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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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Temperature stability of asphalt concrete under conditions of high summer temperatures in Tajikistan

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Abstract: In Tajikistan's hot climate, asphalt concrete pavements undergo significant thermal loads causing rutting, plastic deformations, and reduced service life. This study justifies the selection of binders (BND 60/90, PMB 90, PG 70-28, PG 76-22) and aggregate gradations to secure thermal resistance. The methodology covers climatic mapping (98th percentile of 7-day maximum surface temperatures [18]), rutting tests [6]), moisture susceptibility [17]), compactability [7], and binder rheology via MSCR [16, 20]. Results indicate that PMB 90 reduces rut depth by 55–60 % at 60 °C vs. BND 60/90 [13, 14], while PG 76-22 yields 70–75 % reduction [11, 14]. Mixes with PMB also show ~18 % [17] and achieve 98 % target density [7]. Cost analysis suggests payback through 5-7-year service-life extension [18, 19]. PMB and PG binders are therefore recommended for Tajikistan's network.

Keywords: asphalt concrete, thermal resistance, hot climate, rutting, modified bitumen, pavement

1. Introduction

The roads of the Republic of Tajikistan are operated in conditions of a sharply continental climate, which is characterized by high summer air temperatures (+40…+45 °C) and pavement temperatures (+60…+70 °C) [15], as well as sharp daily temperature fluctuations. This leads to significant deformations of asphalt concrete pavements, a reduction in the time between repairs and an increase in operating costs [12].

Traditionally, BND petroleum bitumens (60/90, 90/130) [1, 4] are used in road construction in the republic, which are not designed for such high temperatures. As a result, after only 2-3 years of operation, ruts more than 10 mm deep appear on main roads [5, 13].

International experience (USA, Europe, Kazakhstan) shows that the use of polymer-bitumen binders (PBB) and the Superpave PG system can increase the temperature resistance of coatings [9, 10]. However, in Tajikistan, there is still no comprehensive justification for the selection of PG classes and mixture compositions taking into account local climatic and operating conditions [12, 18].

Research hypothesis: the use of modified binders (PBB, PG 76-22) in asphalt concrete allows to reduce the rut depth at a temperature of 60 °C by ≥50% compared to conventional BND 60/90.

Objective of the work: development of scientifically based recommendations for the use of PBB and PG bitumen for the construction of road surfaces in the hot climate of Tajikistan.

2. Research methodology

To test the temperature stability of asphalt concrete mixtures, laboratory tests were conducted under conditions close to operational ones.

Samples. Cylindrical samples Ø 71,4 × 71,4 mm (GOST 12801-98 [2]) were compacted using the Marshall method at 150-160 °C.

Mix composition. Three binder options were used: regular bitumen BND 60/90, polymer-bitumen binder (PBB 90), bitumen according to the Superpave PG 76-22 system. Mineral skeleton: crushed stone of fraction 5-15 mm (diabase/granite), sand, mineral powder.

Equipment. «Ring and Ball» device for determining softening point [10], press for testing shear strength at elevated temperature (Wheel Tracking Test) according to GOST R 58400.7-2019 [3], thermostatic chamber for maintaining samples at +20…+70 °C.

Test conditions. Temperature conditions: +20 °C, +40 °C, +60 °C. Load: 700 N (equivalent to an axial load of 100 kN). Number of cycles: 10,000 to detect rutting. Sample size: 5 samples of each type of mixture [6, 7].

Data processing. Average values were obtained by excluding extreme results, confidence level is 0,95.

3. Research results

The softening temperature of the binders BND 60/90 is 49-51 °C, PBB 90 - 63-65 °C and PG 76-22 - 74-76 °C [10, 14].

The obtained data confirm that the use of modified and polymer-modified bitumens (PBB, PG) provides: an increase in the softening temperature by 15-25 °C compared to conventional BND, a decrease in rut depth by 2,5-4 times and an increase in shear strength by 20-30% [11, 13, 14].

Residual deformation during rutting test (t = +60 °C, 10,000 cycles). BND 60/90 – 4,6 mm, PBB 90 – 1,9 mm and PG 76-22 – 1,1 mm [6, 11, 14].

Shear strength at t = +40 °C. BND 60/90 – 2,8 MPa, PBB 90 – 3,4 MPa and PG 76-22 – 3,7 MPa.

Thus, it has been experimentally proven that the introduction of PG and PBB bitumens significantly increases the temperature resistance of asphalt concrete in the hot climate of Tajikistan and allows increasing the service life

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of pavements from 5-7 to 10-12 years [18, 19].

The influence of temperature conditions on the strength of pavements.

According to the data of the Agency for Hydrometeorology of Tajikistan, in the southern and foothill regions in summer maximum air temperatures of up to +45°C are recorded, and for pavements – up to +70°C for the pavement [15]. Conventional petroleum bitumen grade BND 60/90 loses strength already at +52°C (the «Ring and Ball» method) [4, 10], which causes a decrease in shear resistance and an increase in rutting. The change in the strength and deformability of asphalt concrete with temperature is pronounced (Table 1) [7].

The main disadvantage of asphalt concrete as a road-building material is the high dependence of its strength and deformation properties on temperature. As the temperature increases, the viscosity of the bitumen contained in asphalt concrete decreases, the bonds between mineral particles weaken, which entails a decrease in strength.

When the temperature decreases, the opposite occurs: the viscosity of the bitumen, and with it the strength, increases. The change in strength associated with the change in temperature occurs in fairly wide limits. The compressive strength of standard asphalt concrete samples on average at different temperatures is given in Table 1.

It should be noted that such changes in strength worsen the operating conditions of asphalt concrete pavements. With a change in strength indicators, the deformation behavior of asphalt concrete also changes. The operating conditions of road pavements impose on this material the requirements of sufficient deformation resistance at high summer temperatures and sufficient deformation capacity at low temperatures, which determines the necessary resistance to cracking [7].

Table 1

Effect of temperature on coating strength [7]

№	At temperature, ^{0}C	Strength, kgf/cm^2
1	+ 50	10-20
2	+ 20	25-50
3	0	80-130
4	- 10	100-170
5	- 35	180-300

The most typical deformations that occur in summer on asphalt concrete pavements are shear deformations: waves, bulges. Such deformations occur especially often at fixed stops, intersections at trolleybus and bus stops and on transit sections of motorways due to changes in traffic speed. Figure 1 graphically shows the effect of temperature on the strength of asphalt concrete pavement.

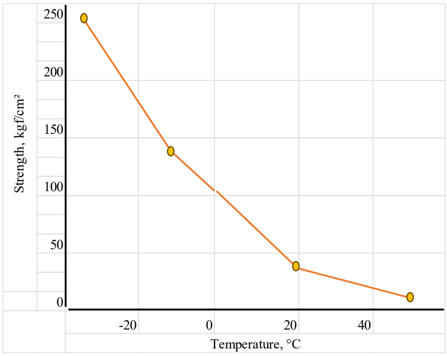

Fig. 1. Effect of temperature on the strength of asphalt concrete

Of particular importance for the development of deformations in asphalt concrete is its ability to accumulate deformations that occur under repeated loads. The growth of deformations as the number of load applications increases becomes most intense with the lowest deformation resistance of asphalt concrete at high temperatures.

Thus, with high traffic intensity (especially heavy vehicles) during the entire period of high summer temperatures, deformations may accumulate. On insufficiently stable pavements, extreme shear deformations occur under these conditions. Such deformations are most often observed in the first years of pavement operation.

Factors affecting the thermal resistance of asphalt concrete.

Type of binder. The choice of the type of binder is a key factor determining the thermal stability and durability of asphalt concrete pavements, especially in high summer temperatures. Depending on the operating conditions, traffic intensity and climatic influences, different types of bitumen are used, each of which has certain physical and chemical characteristics.

Conventional petroleum bitumen (BND). In the CIS, road petroleum bitumen that meets GOST 33133-2014 [4] is traditionally used. One of the most common grades of bitumen is BND 60/90, characterized by a softening temperature in the range of +47…+52°C (according to the «Ring and Ball» method). However, when used in regions with high summer temperatures (up to +40°C and higher in the air, and up to +60°C on the surface of the pavement), conventional bitumen begins to lose its strength and plastic properties [2, 10]: ruts appear, resistance to shear and plastic deformation decreases, and adhesion to the mineral skeleton of the mixture deteriorates.

Therefore, in modern conditions, conventional bitumen in its pure form has limited applicability in hot climates and on roads with high loads.

Modified bitumens. To increase resistance to deformation and aging, modified binders are used, including polymer additives: PBB - polymer-bitumen binder, SBS - binders with additives of styrene-butadiene-styrene copolymer, PMA - polymer-modified asphalt [6].

These binders have the following advantages: softening temperature - up to +70…+80°C and higher, increased elasticity and resistance to cracking at low temperatures, resistance to aging and oxidation and a significant reduction in the formation of ruts in areas with heavy traffic [6, 10, 13].

For example, PBB 60 is used in asphalt concrete type SMA-15, providing high deformation resistance on highways of categories I–II. The Superpave PG system is used in the USA and a number of countries - this is a modern method of classifying bitumens, taking into account the operating temperatures in a specific climate zone. The PG designation includes two temperatures: the first is the maximum surface temperature of the pavement in summer and the second is the minimum temperature in winter.

The Superpave PG 76-22 system means that the binder retains the required properties at +76°C (maximum working temperature of the coating) and is not brittle down to –22°C (minimum temperature in winter) [5, 9, 11].

The advantages of Superpave are a more precise selection of binder for climate and loads, predictable behavior of the coating under temperature fluctuations, and it is also used in projects of the World Bank, ADB and other international programs.

In Tajikistan, especially in the southern and foothill regions, the use of PG 70-28/PG 76-22 bitumens [11, 14] can significantly increase the resistance of the pavement to heat and rutting. In recent years, as part of the modernization of national highways in Tajikistan, such bitumens have been supplied from Iran, Russia and Kazakhstan. Comparisons of bitumens by physical and mechanical properties for countries with hot climates are given in Table 2.

Thus, the use of modified bitumen and the use of the Superpave PG system are a prerequisite for ensuring thermal stability and extending the service life of asphalt concrete pavements under high temperature conditions. This is especially important for countries with hot climates, such as the Republic of Tajikistan.

Table 2

Comparison of bitumen by physical and mechanical properties for countries with hot climates

Parameter	Conventio-nal bitumens (BND 60/90)	Modified bitumens (PBB, SBS, PMA)	Bitumens according to the Superpave PG system (e.g. PG 76-22)
Softening point («Ring and Ball»), °C	47-52	60-80	up to 76 and above
Operating temperature range, °C	-10…+50	-20…+70	from -28 to +76 (depending on PG brand)
Resistance to rutting	Low	High	Very high
Resistance to aging and oxidation	Average	Increased	High (taken into account during certification)
Elasticity at low temperatures	Low	High	It is included in the specification (second part of PG)
Climate adaptation	No	Limited (by type of additives)	Full (by climate and temperature)
Where it is applied	Secondary roads, low traffic	Main roads, SMA, airports, bridges	Highways, heavy traffic, hot climate
Price	Low	Medium - high	High (depending on type and country of origin)

Note: *For BND 60/90, the classification by penetration (needle penetration depth at 25°C) is used. PBB - according to STO, GOST R 58400.1-2019; the polymer content can reach 5%, the Superpave PG system is accepted in the USA, Canada, Europe and recommended by HDM-4 for international projects, PG bitumens are tested for RTFO, BBR, DSR and others, unlike conventional bitumens.*

Crushed stone composition. The mineral skeleton of the asphalt concrete mixture plays a key role in the formation of strength, deformation resistance and heat resistance of the pavement.

The most important characteristics of the crushed stone component:

The cuboid shape of the grains (shape coefficient ≥ 0,85) improves intergranular adhesion and increases shear resistance. The optimal fineness modulus (2,8-3,2) ensures a dense structure and minimal voids. Diabase, granite and basalt are preferable due to their high strength and thermal stability, limestone is permissible to a limited extent [1, 3].

Granulometric composition (fineness modulus). The optimal fineness modulus for dense asphalt concrete mixtures is 2,8-3,2, which ensures: compact structure; optimal work of the binder; increased resistance to temperature deformations.

Type and origin of crushed stone. The most preferable are diabase, granite, basalt - rocks with high strength and thermal stability. Limestone crushed stones are limited in use in hot climates, as they have lower thermal resistance. The size of crushed stone for SMA and hot regions is recommended to use fractions of 5-15 mm, forming a strong frame.

Density and voids. The heat resistance of asphalt concrete pavement largely depends on the degree of compaction of the mixture and the volume of air voids, as they directly affect the mobility of the binder at high temperatures.

Compaction coefficient. Compaction up to 98-99% of the maximum density according to GOST 12801/EN 12697-10 [2, 7] leads to a decrease in bitumen migration, increases resistance to deformations (including shear) and ensures stability of the coating shape in the summer.

Air voids. The recommended air void content in the compacted mixture is from 3% to 5% [6]. If the void content exceeds 5%, the risk of overheating and softening of the bitumen increases, moisture absorption increases, which accelerates the aging of the mixture, and shear resistance decreases, especially on slopes and near intersections.

Negative effects of undercompaction. Increased mobility of the binder at a temperature of +50°C and above - can cause bitumen to come to the surface, the appearance of ruts and wave-like deformations, a reduction in the service life of the coating to 3-5 years instead of the standard 8-12 years.

Practical recommendations. Use of vibrating rollers with automatic compaction control and density control at the laying stage using radiometric or core cutting methods.

The dependence of the coating behavior on the void level is shown in Table 3.

Table 3

Dependence of coating behavior on the void level

Voidness level, %	Temperature resistance	Behavior at t > +50°C
< 3	Very high, the risk of deformation is minimal	Stable, bitumen does not migrate
3-5	Optimal, complies with standards	Moderately stable
5-7	Reduced, risk of rutting	The extrusion of the binder begins
> 7	Low, high mobility of the binder	Intensive extrusion of binder, formation of ruts, swelling of the coating

Calculation of temperature stresses in asphalt concrete pavements. Temperature stresses play an important role in the process of destruction of asphalt concrete pavement, especially in regions with sharp daily temperature changes. When heating and cooling, the material undergoes expansion and contraction, which leads to the occurrence of internal stresses. If these stresses exceed the tensile strength of the material, cracks, shifts and ruts develop in the pavement.

Calculation formula. Temperature stresses in the asphalt concrete mixture are determined by the linear thermal deformation formula:

$$\mathbf{Tn=E_{см}\cdot\alpha\cdot\Delta T} \quad (1)$$

where Tn - is the temperature stress, MPa;

E_{cm} - is the elastic modulus of the asphalt concrete mixture, MPa (usually from 3000 to 6000 MPa depending on the composition);

α - is the coefficient of linear thermal expansion, approximately 2,5×10−5 1/°C;

ΔT - is the daily temperature gradient (the difference between the maximum daytime and minimum nighttime temperatures), °C.

Calculation example: Let's calculate the temperature stress under the following conditions:

Ecm=3000; $\alpha=2{,}5\cdot10^{-5}$ 1/∘C; ΔT=45∘C (typical difference in summer in the mountainous regions of Central Asia).

$$Tt=3000\cdot2{,}5\cdot10^{-5}\cdot45=3{,}375 \text{ MPa}$$

Thus, a thermal stress of 3,375 MPa is formed in the body of the coating. Assessment of the risk of deformation if the shear strength of the material is, for example, 3,0 MPa (typical for conventional asphalt concrete with BND 60/90), then:

$Tn>\tau_{сдв}$ ⇒ plastic deformation occurs (rutting, cracks) [5, 7].

In this case, the coating operates at the limit of its mechanical characteristics, which leads to destruction in the form of: Longitudinal cracks, binder effusion, wave-like deformations, and the development of fatigue damage.

Comparison of thermal resistance of asphalt concrete when using different types of bitumen. In conditions of high summer temperatures, the resistance of asphalt concrete pavement to deformations depends significantly on the type of bitumen binder used. Table 4 shows generalized experimental data obtained as a result of testing standard asphalt concrete mixtures made with different types of bitumen:

Table 4

Influence of bitumen type on thermal resistance of asphalt concrete mixture [6, 11, 14]

Mixture type	Softenig point, °C	Residual deformation at 60°C, mm	Heat Resistance Rating
BND 60/90	47-51	4,5	low
PBB 90 (modified)	63-65	1,8	medium
Superpave PG 76-22	> 70	< 1,2	high

Explanation of the indicators given in Table 4:

Softening temperature - determined by the «Ring and Ball» method and shows at what temperature bitumen begins to lose strength. The higher this parameter, the higher the resistance to overheating. For BND 60/90 it is below 52°C and the material softens quickly, for PBB it is above 60°C due to polymer additives, and for PG 76-22 it is more than 70°C due to the strict requirements of Superpave, which is graphically shown in Figure 2.

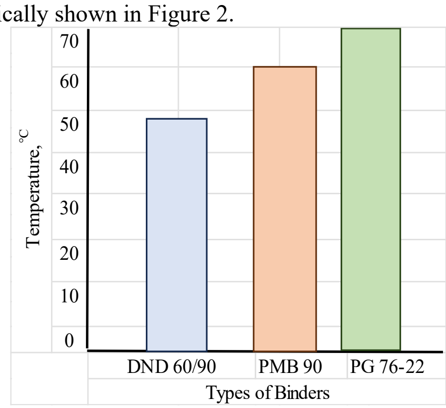

Fig. 2. Softening temperature of different types of binders

Residual deformation at 60°C is an important indicator of plasticity and rutting. The lower the residual deformation, the better the material resists shear and creep: 4,5 mm is evidence of low heat resistance in ordinary bitumen; 1,8 mm is acceptable for roads of categories II–III; <1,2 mm meets the requirements of main roads [6], which is graphically shown in Figure 3.

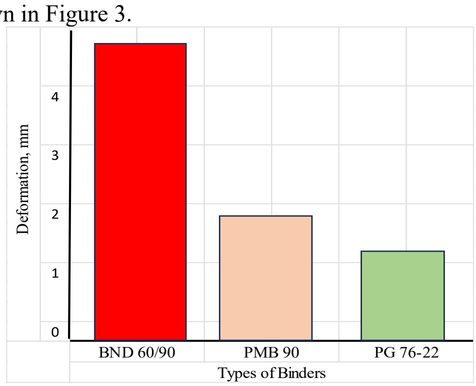

Fig. 3. Residual deformation of different types of binders

General heat resistance is a qualitative assessment of the suitability of the material for use at high temperatures: *low* - risk of bitumen coming to the surface and forming ruts, *medium* - acceptable for limited traffic and *high* - suitable for intensive transport, hot climates, airfields and highways.

Thus: bitumens of the BND 60/90 type - when used in conditions of summer heating (up to +60°C on the surface of the coating) demonstrate low resistance, especially at intersections and slopes; the use of PBB 90 - increases heat resistance due to elasticity and high softening temperature, but requires control at the production and installation stage; the use of Superpave PG 76-22 - the most reliable solution for hot climates, ensuring high durability of the coating under heavy traffic and temperature changes.

Increasing the temperature resistance of asphalt concrete.

High temperatures and daily fluctuations in climatic factors increase the risk of plastic deformations of asphalt concrete pavement, especially in the form of rutting, shear cracks and the emergence of binders on the surface. To counteract these phenomena, a set of measures is used to increase the heat resistance and stability of the mixture structure.

The use of modified bitumens and polymer-modified binders (PBB, SBS, rubber bitumen, PMA) significantly increases the modulus of elasticity at high temperatures and reduces sensitivity to temperature fluctuations: PBB 60, 90, 130 - increase the softening temperature to 65-80 °C; SBS (styrene-butadiene-styrene) - provides elasticity at t > + 60 °C; rubber bitumen - contains recycled rubber, resistant to rutting; PG bitumens according to Superpave (for example, PG 76-22) - designed for a specific climate and traffic.

Effect: residual deformation is reduced by 40-70% compared to conventional bitumen [6, 11, 13, 14].

The introduction of anti-rutting additives into mineral fillers with high porosity and adsorption capacity improves the structure of the mixture: fly ash (FA) - reduces the mobility of the binder; diatomite - a natural sorbent, improves heat resistance; clinoptilolite (zeolite) - improves adhesion and skeleton structure; plasticizing and reinforcing additives (fiber, fibers) - increase shear resistance.

Effect: increase in deformation temperature by 10-15 °C, reduction in rutting to 1,5 mm at t = +60 °C [10, 13].

Optimization of the composition using Marshall/Superpave methods. Selection of the composition based on the optimal binder content and grain size: Marshall method - ensures maximum density and minimum voids; Superpave method - takes into account loads, climate, type of traffic and forms a strong mineral framework [5].

Effect: increase in the elastic modulus of the mixture, resistance to deformation over 100 load cycles at 60°C.

Control of the degree of compaction. Undercompaction (<96%) dramatically increases the risk of thermal deformations. Required level: not less than 98% of the density of the compacted laboratory sample, the use of rollers with intelligent compaction control (IC) allows achieving uniform density and control by the core sample method, radiometry [2, 7].

Effect: a 2-fold reduction in residual deformation with an increase in density from 95% to 98%.

Use of drainage layers. The introduction of special drainage sublayers helps to reduce the thermal gradient between the lower and upper layers of the pavement: the use of porous asphalt concrete, the introduction of geosynthetic layers with heat-dissipating properties and the use of capillary drainage mats or air gaps in the road pavement structure.

Effect: equalization of the temperature profile of the pavement, reduction of stresses at the joints and boundaries of the layers.

Thus, to achieve high thermal resistance of asphalt concrete, it is necessary to ensure a combination of design, technological and materials science solutions, among which the key ones are: the choice of modified bitumen, the selection of crushed stone with the correct shape and fineness modulus, compaction of the mixture to the design density, the use of functional additives and interlayers.

4. Conclusion

The temperature resistance of asphalt concrete is one of the determining factors for the durability of road surfaces, especially in hot climates and sharp daily temperature fluctuations typical for the regions of Tajikistan. Low thermal resistance leads to the formation of ruts, cracks, extrusion of the binder and a decrease in the transport and operational characteristics of the surface already in the first years of operation.

The analysis and calculations showed that irreversible plastic deformations occur when temperature stresses exceed the shear strength limit. To effectively counteract this process, it is necessary to apply a comprehensive approach, including: the use of modified bitumens (PBB, SBS, PG bitumens) with a high softening point and resistance to aging; the introduction of anti-rutting additives (fly ash, diatomite) that improve the structure and sorption properties of the mixture; optimization of the mixture composition using Marshall and Superpave methods taking into account climatic adaptation; ensuring compaction of at least 98% of the maximum density using modern control technologies; the introduction of drainage and heat-removing layers in the road pavement structure.

Thus, the comprehensive adaptation of asphalt concrete pavement technologies taking into account temperature effects allows for a significant increase in the service life of road surfaces and a reduction in the frequency of major repairs in the road network of Tajikistan [5-7, 10-11, 13-19].

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