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Case study

Assessment of the effectiveness and the initial cost efficiency of hot recycled asphalt using polymer modified bitumen

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ABSTRACT

The drastic increase in environmental concerns and increasing costs of road construction materials necessitate evaluating some alternative solutions. One of the most suitable alternatives is recycling old asphalt pavement to produce reclaimed asphalt pavement (RAP). The RAP materials have been commonly combined with asphalt mixtures during pavement construction. Incorporating RAP material should demonstrate an equivalent or better performance than conventional asphalt mixtures. Conversely, the inclusion of RAP mainly needs to improve performance compared to conventional asphalt mixtures. The key issue of using RAP is to restore the loss properties of aged materials and normally asphalt Agent Rejuvenator (ARA) was used. Also, adding polymers with RAP into the asphalt mixture becomes necessary to obtain the required performance. This study investigated the RAP effects of elastomeric polymer on the performance of the asphalt mixture following Russian standards (GOST). The impact of using PMB with RAP material on the asphalt mixture's performance was primarily considered by employing tests that can reveal the adhesion property. Additionally, the performance of the pavement was evaluated in terms of strength and low-temperature cracking. For this purpose, numerous test methods were implemented to appraise the asphalt performance, such as compressive strength, moisture susceptibility, shear resistance, tensile strength, porosity of the mineral particles, and residual porosity. The results indicated that the overall performance of the asphalt mixtures prepared with RAP and combined with polymer depicted a better performance. Moreover, the initial construction cost for each asphalt composition was estimated and compared. The utilization of PMB increased the cost of the asphalt mixture. However, such an increase in the cost would lead to an increase in the overall performance, especially for RAP mixtures.

1. Introduction

The utilization of reclaimed asphalt pavement (RAP) is receiving more attention worldwide due to the advantages that it can provide, especially the economic and environmental aspects. The characteristic of RAP makes it a splendid alternative for raw materials and, therefore, can decrease the demand for utilizing virgin aggregates. Thus, RAP becomes a cost-effective and eco-friendly substitute for virgin aggregates. RAP utilization also helps decrease the costly new asphalt employed in paving mixtures. Currently, waste materials, like tire rubber, cooking oil, waste fly ash, and even waste glass, are utilized in pavement construction [1–6].

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Nevertheless, reclaimed asphalt pavement (RAP) is the most widely used recycled material in pavement construction. A study conducted by the Federal Highway Administration exhibited that the average RAP content used in the construction of the hot mix is around 10–20% in the United States, although the specifications permit up to 30% utilization. The principal reason for this limitation is the scepticism about the RAP materials' performance in the long term. The technologies for regenerating old asphalt concrete in Russia are still at the initial stage of development. They have not received such widespread use as abroad, where the volume of use of this material is limited to up to 20% of the total amount of asphalt-concrete mixtures [1–10].

In Russia, two methods are mainly implemented for processing the RAP, denoted as the hot and cold methods. In the hot method, the asphalt pavement is heated using infrared energy, crushed to a depth of 3–4 cm, a new mixture is added without or with stirring, and finally, the mixture is laid and compacted. This technology is carried out by special thermo-profiling machines, including heaters with burners, rippers, and hoppers for receiving a new mixture, mixing equipment, and distributing and laying the asphalt concrete mixture. The addition of a new mixture is currently the most utilized. The experience of using the hot method without adding a new mixture did not provide positive results because the intense heating of the asphalt would worsen the physical and mechanical properties of the material [11]. The cold method includes removing and crushing material from asphalt pavement layers, treating them with emulsified or foamed bitumen with or without adding new mineral materials, laying, and compaction [11].

The use of RAP has grown to be ever more common in the asphalt industry, and numerous studies have investigated the mechanical properties of the asphalt mixtures incorporating RAP. Though, the findings of these studies are different in that the application of RAP is still very restricted and that RAP is not preferred use in asphalt construction, particularly the use of RAP materials in new asphalt concrete mixtures [2]. Including RAP in hot mix asphalt (HMA) yielded a shorter fatigue life [12]. Moreover, higher amounts of RAP caused a reduction in the cracking resistance of HMA [2]. Other investigations have revealed that higher RAP content enhances resilient modulus and permeability while decreasing shear strength. Another study observed that higher proportions of RAP influence lowering shear strength [13]. Using recycled asphalt material decreases the rutting resistance because of the round aggregate presence in the recycled asphalt material. The addition of RAP material decreased the fatigue resistance [14]. Unlike virgin aggregates, RAP can decrease the bearing capacity of the asphalt mixture. Increasing the content of RAP gave in more significant permanent deformation and a lower California bearing ratio (CBR) when potentially used as base and subbase materials.

Consequently, it is suggested that the RAP must be combined with virgin aggregates and that the amount of RAP must not exceed 50% [15]. Many studies stated that using low amounts of RAP did not affect the characteristics of the asphalt mixtures [16] [17]. Many countries permit the usage of 15–40% of RAP for mixture designs [18] because adding RAP at a higher ratio may cause various shortcomings, such as low temperature and fatigue cracking and the high RAP content also leads to poor adhesion properties and more moisture damage [19–24]. Also, 20–50% of RAP for building flexible asphalt pavement can save 14–34% of construction costs [25].

Incorporating RAP into the HMA mixtures must be used according to specific criteria. For example, HMA mixes containing RAP must satisfy the requirements for mixtures with virgin materials. The obtained performance of mixtures containing RAP must be equal to or better than the performance of conventional asphalt mixtures [26].

The utilization of polymer-modified bitumen (PMB) to acquire better asphalt pavement performance has been verified. The polymer enhances the rheology and strength of the asphalt mixtures [27]. Styrene-butadiene-styrene (SBS) modified asphalt was implemented because it can significantly help mitigate rutting and fatigue cracking [28–31]. Thus, it is logical to incorporate the SBS modifier into the RAP mixture to increase the asphalt pavement performance. The use of SBS polymer enhances the characteristics of recycled asphalt mixtures even with high content of RAP material. Adding polymer-modified bitumen to the RAP mixtures such as SBS has also exhibited good performance in rutting and cracking [32–35]. The addition of PMB notably enhanced the fatigue resistance for asphalt mixtures up to 50% RAP content. This implies that PMB can be used in asphalt mixtures to avoid fatigue cracking failures [14].

In this study, using different test methods, RAP materials have been used with PMB to measure the final performance of the asphalt pavement. The effect of incorporating PMB with RAP material on the asphalt mixture's performance was mainly evaluated using tests that can indicate the adhesion between the RAP and the virgin mixture, which is a critical issue for the asphalt mixtures prepared with RAP material. Besides, the performance of the pavement mixture was assessed in terms of strength and low-temperature cracking. Moreover, the cost efficiency of using RAP materials was appraised for two countries (the Republic of Iraq and the Russian Federation). In summary, this study concentrates on the adhesion between the RAP and the bitumen and the impact of using PMB on this property. This is combined with cost estimation to guide the agencies for the best alternative.

Table 1
Properties of the neat bitumen.

Test	Results	Specification limits (GOST 22245–90)
Penetration (25 °C; 0.1 mm)	82	61–90
Penetration (0 °C; 0.1 mm)	23	20 (min.)
Softening point (°C)	48	47 (min.)
Penetration index (PI)	-0.48	-1 to + 1
Ductility (25 °C; cm)	100	55 (min.)
Ductility (0 °C; cm)	4	3.5 (min.)
Flash point (°C)	230 +	230 (min)
Brittleness temperature (°C)	-22	-15 (min)
Change in softening point after aging, Δt	4	5 (max.)

2. Materials and methods

2.1. Material

In this study, the neat bitumen with a 60/90 penetration grade has been utilized. Some standard tests have been implemented to assess the physical characteristics, as shown in Table 1. These tests were applied following the Russian governmental standard (GOST 22245–90).

The polymer type used in this study was Styrene Butadiene Styrene (SBS). The DOREKSPERT laboratory supplied the polymer-modified samples. The physical characteristics of the PMB-40 are tested according to the Russian governmental standard (GOST R 52056–2003), as illustrated in Table 2.

According to the Russian governmental standard (GOST 9128–2009), the aggregate used in asphalt pavement construction is classified based on particle size as crushed stone (coarse aggregate), sand (fine aggregate), and mineral powder (filler). The physical characteristics of the aggregate are presented in Table 3. The aggregate gradation has been selected following the Russian specifications.

The properties of the RAP material used in this study are shown in Table 4.

2.2. Design of asphalt mixtures

2.2.1. Bitumen content determination

The design of the asphalt mixtures was done using several tests to estimate the bitumen content for asphalt mixtures. According to the Russian standard, the optimum bitumen content is the average content that falls within the standard limits of several tests, such as water saturation, porosity, water resistance and compressive strength, as shown in Fig. 1.

The results showed that the average bitumen content is around 4.7%, within the standard limits. The bitumen content was selected for RAP mixtures based on the amount of absorbed bitumen. The absorbed bitumen was found using an oven at 500 C temperature (Fig. 2). At such elevated temperatures, the absorbed bitumen in the RAP is evaporated and found to be around 1.5–1.2. Accordingly, the bitumen content is estimated.

2.2.2. Selection of asphalt mixture compositions

Four different composition options were prepared, as shown in Table 5. Composition No.1 consists of virgin aggregate particles mixed with neat bitumen. Composition No.2 contains PMB instead of neat bitumen. Composition No.3 consists of virgin aggregate particles mixed with neat bitumen and RAP. For Composition No.4, the virgin aggregate particles were mixed with RAP and PMB.

2.2.3. Determination of the percentage of polymer (SBS)

To determine the optimum percentage of polymer (SBS), three amounts of SBS (4%, 5%, and 6%) were tested considering the asphalt performance and its limits, as shown in Table 6.

The 4% and 6% SBS modification utilization demonstrated mechanical characteristics outside the standard limits for some compositions. At the same time, using 5% SBS modification resulted in mechanical characteristics that fall within the standard limits. Based on this, the optimum utilization percentage of SBS is 5% which is also compatible with the recommendation of the Russian standard and is suggested to be used by several studies [36–38].

3. Methods

This study performed several tests to evaluate the asphalt mixture performance. Below is detailed information regarding the utilized test methods.

Table 2
Properties of the PMB-40.

Test	Results	Specification limits (GOST R 52056–2003)
Penetration (25 °C; 0.1 mm)	56	40 (min.)
Penetration (0 °C; 0.1 mm)	27	25 (min.)
Softening point (°C)	71	56 (min.)
Ductility (25 °C; cm)	25	15 (min.)
Ductility (0 °C; cm)	11	8 (min.)
Flash point (°C)	230 +	230 (min)
Brittleness temperature (°C)	-20	-15 (min)
Elastic recovery (25 °C)	92	80 (min.)
Elastic recovery (0 °C)	84	70 (min.)
Change in softening point after aging, Δt	3.6	5 (max.)
Homogeneity	uniform	uniform

Table 3
Gradation of the aggregate.

Test	Selected Gradation For Virgin Aggregate	Selected Gradation For Virgin Aggregate + RAP	Specification Limits (GOST 9128–2009)
Sieve analysis			
Sieve no			
40	100	100	100
20	97.75	97.68	90–100
15	89.68	89.82	80–100
10	74.47	77.13	70–100
5	54.24	54.33	50–60
2.5	49.11	47.37	38–60
1.25	43.09	41.29	28–60
0.63	35.08	33.08	20–60
0.315	20.49	20.97	14–34
0.14	13.47	13.81	10–20
0.071	10.59	11.04	6–12

Table 4
Properties of the RAP material.

Names of indicators	Specification limits	Results
Bitumen content, %	not standardized	5.39
density of the mineral part, g / cm3	not standardized	2.78
Coefficient of variation in the content of fractions 0.071–5 mm	no more than 0.25	0.12
Coefficient of variation in the content of grains smaller than 0.071 mm	no more than 0.20	0.12
Coefficient of variation in the content of bitumen	no more than 0.20	0.18

3.1. Average density of the compacted sample

The principle of the method is to determine the average density of samples made in the laboratory or selected from the structural layers of road pavements, taking into account the pores within the pavement. In this test method, samples are weighed in the air and then immersed for 30 min in a vessel with water having a temperature of (20 ± 2) ° C so that the water level in the vessel is at least 20 mm higher than the surface of the samples, after that the samples are weighed in water. The average density of the sample from the mixture, g / cm3, is calculated by the following formula (Eq. (1)).

$$\rho_m = \frac{g\rho^B}{g_1 - g_2} \tag{1}$$

where g is the mass of the sample in the air (g); ρ^B is the density of water, equal to 1 (g/cm3); g_1 is the mass of the sample immersed in water (g); g_2 is the mass of the sample kept for 30 min in water and re-suspended in the air (g).

3.2. Determination of compressive strength

This test method intends to determine the load the sample can bear before fracturing under given conditions. The compressive strength of the samples is determined by utilizing an electro-mechanical press at a pressing speed of (3.0 ± 0.3) mm/min (Fig. 3).

In this method, the samples are tested at different temperatures using water baths like (50 ± 2) °C, (20 ± 2) °C, or (0 ± 2) °C. The temperature (0 ± 2) °C is achieved by mixing water with ice. Samples from hot mixes are kept at a given temperature for 1 h in water. The sample taken from the water bath is placed in the centre of the lower plate of the press, and then the upper plate is lowered and stopped above the level of the sample surface by 1.5–2 mm.

Compressive strength R_c, MPa, is calculated by the formula (Eq. (2)).

$$R_c = \frac{P}{F}10^{-2} \tag{2}$$

where P is the breaking load (N); F - initial cross-sectional area of the sample (cm2); 10^{-2} - conversion factor to MPa.

The compressive strength technical requirements for asphalt concrete (Type B) according to the Russian standard are presented in Table 7.

3.3. Determination of moisture susceptibility

This test aims to assess the degree of drop in compressive strength of the samples after exposure to water under a vacuum. Moisture Susceptibility K_b is calculated by the formula (Eq. (3)).

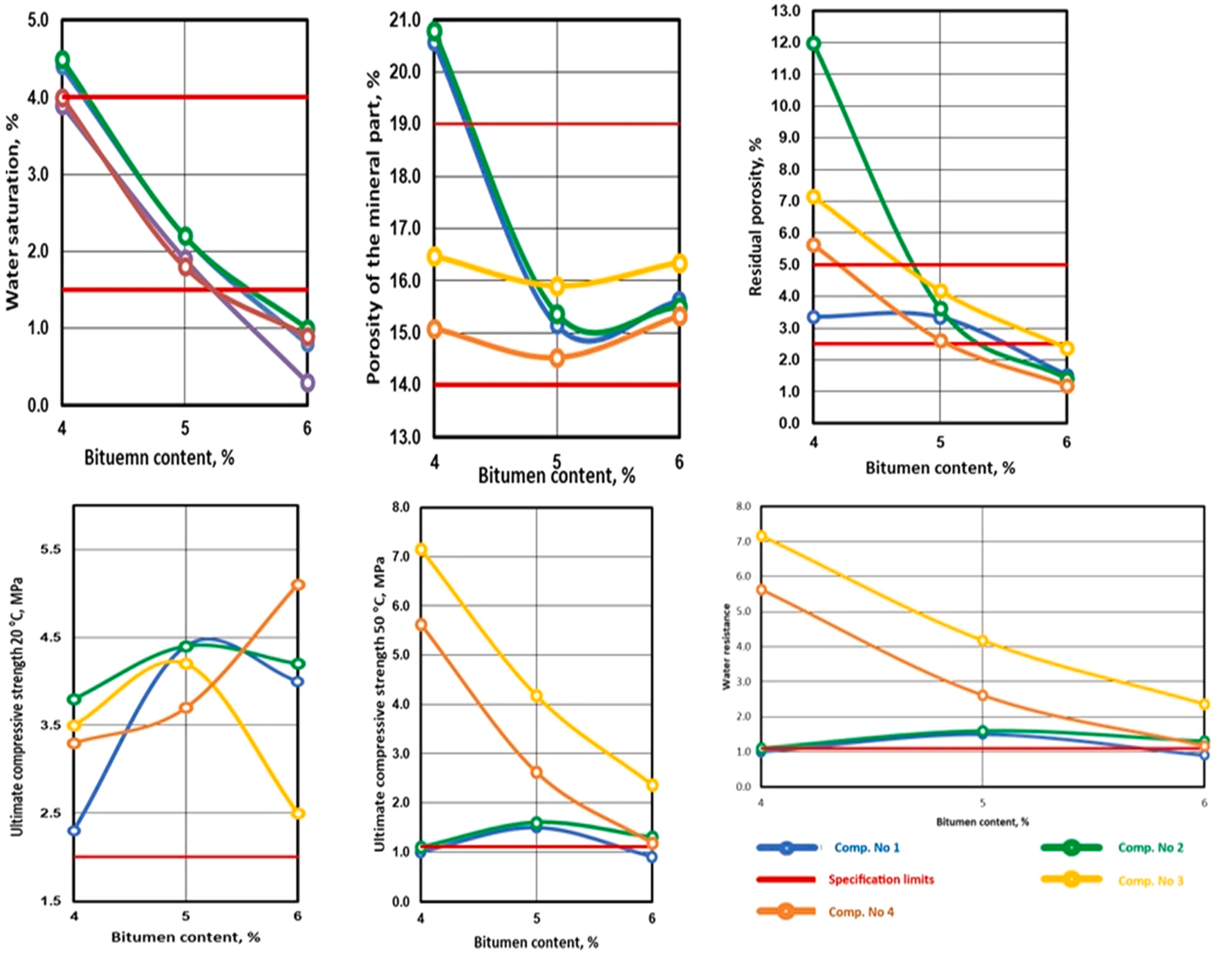

Fig. 1. OBC determination.

Fig. 2. Lab Drying Oven.

$$K_b = \frac{R_C^B}{R_C^{20}} 10^{-2} \tag{3}$$

where R_C^B is the compressive strength of samples conditioned by vacuum saturation with water at a temperature of (20 ± 2) °C for 1-hour (MPa); and R_C^{20} is the compressive strength of unconditioned (control) samples at a temperature of (20 ± 2) °C samples (MPa).

The minimum moisture susceptibility for asphalt concrete (Type B) according to the Russian standard (GOST 12801–98) is 0.7.

Table 5
Mixture compositions.

Materials	Composition No.1	Composition No.2	Composition No.3	Composition No.4
RAP (%)	0	0	29.6	29.7
Crushed stone (%)	40.0	40.0	29.6	29.7
Sand (%)	46.7	46.7	29.6	29.7
Mineral powder (%)	8.6	8.6	7.7	7.7
Neat bitumen (%)	4.7	0	3.5	0
PMB (%)	0	4.7	0.0	3.2
Total (%)	100	100	100	100

3.4. Shear resistance

This test method determines the maximum loads and the corresponding limiting deformations of standard cylindrical specimens under two stress-strain states (Figs. 4 and 5).

The loading rate of the samples for both compression schemes is the same, equal to (50.0 ± 1.0) mm/min. Before testing, the samples and the crimping device are kept for 1 h at a specified temperature (50 ± 2) °C in water. The sample taken from the water bath is installed in the centre of the lower press plate in the first compression scheme or the lower part of the crimping device in the second compression scheme. During the sample test, the maximum reading of the force meter is recorded, which is taken as the breaking load. At the same time, with the help of the displacement indicator, the ultimate deformation corresponding to the breaking load, or the beginning of the yield stage is measured.

For each specimen tested using uniaxial compression and Marshall stability breaking head, power destroys the testing sample model, A, which is calculated according to the following formula (Eq. (4)).

$$A = \frac{Pl}{2} \tag{4}$$

Where A is the power that destroys the testing sample model (kN.mm); P is the breaking load (kN); l is the ultimate deformation at the time of the destruction of the HMA sample (mm); g_5 is the mass of the sample kept for 30 min in water and re-suspended in the air (g).

The internal friction coefficient of asphalt concrete is tg_{φ} calculated by the formula (Eq. (5)).

$$tg_{\varphi} = \frac{3(A_m - A_c)}{3A_m - 2A_c} \tag{5}$$

where A_m, A_c is the average load-deformation of asphalt concrete samples during testing for Marshall scheme and uniaxial compression, respectively.

Cohesion C_{π}, MPa, is calculated by the formula (Eq. (6)).

$$C_{\pi} = \frac{1}{6}(3 - 2tg_{\varphi})R_c \tag{6}$$

where R_c, MPa, is the compressive strength is calculated by the formula (Eq. (7)).

$$R_c = \frac{P}{F}10^{-2} \tag{7}$$

where P is the breaking load (N); F is the initial cross-sectional area of the sample, cm2; 10^{-2} is the conversion factor in MPa.

The minimum Internal friction angle for asphalt concrete (Type B) according to the Russian standard (GOST 12801–98) is 0.81 (min.), and the minimum cohesion at 50 ºC is 0.36 MPa.

3.5. Determination of tensile strength

This test method determines the load required to fracture (crack) the sample. Before testing, the samples are cured at a given temperature (0 ± 2) °C for at least 1 h in water. The tensile strength is determined on press at a given constant speed of (50 ± 1) mm/min. The sample is placed in the centre of the lower plate of the press on the side surface (Fig. 6), and then the upper plate is lowered and maintained at 1.5–2 mm above the level of the sample surface. The maximum reading of the force meter is taken as the breaking load.

Tensile strength at break up (crack) R_p, MPa, is calculated by the formula (Eq. (8)).

$$R_p = \frac{P}{hd}10^{-2} \tag{8}$$

where P is the breaking load (N); h is the sample height (cm); d is the sample diameter (cm); 10^{-2} is the conversion factor to MPa.

Table 6
SBS polymer content determination.

Composition No.	Density g/cm3			Water saturation, % by volume			Porosity of the mineral part, % by volume			Residual porosity, % by volume			Ultimate compressive strength 20 °C, MPa			Ultimate compressive strength 50 °C, MPa		
SBS content, %	**4**	**5**	**6**	**4**	**5**	**6**	**4**	**5**	**6**	**4**	**5**	**6**	**4.0**	**5.0**	**6.0**	**4.0**	**5.0**	**6.0**
Composition No. 1	2.30	2.48	2.49	4.4	2.2	0.8	20.6	15.2	15.6	3.4	3.3	1.5	2.3	4.4	4.0	1.0	1.5	0.9
Composition No. 2	2.29	2.47	2.49	4.5	2.2	1.0	20.79	15.37	15.50	11.98	3.62	1.40	3.8	4.4	4.2	1.1	1.6	1.3
Composition No. 3	2.42	2.46	2.47	3.9	1.9	0.3	16.47	15.90	16.35	7.16	4.18	2.37	3.5	4.2	2.5	1.2	1.8	1.2
Composition No. 4	2.46	2.50	2.50	4	1.8	0.9	15.09	14.53	15.33	5.63	2.62	1.18	3.3	3.7	5.1	1.5	2.2	1.6
Technical req. min	-	-	-	***1.5***	***1.5***	***1.5***	***14***	***14***	***14***	***2.5***	***2.5***	***2.5***	***2.0***	***2.0***	***1.1***	***1.1***	***1.1***	***1.1***
max	-	-	-	***4***	***4***	***4***	***19***	***19***	***19***	***5***	***5***	***5***	-	-	-	-	-	-

Fig. 3. Compressive strength test.

Table 7
Compressive strength standard limits for asphalt concrete (Type B).

Test	Specification limits (GOST 12801–98)
Compressive strength (50 °C; MPa)	1.10 (min.)
Compressive strength (20 °C; MPa)	2.0 (min.)
Compressive strength (0 °C; MPa)	13.0 (max.)

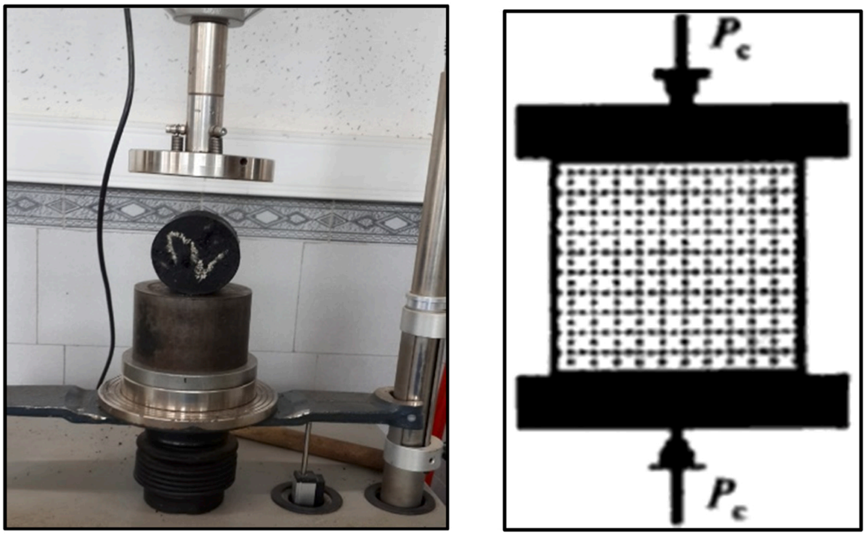

Fig. 4. Shear Resistance Using Uniaxial Compression.

The Tensile strength for asphalt concrete (Type B) according to the Russian standard (GOST 12801–98) at 0 °C is between 3.0 and 7.5 MPa.

3.6. Determination of the porosity of the mineral particle

The essence of the method is to determine the volume of pores present in the mineral particle of a compacted mixture. The porosity of the mineral particle is determined based on the predetermined values of the average and accurate densities of the mineral particle of

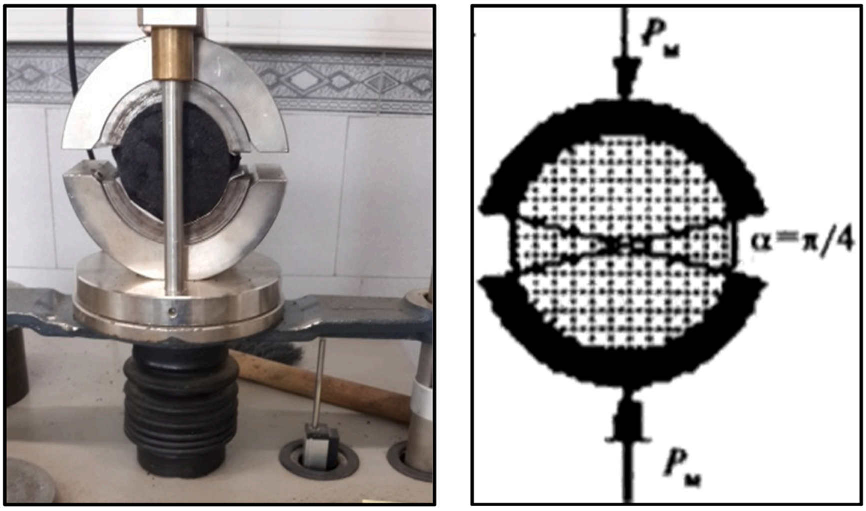

Fig. 5. Shear Resistance Using Marshall Stability Breaking Head.

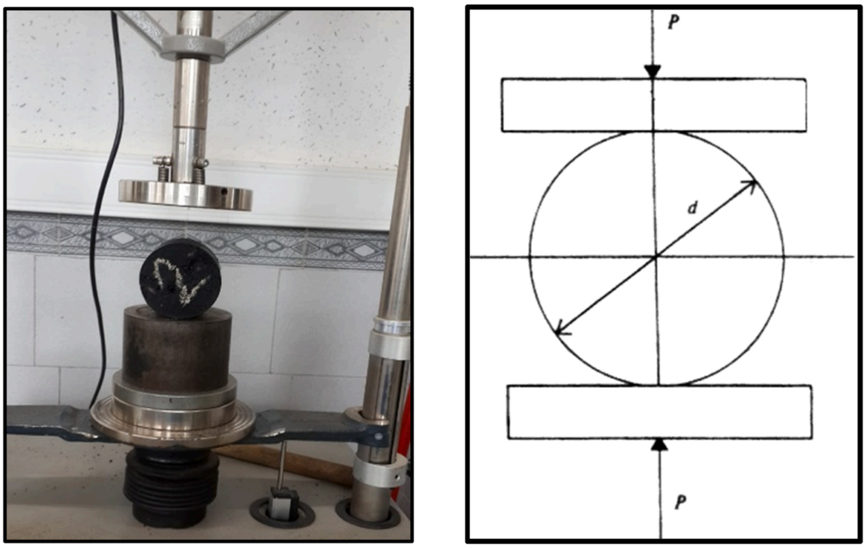

Fig. 6. Tensile Strength Machine.

the mixture. The porosity of the mineral part V,%, is calculated to the first decimal place using the following formula (Eq. (9)).

$$V = \left[1 - \frac{\rho_m^M}{\rho^M}\right]100 \tag{9}$$

Where ρ_m^M is the average density of the mineral particle of the compacted mixture (g/cm3); ρ^M the actual density of the mineral part of the mixture (g/cm3).

The porosity of the mineral particles for asphalt concrete (Type B), according to the Russian standard (GOST 12801–98) is between 14% and 19%.

3.7. Determination of residual porosity

The aspect of the test method is to determine the volume of pores present in a compacted mixture. The residual porosity of asphalt samples V,%, is determined based on the previously established average and true densities according to the formula (Eq. (10)).

$$V = \left[1 - \frac{\rho_m}{\rho}\right]100 \tag{10}$$

Where ρ_m is the average density of the compacted mixture (g/cm3); ρ is the true density of the mixture (g/cm3).

The residual porosity for asphalt concrete (Type B), according to the Russian standard (GOST 12801–98) is between 2.5% and 5.0%.

3.8. Water saturation

This test method targets determining the amount of water absorbed by the sample at a given saturation mode. Water saturation is determined for samples prepared in the laboratory or core samples extracted from the pavement layer. In this test method, samples are weighed in air and water and placed in a vessel with water at a temperature of (20 ± 2) °C. The water level above the samples should be at least 3 cm. The vessel with the samples is installed in a vacuum unit, where a pressure of not more than 2000 Pa (15 mm Hg) is maintained for 1 h. Then the pressure is brought to atmospheric pressure, and the samples are kept in the same vessel with water at a temperature of (20 ± 2) °C for 30 min. After that, the samples are removed from the vessel, weighed in water, wiped off with a soft cloth, and weighed in air. Water saturation of the sample, %, is calculated by the formula (Eq. (9)).

$$W = \frac{g_5 - g}{g_2 - g_1} \tag{9}$$

where g is the mass of the sample suspended in air (g); g1 is the mass of the sample suspended in water (g); g2 the mass of the sample, kept for 30 min in water and weighed in air (g); g5 is the mass of the sample kept for 30 min in water and re-suspended in the air (g).

The water saturation for asphalt concrete (Type B) according to the Russian standard (GOST 12801–98) at 20 °C is between 1.5% and 4.0%.

4. Results and discussion

4.1. Average density of the compacted sample results

Density is an essential factor in asphalt mixture design. The rise in density through compaction will increase shear resistance and enhance asphalt mixture performance; suppose that sufficient bitumen is available to avoid durability problems and not excessing amount that can bring about rutting problems. Fig. 7 illustrates the obtained results for the average bulk-specific gravity of the four compositions.

It can be noticed that the average density of the four compositions does not vary, and it is between 2.46 and 2.48. The results show that the density value slightly decreased when the PMB and RAP were added to the mixture for compositions 3 and 4. Compaction efficiency decreased because of the addition of PMB and RAP. Various factors affect the compaction efficiency of the RAP mixtures, such as the RAP content, the gradation of the RAP particles, and the inclusion of modification. Several studies have also shown that recycled mixtures mixed with polymer-modified bitumen, especially the SBS, are more difficult to compact than those with unmodified bitumen [39] [40]. Also, the elastic behaviour of the PMB led to the mixtures showing a little lower density than the conventional mixture (Composition No.1).

4.2. Compressive strength results

When combined with other physical characteristics, the compressive strength may indicate the overall mixture performance. It is a decisive factor in determining its appropriateness for use under given loading circumstances and environment as road material. According to the Russian standard, the compressive strength is tested at three different temperatures to cover the performance of the asphalt mixture for different environmental conditions. Figs. 8–10 present the compressive strength results at 50 °C, 20 °C, and 0 °C,

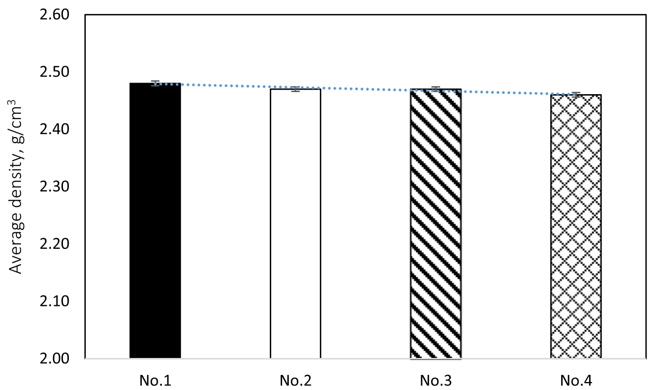

Fig. 7. Average Density Results.

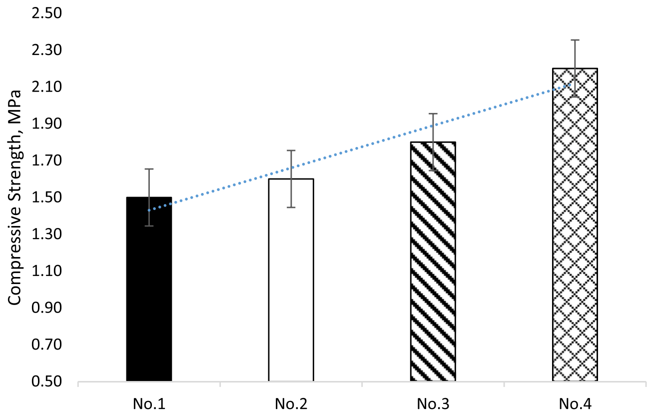

Fig. 8. Compressive Strength Results at 50 °C.

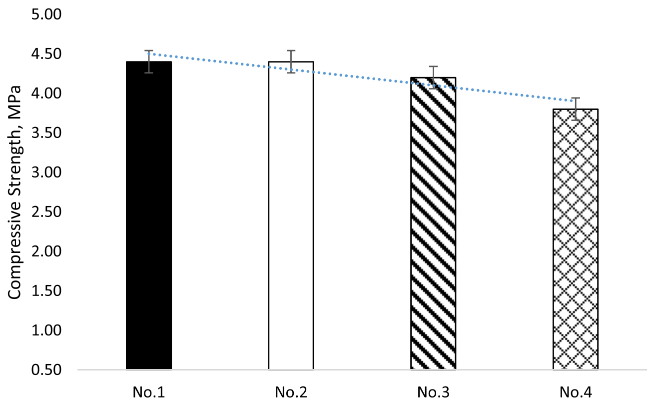

Fig. 9. Compressive Strength Results at 20 °C.

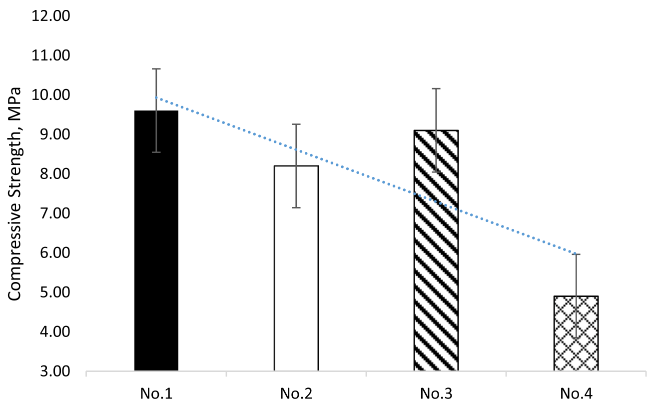

Fig. 10. Compressive Strength Results at 0 °C.

respectively.

All combinations' compressive strength at 50 °C is above the minimum standard limit (1.10 MPa). The inclusion of PMB in composition No.2 yielded a higher compressive strength than the conventional mixture (composition No.1). Similarly, incorporating the RAP material into the mixture increased its compressive strength, as seen in composition No.3. For composition No.4, mixing RAP and PMB resulted in the highest compressive strength. The addition of PMB increased compressive strength due to the increase in viscosity of the bitumen as the utilized elastomeric polymer (SBS) forms discrete particles in the bitumen and its function as a thickener. Also, adding RAP material to mixtures increased its compressive strength as the gradation of milled RAP is commonly finer and denser than virgin aggregates.

On the other hand, the opposite can be seen for the compressive strength results at 20 °C and 0 °C (Figs. 9 and 10). The incorporation of the PMB (Composition No.2) reduced the compressive strength as the elastomeric modification type may have no significant effect on the low-temperature properties of the asphalt pavement. However, the results are still within limits (min. 2.00 MPa at 25 °C and not more than 13.00 MPa at 0 °C). The drop in the performance of the asphalt mixture is also noticed when the RAP is incorporated (Composition No.2 and No.3), which may be referred to as the shrinkage of the bitumen at such low temperatures. Also, it may be attributed to the poor adhesion developing at low temperatures between the RAP and the virgin aggregate, as well as the bitumen, which occurs when a high amount (more than 25%) of RAP is utilized. Some recent studies agree that inadequate performance is detected when more than 25% of RAP is included [26].

4.3. Moisture susceptibility test results

Moisture susceptibility is a significant cause of deformation in hot-mix asphalt pavements. To assess the possibility of moisture damage to hot asphalt mixtures, moisture susceptibility testing can be performed. Findings from the moisture susceptibility test could be utilized to forecast the possibility of long-term stripping. Fig. 11 illustrates moisture susceptibility for the four compositions.

The compositions gave results above the minimum standard limits (min. 0.7). The inclusion of the PMB in composition No.2 resulted in a slight increase in the moisture resistance compared to the conventional mixture (composition No.1). The incorporation of RAP (composition No.3) showed a remarkable reduction in moisture resistance. The drop in moisture resistance for composition No.3 is associated with moisture interaction with the bitumen-RAP adhesion within the hot mix asphalt mixture. This interaction would lead to a reduction of adhesion between the bitumen and RAP. This reduction in the adhesion was overcome by adding PMB to the RAP in composition No.4, which showed a higher moisture resistance than the other compositions. Adding PMB resulted in more adhesive material and better interaction between the PMB and the RAP.

4.4. Shear resistance test results

The Russian Federal national standard for HMA (GOST 9128–2013) has presented the requirements for internal friction coefficient (tg_{φ}) and cohesion (C_{π}) of HMA as a requirement to make sure shear resistance requirements of the HMA layer in the pavement. The shear resistance of HMA examines the stress state in asphalt. The internal friction coefficient (tg_{φ}) of asphalt concrete and cohesion (C_{π}) results are exhibited in Figs. 12 and 13.

The internal friction coefficient for composition No.1 is low compared to the other compositions. Nevertheless, the results for all compositions are still above the minimum limit (min. 0.81). The introduction of PMB into composition No.2 and the RAP into compositions No.3 and No. 4 increased the internal friction coefficient of the asphalt mixtures. This indicates that the high content of RAP has a high internal friction coefficient. The bitumen's viscosity also significantly impacts the internal friction angle. The internal friction of the asphalt mixture is a function of aggregates interlocking. The interlocking between the aggregate particles is related to the bitumen as a binder. The polymer-modified bitumen is more viscous than the unmodified bitumen, and such high viscosity makes the aggregates interlock closer; thus, the internal friction angle of the modified asphalt mixture is higher.

The cohesive strength of a material is the strength of bonding between the particles or surfaces that make up that material. The cohesion results are demonstrated in Fig. 13.

The compositions yielded a cohesion value above the minimum requirement (min. 0.36 MPa). Similarly, the conventional sample (composition No.1) depicted the lowest cohesion compared to the other compositions. Adding the PMB into compositions No.2 and No.4 led to a substantial increase in the cohesion value. Moreover, the highest was composition No.4, which may be ascribed to the higher properties of the PMB compared to the neat bitumen. In other words, the shear strength of the asphalt mixture arises substantially as the viscosity of bitumen increases.

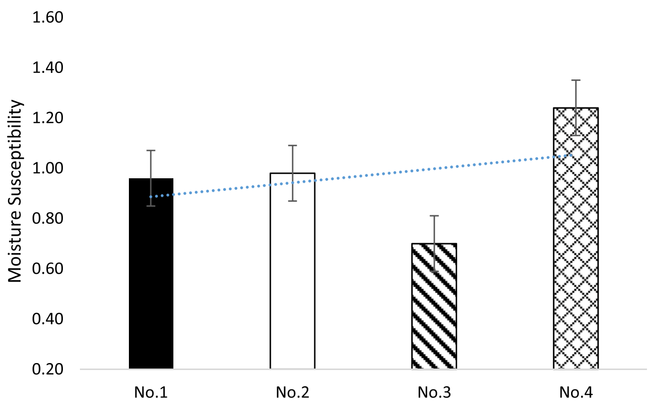

Fig. 11. Moisture Susceptibility Results.

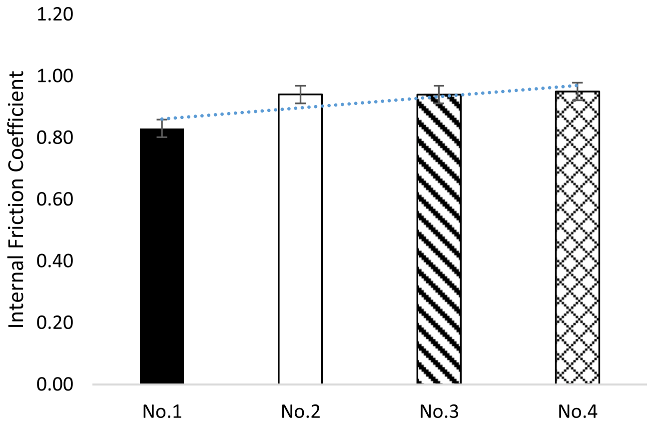

Fig. 12. Internal Friction Coefficient (tg_{φ}) Results.

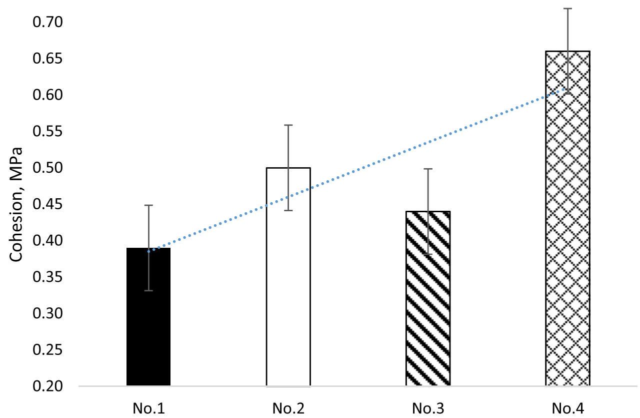

Fig. 13. Cohesion (C_{π}) Results.

4.5. Tensile strength test results

This test aims to simulate the low-temperature cracks, and therefore, the test is conducted at 0 °C. The results of the tensile strength are indicated in Fig. 14.

Based on the results, it can be observed that composition No.3 failed to satisfy the minimum tensile strength value (3.0 min. MPa.). The other compositions were within the specified limits. Composition No.2 presented the highest tensile strength value. It can be deduced that the inclusion of the RAP (as in Compositions No.3 and No.4) reduced the tensile strength of the hot asphalt mixtures. As mentioned earlier, high RAP content (more than 25%) would depict poor adhesion with other asphalt mixture components at low temperatures. Although the addition of PMB to the RAP (composition No. 4) increased the tensile strength of the mixture to some extent and succeeded in meeting the minimum specification limit. This is due to the higher viscosity depicted by the polymer-modified bitumen, which plays a vital role in increasing the internal friction between the RAP aggregate and the film asphalt binder and may cause in increasing the film thickness and the adhesion between asphalt particles.

4.6. The porosity of the mineral particles and residual porosity test results

The results of the porosity of the mineral particles of asphalt and the residual porosity of the asphalt samples are presented in Figs. 15 and 16. The results fall within the standard upper and lower limits for all samples. For both porosities of the mineral particles and the residual porosity, including the RAP into the mixture increased the porosity to some extent. This indicates that micro-cracks may develop with a higher permeable pore ratio. In other words, the RAP depicts a lower resistance to microcracking. Also, the volume of pores in the RAP mixtures is higher due to the loss of bonding force that may develop using recycled aggregate filled with absorbed bitumen.

4.7. Water saturation test results

As indicated in Fig. 17, the water saturation rate ranges between 2.2 and 1.8 for all samples. Including RAP reduced the amount of

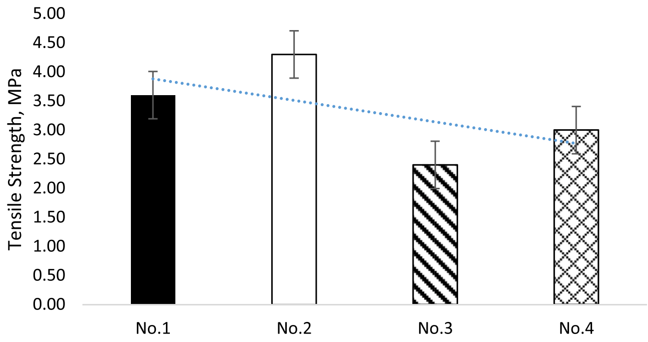

Fig. 14. Tensile Strength Test Results.

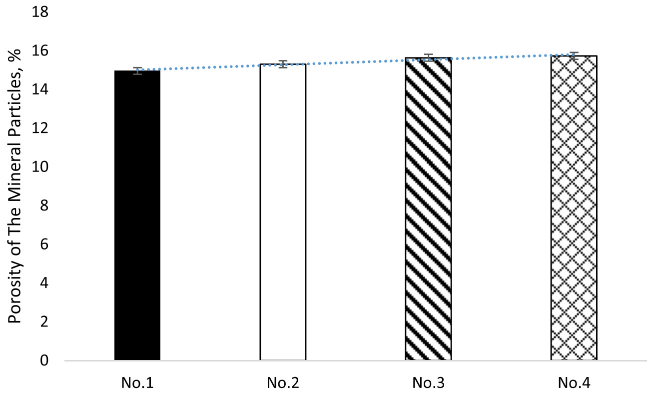

Fig. 15. Porosity of The Mineral Particles Results.

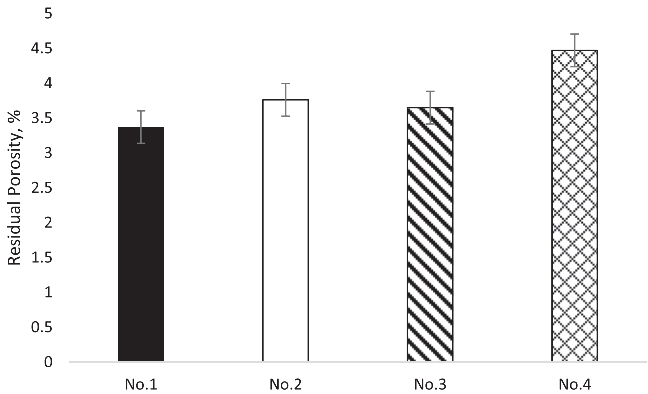

Fig. 16. Residual Porosity Results.

water absorbed by the asphalt samples for compositions 3 and 4. This is because the voids in the aggregate of the RAP particles are already filled with bitumen. Also, the lowest water saturation was noticed for composition 4, as this composition is made up of RAP and PMB. Due to its higher consistency, the PMB would prevent the water from penetrating and coating the aggregate particles more than the neat bitumen.

5. Estimation of cost

The initial construction cost of the four different compositions considering the cases of two countries in the Russian Federation and the Republic of Iraq. The initial cost estimation covers the cost of the utilized materials for pavement construction, such as aggregate, neat bitumen, and polymer-modified bitumen. Also, the cost estimation includes the cost of recycling the asphalt, such as milling, crushing of RAP at the plant in a crusher, preparation of asphalt mixtures at the asphalt plant, asphalt laying and compacting costs,

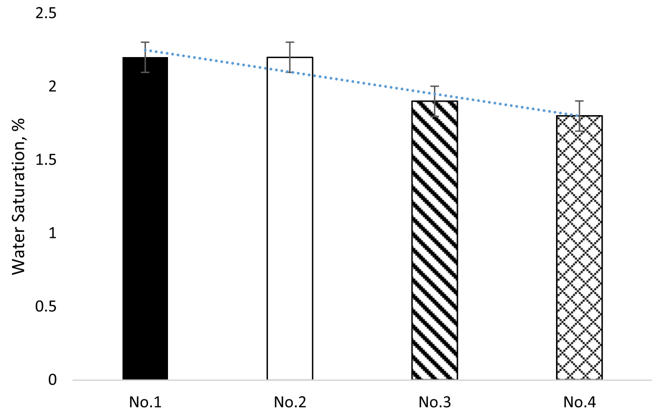

Fig. 17. Water Saturation Results.

transportation of materials.

5.1. Raw materials and recycling costs

The cost of materials includes the cost of the aggregate, bitumen, and polymer modified bitumen as presented in Table 8. The given data was obtained from analysing market prices for materials and roads in Russia and Iraq in 2022.

5.2. Production cost

This stage involves the cost of Hot Mix Asphalt recycling and the process of mixing with new materials to produce HMA mixes. This study uses drum HMA plants to manufacture RAP mixes. The RAP material can be acquired by milling or a crushing process. The cost breakdown of the plant's activities for the conditions of Russia in 2022 in the ruble and Iraq are presented in Table 9.

5.3. Materials transportation and construction activities

In this stage, the expenses of material transport and building and machinery costs are included, as indicated in Table 10. The transportation stage covers the transport of asphalt mixes, RAP, and aggregate to the construction site and the transportation cost of materials from the site to the recycling plant.

5.4. Calculation of the initial cost of RAP

Figs. 18 and 19 compare the cost of asphalt mixtures and coatings for compositions No. 1 - No. 4 in tons. The calculations performed for four options for asphalt concrete mixtures, for the conditions of Russia and the conditions of the state of Iraq, showed that using RAP can significantly reduce the cost of asphalt concrete mixture. Using RAP makes it possible to reduce the cost of the asphalt concrete mixture by 8.0% (when preparing the mixture with neat bitumen) and by 13% (when preparing the mixture with PMB) in the conditions of Russia. A similar trend is observed in the conditions of Iraq; the utilization of RAP reduced the costs by 5.1% (when using bitumen) and by 8.5% (when using PMB). The calculations confirmed the initial assumptions that, despite the higher cost of asphalt concrete with PMB, their use in severe climatic conditions of Iraq is quite justified from a technical point of view. Using RAP allows for significant savings without reducing the performance of asphalt concrete.

5.5. Life cycle cost analysis

The life cycle cost analysis (LCCA) is the total costs (in US dollars) of roadway over a 10-year pavement lifespan. The costs in the LCCA emphasis on the sections that are completely to be paid by stakeholders in a road project.

Table 8
Cost of raw materials.

Material	Unit	Cost (Ruble-Russia)	Cost (USD-Iraq)
Sand	Ton	550.00	8.00
Crushed stone	Ton	1200.00	14.00
Mineral powder	Ton	1700.00	30.00
Neat bitumen 60/90	Ton	12000.00	200.00
PMB	Ton	18000.00	300.00

Table 9
The cost of building asphalt concrete pavement.

Items	Unit	Cost (Ruble-Russia)	Cost (USD-Iraq)
Milling	m^2	45.00	1.00
Crushing of RAP at the plant in a crusher	Ton	90.00	2.00
Preparation of asphalt mixtures at the asphalt plant (without the cost of materials)	Ton	450.00	8.00

Table 10
Materials transportation and construction activities.

Items	Unit	Cost (Ruble-Russia)	Cost (USD-Iraq)
Transportation of materials by dump truck up to 20 km	Ton	300.00	6.00
Asphalt laying and compacting	m^2	90.00	2.00

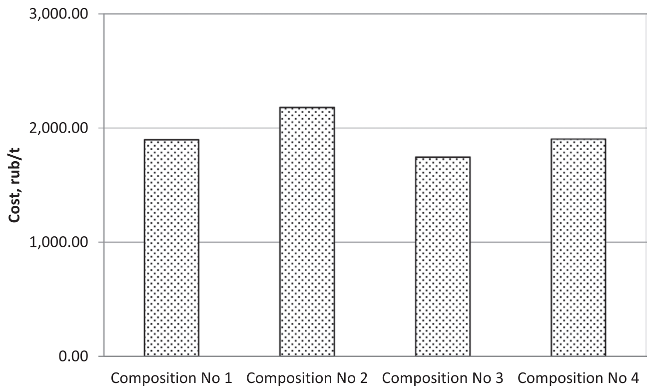

Fig. 18. The cost of various compositions of asphalt concrete mixtures for the condition of Russia.

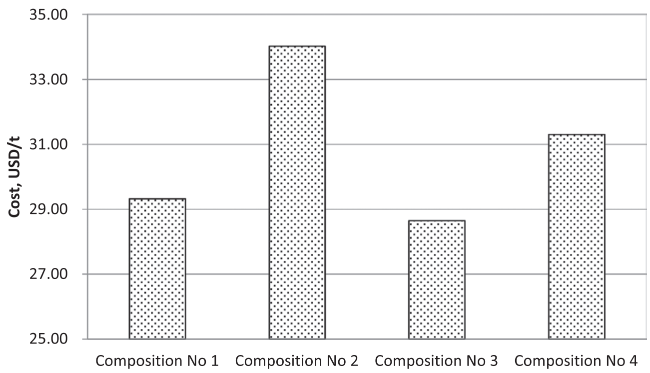

Fig. 19. The cost of various compositions of asphalt concrete mixtures for the condition of Iraq.

The life cycle costs are estimated using various costs for different stages in the road life. This cost includes raw materials cost, production cost, materials transportation and construction activities cost, periodic maintenance and rehabilitation cost, and salvage value (which is estimated considering last cycle construction cost, remaining service life, and last cycle design life [41]. The LCCA of the expenses that is shown in Table 11.

6. Conclusions

This research aims to determine the influence of RAP at 30% combined with PMB on the properties of asphalt concrete by considering the asphalt performance and the initial construction costs. Based on the obtained results, the utilization of 30% RAP material generally exhibited performance results within the Russian standard's limits. Hence, it is possible to use such an amount for asphalt pavement construction. At high temperatures, incorporating RAP material depicted high compressive strength, primarily when the PMB is utilized instead of the neat bitumen. While at low temperatures, the compressive strength is dropped even with the addition

Table 11
Estimation of LCCA.

Composition No	Year	Activity	Unit price ($)	Quantity (%)	Cost	Present worth
Composition 1	0	Initial construction cost			29.32	29.32
	3	Periodic Maintenance	38.01	5	1.90	1.60
	6	Periodic Maintenance	38.01	5	1.90	1.34
	9	Periodic Maintenance	38.01	5	1.90	1.12
	10	Rehabilitation	38.01	15	5.70	3.18
		Salvage value			-3.18	-1.78
		Life cycle cost				34.79
Composition 2	0	Initial construction cost			34.02	34.02
	3	Periodic Maintenance	56.39	5	2.82	2.37
	6	Periodic Maintenance	56.39	5	2.82	1.99
	9	Periodic Maintenance	56.39	5	2.82	1.67
	10	Rehabilitation	56.39	15	8.46	4.72
		Salvage value			-4.72	-2.64
		Life cycle cost				42.13
Composition 3	0	Initial construction cost			28.65	28.65
	3	Periodic Maintenance	38.01	5	1.90	1.60
	6	Periodic Maintenance	38.01	5	1.90	1.34
	9	Periodic Maintenance	38.01	5	1.90	1.12
	10	Rehabilitation	38.01	15	5.70	3.18
		Salvage value			-3.18	-1.78
		Life cycle cost				34.12
Composition 4	0	Initial construction cost			31.3	31.3
	3	Periodic Maintenance	56.39	5	2.82	2.37
	6	Periodic Maintenance	56.39	5	2.82	1.99
	9	Periodic Maintenance	56.39	5	2.82	1.67
	10	Rehabilitation	56.39	15	8.46	4.72
		Salvage value			-4.72	-2.64
		Life cycle cost				39.41

of PMB into the RAP mixture. Thus, applying RAP material in regions where the temperature is preferable. The inclusion of RAP demonstrated a notable decrease in moisture resistance. The PMB can be used instead of neat bitumen to overcome this reduction and raise moisture resistance. Using RAP material enhanced the asphalt mixture's internal friction and cohesion characteristics. The inclusion of RAP demonstrated a notable decrease in moisture resistance. The PMB can be used instead of neat bitumen to overcome this reduction and raise moisture resistance. Using RAP material enhanced the asphalt mixture's internal friction and cohesion characteristics.

Additionally, the combination of PMB and RAP improved these characteristics. Accordingly, the addition of PMB to the RAP mixture is desirable. A tensile strength test measures the low-temperature cracks. The RAP mixture was unable to meet the minimum standard limits. The application of RAP in cold regions can be conducted by mixing with PMB, which improves tensile strength. The incorporation of RAP decreased the water resistance of the mixture. Also, using PMB with a RAP mixture did not result in a higher resistance, and neat bitumen added slightly better results. Moreover, the initial construction cost of the four compositions was estimated. Based on the cost outcome, using RAP can considerably decrease the initial cost of the asphalt concrete mixture.

To enhance the performance of the asphalt pavement, PMB can be incorporated, which increases the total cost. The utilization of RAP can overcome such an increase without affecting the overall performance. Therefore, based on the available budget and the type of road, the decision can be made whether to use the PMB or not.

The study considered the SBS polymer with RAP mixtures in the laboratory. Further studies may examine the behaviour of such mixtures on the site considering short- and long-term ageing. The generated carbon emissions may also be investigated as the PMB requires higher production temperatures than the neat bitumen.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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