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INVESTIGATION OF THE RHEOLOGICAL PROPERTIES OF RUBBER–BITUMEN BINDERS

Viktors Haritonovs
Riga Technical University,Riga, Latvia
e-mail: viktors.haritonovs@rtu.lv

Abstract. This research is devoted to improving the structure and rheological properties of rubber–bitumen binders (RBB) through the modification of petroleum bitumen with crumb rubber and devulcanized rubber particles. The literature review comprehensively examines the physicochemical properties of bitumen, micellar and macromolecular structure theories, mechanisms of interaction between rubber particles and bitumen, and the scientific basis of rheological changes.

In the experimental part, 70/100 grade bitumen was used, and the influence of various rubber contents on the softening point, ductility, penetration, viscosity, and low-temperature brittleness was investigated. The results demonstrated that devulcanized rubber particles effectively integrate into the bitumen structure, form an elastic network, and enhance the stability of the binder at both high and low temperatures.

Rheological tests (Fraass breaking point, ring-and-ball softening point, penetration, and ductility tests) showed improved resistance to deformation, reduced phase angle, and increased complex modulus in modified binders. The findings confirm that rubber-modified bitumen is an effective solution for improving the long-term durability of road pavements.

Keywords: crumb rubber; petroleum bitumen; modification; rheological properties

Introduction. With the rapid development of the road construction industry, improving the quality of bituminous binders remains a pressing challenge. The use of rubber–bitumen binders is considered one of the most effective approaches to addressing this issue. This technology enables the recycling of waste tires and significantly improves the durability and service life of road pavements [1].

Conventional bitumen is highly sensitive to cracking, temperature fluctuations, and mechanical loads during pavement service. The incorporation of rubber particles increases flexibility, enhances temperature resistance, and improves binder stability [2]. Modification of bitumen with rubber particles is therefore an efficient method for enhancing the properties of road construction materials. In addition to improving mechanical performance, thermal stability, and durability, this approach offers significant environmental benefits by recycling end-of-life vehicle tires [3,4].

Each year, millions of waste tires accumulate in landfills, causing severe environmental damage. Tire incineration releases toxic gases and increases soil and water contamination risks. Recycling waste tires for bitumen modification is one of the most effective solutions to this environmental problem. Tires contain chemically stable compounds that persist in the environment for long periods and release heavy metals and other toxins into the atmosphere. The production of rubber–bitumen binders converts these wastes into valuable resources.

The use of rubber-modified bitumen reduces road maintenance costs due to improved strength and flexibility, which extend pavement service life. This advantage is particularly evident on heavy-traffic roads. Modification with synthetic polymers such as SBS or EVA requires significant financial investment [5], whereas crumb rubber provides a cost-effective alternative, especially in countries with a strong raw-material base such as Kazakhstan.

Over the past decade, research on rubber-modified bitumen has intensified. Studies indicate that a deeper understanding of the interaction mechanisms between rubber and bitumen is essential for improving pavement quality. Under Kazakhstan's climatic conditions, this method significantly enhances crack resistance in cold regions.

Materials and Research Methods

The primary materials used in this study were 70/100 grade petroleum bitumen and crumb rubber obtained from recycled vehicle tires.

The 70/100 grade petroleum bitumen is produced by distillation of heavy petroleum residues followed by oxidation. It has a homogeneous structure, dark brown to black color, a softening point (ring-and-ball method) of 46–48 °C, penetration at 25 °C of 75–90 (0.1 mm), Fraass breaking point of −7…−8 °C, ductility of 110–150 cm, and viscosity at 135 °C of 0.3–0.5 Pa·s.

Its chemical composition includes aromatic oils (40–55%), resins (20–30%), asphaltenes (10–20%), and saturated hydrocarbons (5–10%), providing high mechanical strength and thermal stability.

Crumb rubber was produced from end-of-life vehicle tires by mechanical grinding (particle size < 0.5 mm) supplied by EcoShina (Shymkent, Kazakhstan). The material is characterized by high hardness and elasticity, thermal and chemical resistance, the ability to absorb aromatic oils from bitumen, and high carbon black content, which improves mechanical strength and temperature resistance.

Particle size, morphological uniformity, and chemical stability of rubber particles directly influence the properties of modified bitumen.

The characteristics of the 70/100 grade road bitumen are presented in Table 1. Test results confirmed that the bitumen meets the requirements of ST RK 1373-2013.

Table 1 – Characteristics of 70/100 grade petroleum road bitumen

№	Name of the indicator	Road bitumen 70/100	Actual value	Test method
1	25 °C penetration, not less, mm	71-100	79	ST RK 1226
2	0 °C penetration, not less, mm	22	23	
3	Softening temperature for the ring and ball, °C, not less	47	47	ST RK 1227
4	Elongation at 25 °C, cm, not less	75	>150	ST RK 1374
5	Elongation at 0 °C, cm, not less	3,7	4.6	
6	Dynamic viscosity at 60 °C, Pa*s, not less	145	240	ST RK 1211
7	Kinematic viscosity at 135 °C, mm2/s, not less	250	434	ST RK 1210
8	Ignition temperature °C, not less	230	286	ST RK 1804
9	Fraas brittleness temperature, °C, not more	–20	–22	ST RK 1229
10	Penetration index	from –0.1 to +1.0	–0.9	
11	Solubility %, not less	99.0	99.9	ST RK 1228
12	Paraffin content %, not more	2.5	0.3	ST RK 1230

Bitumen modification was carried out using a laboratory setup consisting of an FLC-IV high-shear mixer, reactor, electric furnace, thermometer, and automatic temperature controller (Figure 1).

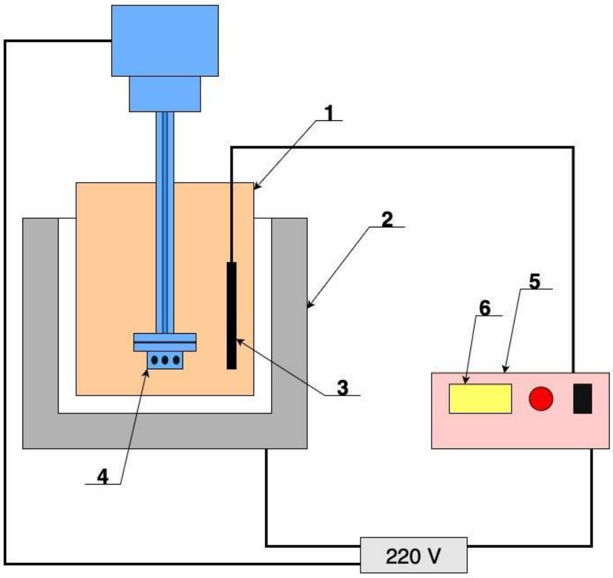

Figure 1 – Scheme of the bitumen modification unit
1 – reactor; 2 – electric furnace; 3 – thermometer; 4 – high shear mixer; 5 – high shear mixer speed controller; 6 – automatic temperature controller

The experimental setup consisted of a cylindrical reactor (1) with a length of 20 cm and an inner diameter of 15 cm. The reactor was heated using an electric furnace (2). Temperature monitoring and control inside the reactor were ensured by a thermometer (3) connected to a temperature controller. The mixing rate of bitumen with rubber particles was controlled by a mixer. The rotational speed of the high-shear mixer (4) was regulated by a speed controller (5). Heating control was achieved by adjusting the power supply of the furnace through an automatic temperature controller (6), and the process temperature was displayed on a digital panel.

The average mass of the modified bitumen sample was 170–200 g. Sample preparation for analysis was carried out as follows. Prior to modification, the bitumen sample was heated to a fluid state (at a temperature not exceeding 140 °C), after which rubber particles were gradually added. The rubber was then incorporated into the molten bitumen, and the mixture was continuously stirred and heated until a homogeneous composition was obtained. The temperature was maintained within the range of 180–190 °C, and depending on the type of modifier, the mixing duration varied from 60 to 180 minutes.

To evaluate the conformity of the prepared modified bitumen binders, the following key physicomechanical properties were determined: softening point, needle penetration depth (penetration), ductility (elasticity), and Fraass breaking point temperature. The softening point was determined by the ring-and-ball method in accordance with ST RK 1227. Penetration was measured using a penetrometer in accordance with ST RK 1226. Ductility, which indirectly characterizes the adhesion of bitumen and is related to the nature of its components, was determined using a CKB-974N ductilometer in accordance with ST RK 1374. The Fraass breaking point temperature was determined using an ATX-04 apparatus designed to evaluate the low-temperature brittleness of bitumen.

Results and Discussion

Modified binders were prepared using conventional crumb rubber (CCR) and devulcanized rubber particles (DRP) at concentrations of 5–25 wt.% in BND 100/130 bitumen. The modification significantly affected bitumen properties (Table 2).

Table 2 – Results of modifying BND 100/130 bitumen with CCR and DRP

Composition	Softening temperature for the ring and ball, not lower, °C 25 °C	Needle penetration depth at 25 °C, not lower, mm	Elongation at 25 °C, not lower, cm	Brittleness temperature on Fraas, not higher, °C
BND 100/130	44	113	150	-24
BND 100/130 - 95% CCR - 5%	45,8	69	139,7	-17,7
BND 100/130 - 95% DRP - 5%	55,7	117	63,2	-18,8
BND 100/130 - 90% CCR - 10%	54,5	65	115,8	-18,6
BND 100/130 - 90% DRP - 10%	64,5	105	48,4	-19,5
BND 100/130 - 85% CCR - 15%	56,8	63	53	-19,1
BND 100/130 - 85% DRP - 15%	61	94	37	-26,5
BND 100/130 - 80% CCR - 20%	61,9	60	21,9	-20,3
BND 100/130 - 80% DRP - 20%	63,5	83	33	-34
BND 100/130 - 75% CCR - 25%	65,6	56,3	15,6	-30,6
BND 100/130 - 75% DRP - 25%	67,1	72	25	-27,7

The table presents the results of modifying BND 100/130 grade petroleum road bitumen using conventional crumb rubber (CCR) and devulcanized rubber particles (DRP). The modifier content was varied from 5 to 25 wt.%, and the dynamic changes in the main physicomechanical properties of the material were comparatively analyzed.

According to the ring-and-ball softening point test, the base bitumen exhibited a softening temperature of 44 °C. With the addition of CCR, this value increased to the range of 45–65 °C, while the use of DRP led to a further increase to 55–67 °C. This indicates a more effective incorporation of DRP into the bitumen structure and a reduced tendency of the material to soften at elevated temperatures.

Penetration results show that in CCR-modified samples, the needle penetration depth decreased significantly (from 113 to 56.3 mm), indicating pronounced stiffening of the material. In contrast, when DRP was introduced, penetration values remained relatively high compared to the initial bitumen (117–72 mm), demonstrating that devulcanized rubber is able to increase stiffness while preserving the elastic properties of the binder.

In terms of ductility, samples modified with CCR exhibited a gradual decrease compared with the base bitumen (150 cm → 15.6 cm). Although ductility values in DRP-modified samples were also lower (63.2–25 cm), the material retained an elastic structure, which can be attributed to the ability of DRP to form a macromolecular network within the bitumen matrix.

Regarding the Fraass breaking point temperature, CCR-modified samples showed values in the range of −17 to −30 °C, whereas a more pronounced decrease in brittleness temperature was observed in DRP-modified binders (from −18.8 °C to −34 °C). These results indicate that DRP modification effectively reduces low-temperature brittleness and enhances material performance under cold climatic conditions.

Overall, the table data demonstrate that devulcanized rubber particles (DRP) penetrate the bitumen structure more actively than conventional crumb rubber (CCR), significantly improving the rheological properties of the binder while maintaining high-temperature stability, adhesion, and low-temperature elasticity.

Conclusions

Based on the research results, the following conclusions can be drawn:

1. Devulcanized rubber particles are the most effective modifier for bitumen.
2. DRP-modified bitumen exhibits high resistance at elevated temperatures and flexibility at low temperatures, improving climatic durability of pavements.
3. Conventional crumb rubber improves high-temperature resistance but degrades low-temperature properties.
4. The optimal rubber content ranges from 10 to 20 wt.%.
5. The physicochemical activity of devulcanized rubber enhances structural stability and rheological performance of bitumen.
6. Binders containing 15–25 wt.% conventional crumb rubber meet RBB 50/70 requirements.
7. Binders containing 5–25 wt.% devulcanized rubber comply with Kazakhstan RBB 70/100 standards.

Overall, rubber-modified bitumen binders demonstrated superior rheological performance compared to conventional bitumen, confirming their effectiveness for long-term and reliable pavement construction, especially in regions with significant climatic variations.

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РЕЗЕҢКЕ БИТУМДЫ БАЙЛАНЫСТЫРҒЫШТАРДЫҢ РЕОЛОГИЯЛЫҚ ҚАСИЕТТЕРІН ЗЕРТТЕУ

Викторс Харитоновс
Рига техникалық университеті,Рига қаласы, Латвия
e-mail: viktors.haritonovs@rtu.lv

Аңдатпа. Бұл ғылыми зерттеу жұмысы резеңке-битумды байланыстырғыштардың (РББ) құрылымы мен реологиялық қасиеттерін жақсарту мақсатында битумды резеңке ұнтағымен, девулканизацияланған резеңке үгіндісімен модификациялауға бағытталған. Әдеби шолу барысында битумның физика-химиялық қасиеттері, мицеллалық және макромолекулалық құрылым теориялары, резеңке бөлшектерінің битуммен әрекеттесу механизмі және реологиялық өзгерістердің ғылыми негізі жан-жақты қарастырылды.

Тәжірибелік бөлімде 70/100 маркалы битум қолданылып, резеңке үлестерінің әртүрлі мөлшерде қосылуы материалдың жұмсару температурасына, созылғыштығына, пенетрациясына, тұтқырлығына және төмен температуралық морттыққа әсері анықталды. Нәтижелер девулканизацияланған резеңке үгіндісінің битум құрылымына тиімді енгенін, серпімді тор түзетінін және дайын байланыстырғыштың жоғары және төмен температураларда тұрақтылығын арттыратынын көрсетті.

Реологиялық сынақтар (Фраас, сақина-шар, пенетрация, дуктилометрия) модификацияланған битумдардың шөгуге қарсы тұру қабілетінің жоғарылағанын, фазалық бұрыштың азайғанын және комплекс модулінің артқанын көрсетті. Зерттеу нәтижелері резеңкемен модификацияланған битумның жол жамылғыларының ұзақ мерзімді беріктігін арттыруға тиімді екенін дәлелдеді.

Түйін сөздер: резеңке үгіндісі; мұнай битумы; модификация; реологиялық қаситеттер.

ИССЛЕДОВАНИЕ РЕОЛОГИЧЕСКИХ СВОЙСТВ РЕЗИНО-БИТУМНЫХ ВЯЖУЩИХ

Викторс Харитоновс
Рижский технический университет,г.Рига, Латвия
e-mail: viktors.haritonovs@rtu.lv

Аннотация. Данное исследование посвящено модификации битумных вяжущих с использованием резиновой крошки, девулканизированной резины, эпоксидной смолы и пластификаторов с целью улучшения структуры и реологических свойств резинобитумных вяжущих (РБВ). В литературном обзоре рассмотрены физико-химические свойства битумов, мицеллярная и макромолекулярная теории строения, механизмы взаимодействия резины с битумом и влияние модификации на реологические характеристики.

В экспериментальной части исследованы битум марки 70/100 с различными содержаниями резиновой крошки. Определены изменения температуры размягчения, растяжимости, пенетрации, вязкости и хрупкости при низких температурах. Установлено, что девулканизированная резина лучше взаимодействует с битумом, формируя однородную эластичную структуру и обеспечивая улучшенные характеристики при высоких и низких температурах.

Реологические испытания (Fraass, Ring-and-Ball, пенетрация, дуктилометрия) показали повышение устойчивости к колееобразованию, снижение фазового угла и увеличение комплексного модуля. Полученные результаты подтверждают высокую эффективность использования резиновой модификации битума для увеличения долговечности дорожных покрытий.

Ключевые слова: резиновая крошка; нефтяной битум; модификация; реологические свойства