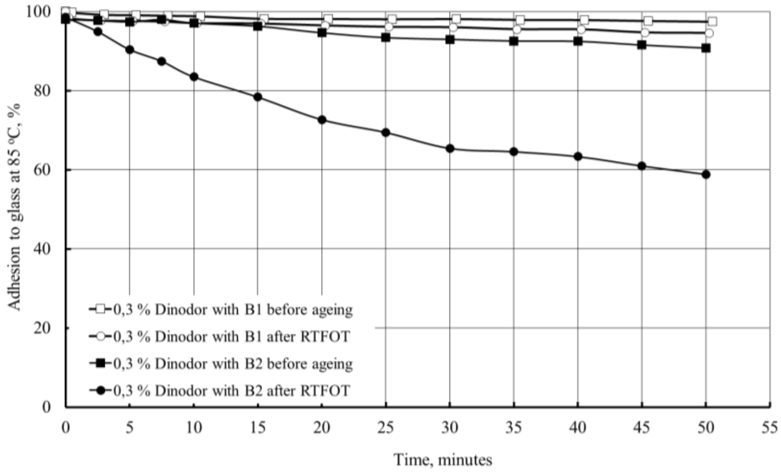

Fig. 5. Dynamics of changes in adhesion of bitumens B1 and B2 modified with 0.3 wt. % of the Dinodor A1 promoter, with test time. Source: own study

3.3. Effect of adhesion promoters on wettability

Adhesive promoters serve a dual purpose: not only do they enhance adhesion, but they also influence the wetting behavior of aggregates by bituminous binders during the asphalt mixing process at the plant. The effect consists of a reduction in the contact angle (surface tension) of binders on the surface of aggregates during the wetting process. As a result, the binder spreads more easily over the material surface. Without the use of adhesive promoters, achieving a similar effect would necessitate reducing the viscosity of the bitumen binder, typically by increasing the technological heating temperature of the asphalt mixture components. Thus, due to the use of adhesive promoters offers the potential to lower the technological heating temperatures required for bitumen binders.

The research involved determining the contact angles of bitumen binder B2, original and modified with the adhesive promoters used in the research, in an amount of 0.3 and 0.5 wt. %. The test was performed for non-aged (Fig. 6) and aged (Fig. 7) bituminous binders.

Data presented in Figs 6-7 indicate that the adhesive promoters under consideration effectively decrease the contact angle of bituminous binders. The Wetfix BE promoter, compared to the Dinodor A1 promoter, slightly decreases the contact angle, while this difference increases with increasing concentration of promoters in the bitumen B2. In the case of a promoter concentration of 0.3 wt. %, the difference in the contact angle values does not exceed 2 °, with an increase in the concentration to 0.5 wt. %, the difference increases to 5 °.

After aging of bitumen binders, an increase in the contact angles of 2-3 ° is observed, compared to bitumens before aging. Binders with the Wetfix BE adhesive promoter, compared to binders modified with the Dinodor A1 promoter, irrespective of the concentration of the promoter used, are characterized by contact angles of 4-5 ° lower.

The data presented in Figs 6-7 suggest that the heating temperatures for bitumen binders modified with the studied adhesive promoters can be reduced during the production of asphalt mixtures. To obtain technological temperatures for heating bitumen during the production of asphalt mixtures, it is advisable to focus on the contact angles of aged binders, since during aging, an increase in the contact angles of 4-5 ° is observed, which on average leads to a change in the technological temperature of up to 10 °C.

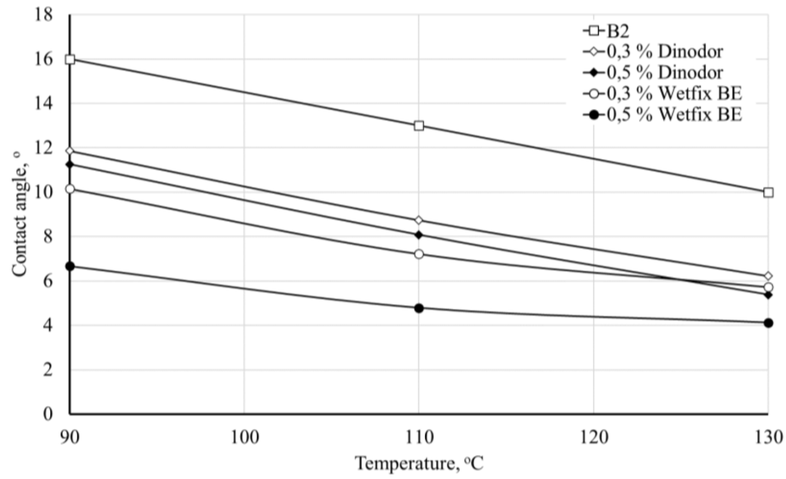

Fig. 6. The influence of adhesive promoters on the contact angle of binders made on bitumen B2. Source: own study

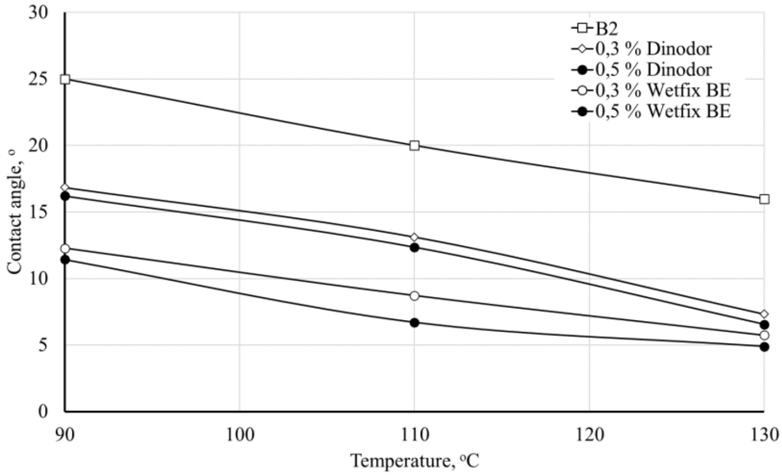

Fig. 7. The effect of adhesive promoters on the contact angle of binders made on bitumen B2 after ageing. Source: own study

4. Conclusions

Based on the experimental data obtained during the research, the following conclusions can be drawn.

1. Dinodor A1, irrespective of the initial bitumen and the concentration of the promoter used in the study, increases adhesion to the glass surface to almost 100 %, which meets the standardized requirements of the regulatory documents in Ukraine. When assessed the adhesion by the bottle rolling test, bituminous binders with 0.5 wt. % of the Dinodor A1 promoter exhibits high adhesion, exceeding the 60 % level, required in Ukraine. A minimum concentration of the Dinodor A1 promoter can be recommended as 0.5 wt. % of the bitumen amount. Nevertheless, this recommendation is of a general nature and must be verified directly on the materials that will be utilised for the production of asphalt mixtures at the plant.
2. The adhesive promoters Dinodor A1 and Wetfix BE are characterized by practically equivalent improvements in adhesion capacity, at concentrations of 0.5 wt. % and above, irrespective of the properties of the original bitumen used for modification. The promoters Dinodor A1 and Wetfix BE display comparable thermal stability values after RTFOT aging, which simulates the change in the properties of binders directly during the asphalt mixing process at the plant and the road pavement construction process. At the same time, bitumen fundamentally affects the thermal stability of amine-type adhesive promoters. Under the same conditions, the same promoter can both maintain and lose adhesion depending on the bitumen. Therefore, the effective promoter concentration, determined after bitumen aging, will depend on the bitumen.
3. By using the adhesive promoters considered in the research, it is possible to reduce the technological temperatures of the asphalt mixing process.
4. The selection of the most suitable and effective adhesion promoter should be guided by preliminary test results performed on the materials that will be used to make the asphalt mixture. In instances where adhesion promoters demonstrate equivalent effectiveness, economic indicators should serve as the decisive factor.

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