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RESEARCH ARTICLE

OPTIMIZATION OF ASPHALT CONCRETE PROPERTIES THROUGH MODELING

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Abstract. *This study presents the results of mathematical modeling of the thermal conductivity and strength properties of asphalt concrete mixtures, utilizing a three-factor Box–Behnken experimental design implemented within the STATISTICA software environment. The variable factors considered in the modeling were the temperature of technological processing, the duration of thermal exposure, and the gravel-to-bitumen content ratio in the mixture. The main objective was to quantitatively evaluate the impact of composition and thermal strengthening conditions on the thermal and mechanical performance of asphalt concrete. These performance indicators are highly important for the effective design, construction, and long-term operation of road structures in diverse climatic regions. To determine the statistical significance of the studied factors, analysis of variance (ANOVA) was conducted. Regression equations for the response functions were developed, and response surface plots as well as main effects profiles were generated. The results demonstrated that the bitumen content and processing temperature significantly influenced the strength characteristics, whereas thermal conductivity exhibited lower sensitivity to parameter variations. High values of determination coefficients (R^2 and adjusted R^2) confirmed the consistency between the statistical models and experimental outcomes. In addition, engineering calculations addressing pavement freezing depth and design soil moisture were performed using the modeled thermal properties of asphalt concrete. These findings confirmed the practical applicability of the developed model, showing that optimization of mixture composition contributes to improved pavement durability, enhanced energy efficiency, and the development of updated regulatory standards and advanced road construction technologies.*

Keywords: *asphalt concrete, thermal conductivity, mechanical strength, moisture content, STATISTICA, ANOVA, Box–Behnken design, regression modeling, freezing depth, thermal strengthening.*

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ҒЫЛЫМИ МАҚАЛА

АСФАЛЬТОБЕТОН ҚАСИЕТТЕРІН МОДЕЛЬДЕУ АРҚЫЛЫ ОҢТАЙЛАНДЫРУ

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Аңдатпа. *Бұл зерттеуде STATISTICA бағдарламалық ортасында жүзеге асырылған үш факторлы Box–Behnken тәжірибелік жоспары қолданылып, асфальтобетон қоспаларының жылуөткізгіштігі мен беріктік қасиеттеріне бағытталған математикалық модельдеу нәтижелері ұсынылды. Модельдеуде қарастырылған негізгі айнымалы факторлар – технологиялық өңдеу температурасы, термиялық әсер ету ұзақтығы және қиыршық тас пен битумның қоспадағы арақатынасы болды. Зерттеудің басты мақсаты – асфальтобетонның жылу-техникалық және механикалық көрсеткіштеріне құрам мен термиялық қатайту жағдайларының әсерін сандық тұрғыдан бағалау. Бұл көрсеткіштер әртүрлі климаттық жағдайларда жол құрылымдарын тиімді жобалау, салу және ұзақ мерзімді пайдалану үшін ерекше маңызға ие. Факторлардың статистикалық маңыздылығын анықтау мақсатында дисперсиялық талдау (ANOVA) жүргізілді. Жауап функциялары үшін регрессиялық теңдеулер құрылып, жауап беттерінің графиктері мен негізгі әсерлердің профильдері жасалды. Нәтижелер битум мөлшері мен өңдеу температурасының беріктік сипаттамаларына айтарлықтай ықпал ететінін, ал жылуөткізгіштіктің параметрлердің өзгерісіне төменірек сезімталдық танытатынын көрсетті. Детерминация коэффициенттерінің (R^2 және түзетілген R^2) жоғары мәндері статистикалық модельдер мен тәжірибелік деректер арасындағы сәйкестікті растады. Сонымен қатар, асфальтобетонның жылутехникалық қасиеттеріне сүйене отырып, жол жабындарының тоңу тереңдігі мен топырақтың есептік ылғалдылығына байланысты инженерлік есептер орындалды. Бұл нәтижелер ұсынылған модельдің практикалық құндылығын дәлелдеп, қоспа құрамын оңтайландыру арқылы жол жабындарының беріктігін арттыруға, энергия тиімділігін жоғарылатуға және нормативтік құжаттарды жетілдіруге мүмкіндік беретінін көрсетті.*

Түйін сөздер: *асфальтобетон, жылуөткізгіштік, беріктік, ылғалдылық, STATISTICA, ANOVA, Box–Behnken жоспары, регрессиялық модельдеу, тоңу тереңдігі, термиялық қатайту.*

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НАУЧНАЯ СТАТЬЯ

ОПТИМИЗАЦИЯ СВОЙСТВ АСФАЛЬТОБЕТОНА С ПОМОЩЬЮ МОДЕЛИРОВАНИЯ

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Аннотация. *В статье представлены результаты математического моделирования теплопроводности и прочности асфальтобетонных смесей с применением трёхфакторного планирования эксперимента Бокса–Бенкена, выполненного в программной среде STATISTICA. В качестве варьируемых факторов рассматривались температура технологической обработки, продолжительность термического воздействия и соотношение щебня и битума в составе смеси. Основной целью исследования являлась количественная оценка влияния состава и условий термоупрочнения на теплотехнические и прочностные характеристики асфальтобетона. Эти показатели имеют особое значение при проектировании, строительстве и эксплуатации дорожных конструкций в различных климатических условиях. Для оценки статистической значимости факторов был проведён дисперсионный анализ (ANOVA). Построены регрессионные уравнения отклика, поверхности отклика и профили основных эффектов. Результаты показали, что содержание битума и температура обработки оказывают наиболее сильное влияние на прочностные характеристики, тогда как теплопроводность в меньшей степени зависит от варьируемых параметров. Высокие значения коэффициентов детерминации (R^2 и скорректированного R^2) подтвердили достоверность статистических моделей и их согласованность с экспериментальными данными. Дополнительно были выполнены инженерные расчёты глубины промерзания и расчётной влажности грунта дорожных одежд с использованием полученных теплотехнических свойств асфальтобетона. Эти результаты подтвердили практическую применимость разработанной модели, показав, что оптимизация состава позволяет повысить долговечность дорожных покрытий, улучшить их энергоэффективность, а также использовать данные выводы при разработке нормативной документации и совершенствовании технологий дорожного строительства.*

Ключевые слова:. *асфальтобетон, теплопроводность, прочность, влажность, STATISTICA, ANOVA, трёхфакторный эксперимент, план Бокса–Бенкена, глубина промерзания, термоупрочнение.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

During the preparation of this manuscript, the authors used artificial intelligence tools (ChatGPT) solely for editorial assistance, such as improving phrasing and checking grammar, spelling, and punctuation. All ideas, interpretations, and conclusions are the responsibility of the authors, who take full accountability for the content of the article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Мақаланы дайындау барысында авторлар жасанды интеллект құралдарын (ChatGPT) тек редакциялық көмек мақсатында пайдаланды: тұжырымдарды жетілдіру, грамматикалық, орфографиялық және тыныс белгілеріндегі қателерді тексеру үшін. Барлық идеялар, интерпретациялар мен қорытындылар авторларға тиесілі, және олар мақаланың мазмұнына толық жауапты.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

При подготовке рукописи авторы использовали инструменты искусственного интеллекта (ChatGPT) исключительно для редакторской поддержки: корректировки формулировок, проверки грамматических, орфографических и пунктуационных ошибок. Все идеи, интерпретации и выводы принадлежат авторам, которые несут полную ответственность за содержание статьи.

1 INTRODUCTION

Modern requirements for the quality of the road surface necessitate a comprehensive assessment of its thermal and strength characteristics. This is especially important when designing coatings in conditions of contrasting temperatures and seasonal climate fluctuations. Asphalt concrete mixtures are multicomponent systems, the properties of which depend on the composition, preparation technology and operating conditions. The most significant factors affecting the thermal conductivity and strength of asphalt concrete are the content of crushed stone, the content of bitumen, as well as the pore structure and the degree of saturation with water in the material.

The purpose of this work is to construct statistical models (empirical equations) of thermal conductivity and strength of asphalt concrete mortar based on the experimental three-factor Box-Behnken plan; to conduct a dispersion analysis of the significance of the factors; to study the effect of the moisture state of the material on thermal conductivity; and to apply the simulation results to assess the depth of freezing and the calculated moisture content of the substrate. The realization of this goal will make it possible to develop recommendations for optimizing the composition and technology of preparing asphalt mixtures with specified characteristics.

2 LITERATURE REVIEW

The literature emphasizes that the physical and mechanical properties of pavement materials significantly affect its durability. In particular, the thermal properties of the upper layers of the road play a role in resistance to climatic influences**.** (**Kravchenko & Reut, 2020**). Thus, it is necessary to take into account the thermophysical characteristics of the pavement layers when designing it in order to prevent excessive freezing and related damage. High temperatures in summer and extremely low temperatures in winter create a tense thermal regime of the structure, which can lead to cracks and deterioration of the bearing capacity of the roadbed. At the same time, the strength characteristics of asphalt concrete, for example, resistance to track formation and fatigue strength, determine the ability of the coating to withstand transport loads without destruction.. (**Fredlund & Rahardjo, 2018**).

Special attention has recently been paid to the effect of moisture and water saturation on the properties of asphalt concrete and base soils. Under humidification conditions, the thermal conductivity of materials usually increases, since water has a higher coefficient of thermal conductivity (~0.58 W/m·K) than air (~0.024 W/m·K), which fills the pores in a dry state. (**Brown & Davis, 2020**). Studies show that when the pores of asphalt concrete are saturated with water, its effective thermal conductivity can increase by 20-30% compared to the dry state. On the other hand, moisture negatively affects the strength and durability of asphalt concrete: bitumen loses its adhesion to crushed stone (the "softening" effect), and compressive strength and fatigue resistance decrease. Freeze-thaw cycles are especially harmful, which, in the presence of moisture in the pores, lead to cracks and accelerated destruction of the coating. (**San et al., 2022**). Thus, for regions with heavy precipitation or high groundwater levels, it is important to evaluate the properties of asphalt concrete in both dry and wet conditions. In arid regions, on the contrary, insufficient soil moisture may become a problem, affecting the quality of compaction and requiring special calculation methods. (**Kiyalbaev et al., 2018**).

Previously, studies have been conducted that emphasize the importance of integrated consideration of thermal and strength properties in the design of road clothing. However, there is still a need for a deeper quantitative analysis of the influence of asphalt concrete composition and technological factors on its properties. Traditional empirical approaches do not always allow us to identify nonlinear effects and interactions of factors. To solve this problem, it is advisable to use methods of mathematical modeling and statistical planning of the experiment.

Thus, modern literature demonstrates that improving the quality of road surfaces is possible only with the use of mathematical modeling and statistical analysis methods that take into account the nonlinear and interacting effects of technological and climatic factors. The present work continues these studies by offering a quantitative assessment of the effect of the composition and thermal hardening of the asphalt concrete mixture on its thermal conductivity and strength using the three-factor Box-Benken plan.

3 MATERIALS AND METHODS

Experimental Design and Factors. The study employed statistical modeling methods using the STATISTICA software environment. The experimental planning was carried out based on a three-level, three-factor Box-Behnken design. The selected factors were:

x_1 - temperature, °C (lower level 50°C, baseline 55°C, upper level 60°C). This factor represents the temperature conditions during the thermal processing of samples (simulating different compaction temperatures or heat-treatment durations).

x_2 - duration of thermal exposure, hours (minimum level 6 h, intermediate level 25.5 h, maximum level 48 h). This factor corresponds to the duration of sample thermostating (thermal strengthening) at the specified temperature. x_1.

x_3 - binder (bitumen) content in the mixture, % by mass. In the experiment, this factor was varied such that increasing the bitumen content decreased the gravel content, and vice versa. The low level corresponded to relatively low bitumen content (and high gravel content), whereas the high level corresponded to increased bitumen content. Note: For the "thermal conductivity" response, the primary contribution is expected from the mineral component (gravel), while for the «strength» response, it originates mainly from the bituminous binder. Thus, the factor is conditionally considered as «gravel/bitumen content» x_3 depending on the property being analyzed.

Thus, the Box-Behnken design included combinations of three factors at different levels. This fractional factorial design enables the evaluation of linear, quadratic, and interaction effects with a relatively small number of experiments. A total of 15 tests were performed, of which:

12 experiments corresponded to the main points of the design, where two of the three factors were varied sequentially, while the third factor was kept at its intermediate level. Four tests were conducted for each factor pair (two levels of one factor × two levels of the second factor at a fixed intermediate level of the third), resulting in:

x_1 and x_2 they vary with the average x_3: 2×2 = 4

x_1 and x_3 they vary with the average x_2: 2×2 = 4

x_2 and x_3 they vary with the average x_1: 2×2 = 4

Total: 4 + 4 + 4 = 12 experiments.

3 experiments were performed at the center point of the design (with all factors set at their intermediate levels). $x_1 = 55$ °C, $x_2 \approx 25{,}5$ ч, x_3 = average bitumen content) - to assess the reproducibility and adequacy of the model.

Measurable indicators (responses). Two responses were measured in each experiment:

y_1 - coefficient of thermal conductivity, W/(m·K). The measurements were carried out on asphalt concrete mortar samples using the laboratory steady-state heat flow method (standard guarded hot plate apparatus). Each sample was a prism measuring 50×50×50 mm, prepared from asphalt concrete mixtures of the specified composition. Thermal conductivity was measured at a temperature of 20±2°C in the dry state of the sample. The measurement error was estimated to be within ±5%.

y_2 - compressive strength, MPa. It was determined by the standard method of testing cubes of size 50×50×50 mm for axial compression. After thermal exposure, the samples were cooled to room temperature and tested using a hydraulic press at a constant loading rate. The strength was determined as the stress at the point of sample failure.

Materials. Standard road construction materials were used to prepare the samples: petroleum road bitumen grade BND 70/100 (or an equivalent in terms of viscosity), crushed stone from dense igneous rock (granite) with a fraction size of 5-10 mm, and mineral filler (limestone powder) for mix stabilization.

The mixture composition was selected to approximate the specifications of asphalt concrete type II, with a gravel-to-sand-to-mineral filler ratio of approximately 70:25:5 by mass at a baseline bitumen content of ~5.5%. During the experiment, the bitumen content was varied from ~5% (lower level) to ~6% (upper level), with corresponding adjustments to the gravel proportion.

Temperature x_1 was applied by heating the molds with compacted samples in a thermal chamber to the required temperature, while thermal exposure x_2 was achieved by maintaining the samples at this temperature for the specified duration . After thermal strengthening, the samples were removed and cooled to room temperature prior to testing and measurement of y_1 and y_2..

Data analysis. Based on the obtained experimental data, regression models were constructed for the response variables y_1 and y_2 (thermal conductivity and strength) as functions of the factors x_1, x_2, x_3. A second-order (quadratic) model was assumed to be adequate, which for each response variable takes the following form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

where:
b_0 - intercept (constant term),
b_i -coefficients of the linear terms,
b_{ij} - coefficients of the two-way interaction terms,
b_{ii} - coefficients of the quadratic terms.

The coefficients b_i were estimated using the least squares method based on the 15 design points with the regression module of the STATISTICA software. The significance of each coefficient was tested through analysis of variance (ANOVA). For each factor and interaction, the calculated Fisher criterion (F-statistic) was determined.

$$F_{calculate} = \frac{SS_{factor}/DF_{factor}}{SS_{error}/DF_{error}} \quad (2)$$

where:
S - sum of squares of deviations,
DF_{factor} – degrees of freedom (df).

The obtained $F_{calculate}$ values where compared with the $F_{critical}$ value for the specified significance level (typically $\alpha = 0{,}05$). Based on the p-value, I was assessed whether the effects of the factors were statistically significant (if $p < 0{,}05$) or not. The coefficient of determination R^2 was also evaluated for the models of y_1 and y_2 and the absence of significant autocorrelation of residuals was verified.

Thermal resistance and frost penetration calculation. Alongside processing the experimental results, to interpret the thermal properties of asphalt concrete, the concept of layer thermal resistance was introduced. Thermal resistance R ($m^2 \cdot K/W$) was determined as follows:

$$R = \frac{\delta}{\lambda}, \quad (3)$$

where:
δ - layer thickness (m),
λ - thermal conductivity of the material (Вт/(м·K)).

For a multilayer pavement structure, the total thermal resistance is equal to the sum of the resistances of the individual layers:

$$R_{total} = \sum \frac{\delta_i}{\lambda_i} \quad (4)$$

This concept is used in calculating the depth of ground frost penetration beneath the pavement structure. In the present study, knowing the thermal conductivity λ_i of asphalt concrete (the top layer) from the experiment, a theoretical calculation was performed to determine the seasonal frost penetration depth using a simplified method based on the heat balance principle. Additionally, approaches for determining the design soil moisture content in the frost zone were reviewed-this parameter is essential for assessing frost heave potential and the bearing capacity of the subgrade. Formulas from modern regulatory sources (**Karimov, 2020**) were used to calculate the design moisture content under various soil moisture conditions.

4 RESULTS AND DISCUSSION

Modeling of Thermal Conductivity and Strength. As a result of the statistical analysis, regression equations were obtained describing the dependence of y_1 (thermal conductivity) and $\mathbf{y_2}$ (strength) on the factors x_1, x_2, x_3. The determination coefficients of the models were $R^2_{y_1} \approx 0{,}88$ and $R^2_{y_2} \approx 0{,}96$, indicating sufficient accuracy of the experimental data approximation. The summarized results of the factor significance analysis are presented below.

4.1 Thermal conductivity

Thermal conductivity (y_1). The analysis of variance (ANOVA) showed that the most significant influence on the thermal conductivity coefficient is exerted by factor x_3 - the gravel content (inversely proportional to the bitumen content) in the mixture. As the proportion of the mineral filler increases, λ rises because gravel has higher thermal conductivity than bitumen. The effects of temperature (x_1) and thermal exposure duration (x_2) were statistically insignificant at the 5% significance level ($p > 0.05$), meaning their influence was negligible. In other words, within the range of 50-60°C and 6-48 hours, changes in these parameters did not result in a significant alteration of the thermal conductivity of the formed asphalt concrete. This is an important finding: the thermal conductivity of the material is primarily determined by its composition (structure and density), rather than by short-term thermal exposure regimes. The obtained regression equation for y_1 (in coded variables) includes a significant linear term for x_3 and minor quadratic adjustments for x_1 and x_2. Visualization of the model is presented as response profile graphs (**Figure 4**), where the curves confirm that changes in x_1 and x_2 are almost horizontal (minimal slope), whereas for x_3, a noticeable increase in y_1 is observed.

The experiments were conducted on dried samples, reflecting the thermal conductivity of the material in its dry state (λ_{dry}). In real-world conditions, asphalt concrete may contain a certain amount of moisture (especially in porous mixtures or after prolonged contact with water). Saturation of pores with water leads to an increase in the effective thermal conductivity coefficient, as heat transfer in the presence of water is more intensive than through air. According to the literature, moist asphalt concrete can exhibit a thermal conductivity coefficient 10-50% higher than that of the dry state, depending on the degree of saturation and porosity (**Rositsa&Penka, 2018**).

In particular, various authors have noted that for soils and road construction materials, when moisture content increases from 0 to 100% volumetric saturation, **λ** rises by approximately 1.5 times. In our study, the obtained range of values (λ_{dry}) for dry samples (around 0.6-0.8 W/m·K, depending on the composition) may increase to ~0.9-1.0 W/m·K under full water saturation of the pores. This must be considered in thermal calculations for pavements. On the other hand, the strength of asphalt concrete in the wet state usually decreases. Although a direct assessment of moist asphalt concrete strength was not performed in this study, it is known from experience and literature that water saturation and freeze-thaw cycles lead to strength losses of about 20-30% after several cycles. Therefore, when modeling the in-service performance characteristics, correction factors for moisture conditions should be introduced. In this article, we limited the scope to evaluating the influence of moisture on λ_{dry} and its implications for frost penetration calculations.

The obtained thermal conductivity values of the upper asphalt concrete layer were used to calculate the seasonal frost penetration depth of the soil beneath the pavement. The calculation was performed for a typical two-layer pavement structure: the upper layer-asphalt concrete, and the lower layer-crushed stone or sand-gravel material. The soil heat balance equation for the winter period was applied according to current regulations (Code of Practice of the Republic of Kazakhstan 3.03-19-2006). In accordance with this method, the frost penetration depth (h_f) is determined by the condition of equilibrium between the heat loss from the soil and the heat required to freeze a given soil volume. With known values of the thermal conductivity coefficients and layer thicknesses, the problem is solved iteratively. For simplification, calculations were performed using thermal resistance tables **(Lukashevich, 2020)**.

Example calculation: Two variants were considered: asphalt concrete as the pavement layer with a thickness of 0.05 m (5 cm):

(1) a coarse-grained mixture with high thermal conductivity - $\lambda \approx 0.72$ W/m·K (approximately corresponding to a case with low bitumen content and high gravel content);

(2) a fine-grained sandy mixture with lower thermal conductivity - $\lambda \approx 0.62$ W/m·K (more porous, with a higher bitumen content or added porous filler).

The underlying load-bearing layer-a crushed stone material-was 0.15 m thick, $\lambda \approx 1.5$ W/m·K. The thermal conductivity of the soil (loam) was assumed to be 1.2 W/m·K.

According to the results of the thermal resistance calculation, the total resistance of the structure in the first variant was slightly lower: $R_{total} = 0{,}59$ (m²·K/W), compared to $R_{total} = 0{,}63$ (m²·K/W) in the second variant-due to the lower thermal conductivity of the top layer. The frost penetration depth under typical climatic conditions (accumulated freezing temperature of about 3000-3500°C·days) was approximately ~0.72 m in the first case and ~0.62 m in the second. Thus, reducing the thermal conductivity coefficient of asphalt concrete by ~14% (from 0.72 to 0.62) led to a reduction in frost penetration depth by about 10 cm (about 14% of the initial depth) compared to the higher thermal conductivity pavement. This result is consistent with expectations: a less thermally conductive layer better insulates the subgrade and reduces frost penetration. In practical terms, this means that using asphalt concrete mixtures with reduced thermal conductivity (e.g., high-porosity or with insulating additives) can be an effective method for protecting the roadbed from deep frost penetration. However, as noted, such solutions must be carefully balanced with strength requirements **(Chudinov et al., 2024)**.

Discussion of Results. The mathematical modeling performed confirmed the qualitative findings already familiar to road engineers and provided quantitative clarification. The strength of asphalt concrete, as expected, depends on the binder content and the compaction/exposure regime: more bitumen and longer exposure time result in a stronger mixture, although excessive bitumen is economically inefficient and may reduce the modulus of elasticity. Thermal conductivity, on the other hand, is primarily determined by the mineral framework and porosity: denser, gravel-rich mixtures conduct heat better, which can increase the frost penetration depth of the pavement during winter.

It is interesting to note that higher thermal conductivity of asphalt concrete is not always beneficial-in cold climates, it is actually desirable to have pavement with lower thermal conductivity to protect the subgrade from freezing **(Kovalev & Savukha, 2021)**. Conversely, very low thermal conductivity in summer can lead to overheating of the pavement surface and accelerated aging of the bitumen. Thus, the requirements for thermal conductivity are contradictory: in hot weather, it should dissipate heat; in cold weather, it should retain it. The optimal solution is likely a moderate thermal conductivity value or the use of specialized thermo regulating layers (e.g., insulating interlayers that keep the pavement cool in summer and warm in winter, as proposed by some researchers). Solving such problems is possible using optimization methods, including desirability criteria, which were implemented in the model **(Figures 1-4)**.

The practical value of the results lies in the fact that, by knowing the statistical relationships, the designer can predict how changes in the asphalt concrete mix design (for example, increasing the amount of bitumen or adding porous fillers) will affect its properties and the overall behavior of the pavement structure. The presented calculation example demonstrates that the choice of asphalt concrete mix type can alter the frost penetration depth of the subgrade by several tens of percent, which is comparable to the effect of layer thickness. Therefore, when designing pavements in regions with significant frost penetration, it is reasonable to consider not only the thickness of the layers but also the thermal conductivity of the materials as a design factor. This can be achieved either by adjusting the mix composition (e.g., using porous asphalt concrete as a thermal insulator) or by incorporating an insulating layer. Naturally, strength and wear resistance requirements of the pavement must also be satisfied simultaneously **(Tsytovich, 1973)**.

Finally, the strength results were experimentally validated: the trends obtained in the model (an increase in strength with higher bitumen content and longer thermal compaction time) correspond to the data from direct testing of the samples. This confirms the adequacy of the developed model and its potential use for predicting strength under other combinations of factors within the specified range.

It should be noted that, based on the modeling results, main effects plots and response surface graphs were constructed **(Figures 1-4)**. The influence of each factor on strength and thermal conductivity is presented through linear and quadratic components. It was established that the strength of the mixture increases with higher bitumen content and longer exposure time, with a pronounced nonlinear effect observed. Temperature also has an influence, but to a lesser extent. For thermal conductivity, the most significant factor is gravel content **(Figure 2)**, whereas the effects of temperature and exposure time were statistically insignificant ($p > 0.3$). The desirability surfaces **(Figures 3-4)** make it possible to identify the optimal region of factor combinations that ensure both high strength and sufficient thermal conductivity.

For a more detailed analysis of factor effects, the author performed ANOVA and evaluated the regression model coefficients for each response. Multi-criteria optimization of the responses was also conducted using the desirability function in the STATISTICA environment. The corresponding modeling results are presented below.

For a more detailed analysis of the factor effects, the author conducted an analysis of variance (ANOVA) and evaluated the regression model coefficients for each response variable. Additionally, multi-criteria optimization of the responses was performed using the desirability function within the STATISTICA environment.

Factor	ANOVA; Var.:Heat Insulation, W/m*K; R-sqr=,47589; Adj:,08281 (Аселя теплоизоляция) 3 3-level factors, 1 Blocks, 15 Runs; MS Residual=,0219519 DV: Heat Insulation, W/m*K				
	SS	df	MS	F	p
(1)Temperature, 0C L+Q	0,047254	2	0,023627	1,076303	0,385523
(2)Time, hour L+Q	0,030662	2	0,015331	0,698380	0,525349
(3)Gravel, % L+Q	0,087030	2	0,043515	1,982279	0,199882
Error	0,175615	8	0,021952		
Total SS	0,335075	14			

Figure 1 - ANOVA Analysis of Thermal Conductivity (author's material)

As shown in **Figure 1**, the ANOVA table for the thermal conductivity model (y_1) is presented. It is evident that none of the factors have a statistically significant effect on thermal conductivity at the 0.05 significance level: the Fisher (F) statistics for temperature, time, and gravel content are 1.076, 0.698, and 1.982, respectively, with p-values of 0.386, 0.525, and 0.200. The most noticeable influence is exerted by factor x_3 (gravel)-its combined effect (linear and quadratic) is slightly higher than the others, although it does not reach significance. The low R^2 ≈0,48 and R^2 ≈0,08 indicate that a substantial portion of the experimental data variability for thermal conductivity remains unexplained by this quadratic model.

Effect Estimates; Var.:Heat Insulation, W/m*K; R-sqr=,47589; Adj:,08281 (Аселя теплоизоляция)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=,0219519
DV: Heat Insulation, W/m*K

Factor	Effect	Std.Err.	t(8)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	0,726304	0,042843	16,95255	0,000000	0,627507	0,825100	0,726304	0,042843	0,627507	0,825100
(1)Temperature, 0C(L)	-0,088250	0,104766	-0,84235	0,424057	-0,329841	0,153341	-0,044125	0,052383	-0,164921	0,076671
Temperature, 0C(Q)	0,092625	0,077106	1,20127	0,264001	-0,085181	0,270431	0,046313	0,038553	-0,042591	0,135216
(2)Time, hour(L)	0,114250	0,104766	1,09052	0,307236	-0,127341	0,355841	0,057125	0,052383	-0,063671	0,177921
Time, hour(Q)	0,043286	0,077468	0,55875	0,591621	-0,135356	0,221928	0,021643	0,038734	-0,067678	0,110964
(3)Gravel, %(L)	0,190000	0,104766	1,81356	0,107304	-0,051591	0,431591	0,095000	0,052383	-0,025796	0,215796
Gravel, %(Q)	0,063375	0,077106	0,82192	0,434932	-0,114431	0,241181	0,031687	0,038553	-0,057216	0,120591

Figure 2 - Estimated Factor Effects for the Thermal Conductivity Model (author's material)

Figure 2 shows the effect estimates for the regression coefficients of the thermal conductivity model. The calculated factor effects (linear-L and quadratic-Q), standard errors, t-statistics, p-values, and 95% confidence intervals for the coefficient estimates are presented. As expected from the ANOVA results, none of the factor coefficients are statistically significant at the 0.05 level. Nevertheless, it can be noted that the largest effect in absolute terms is the linear component of gravel content (Effect = +0.190, $p \approx 0.107$), which has a positive influence on thermal conductivity (i.e., increasing the gravel content raises thermal conductivity). The quadratic terms for all factors are small and statistically insignificant ($p > 0.26$), indicating the absence of a pronounced nonlinear response of y_1 within the studied factor range. Thus, changes in temperature and exposure time have virtually no effect on thermal conductivity, whereas increasing the gravel proportion may slightly raise its value **(Rehab et al.,2018)**.

The next step involved multi-criteria optimization of the responses (y_1 and y_2) using the desirability function method. The optimization criteria were selected as maximizing strength while simultaneously ensuring sufficient thermal conductivity. For each response, a desirability function was defined: $d_1(y_1)$ and $d_2(y_2)$, normalized within the range [0; 1] (0 - unsatisfactory value, 1 - best achievable value). The overall desirability D was calculated as the geometric mean:

$$D = \sqrt[n]{d_1(y_1) \cdot d_2(y_2) \dots d_n(y_n)} \quad (4)$$

with n = 2 in this case.

As a result, response and desirability profiles were obtained for each factor (**Figure 3**), as well as desirability surfaces on the factor plane.

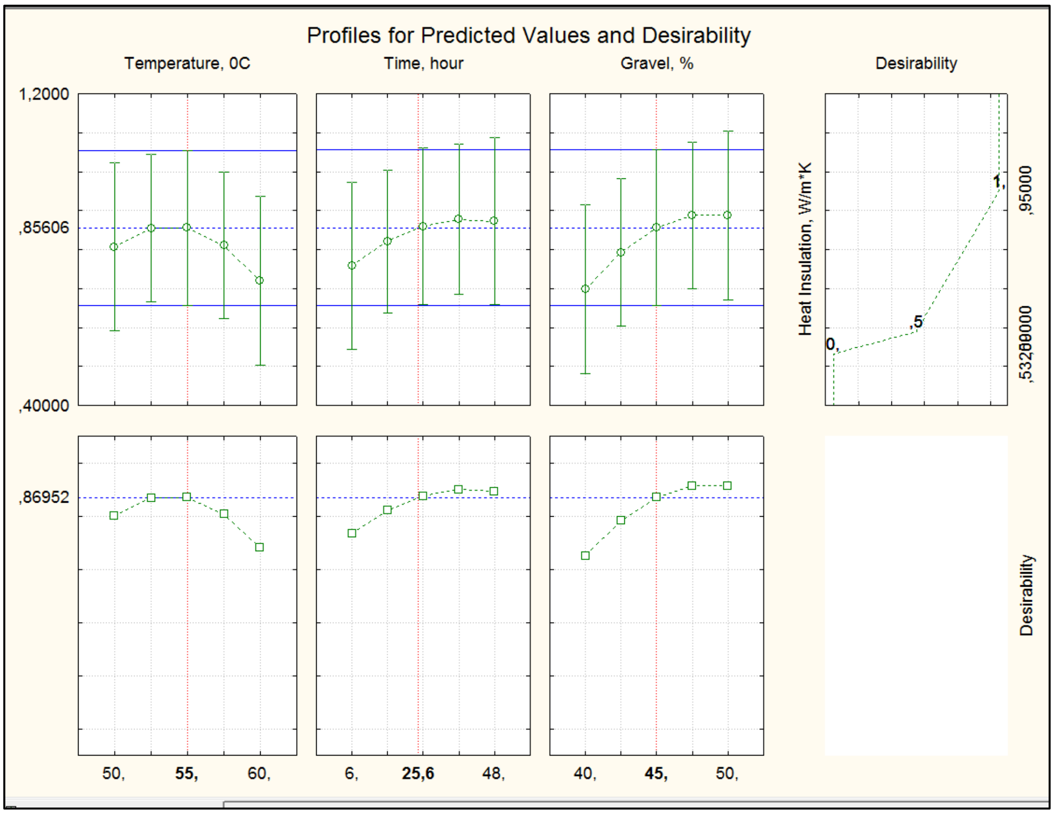

Figure 3 - Response and Desirability Profiles for Thermal Conductivity (y_1) as a Function of Factors x_1,x_2,x_3 (author's material)

Figure 3 shows the profiles of changes in the predicted thermal conductivity values and the corresponding desirability coefficient d_1 when varying each factor (x_1: temperature, x_2: time, x_3: gravel content). Vertical red lines indicate the position of the optimal factor combination identified through optimization. Horizontal lines indicate the baseline response level and boundary values. The graphs show that factor x_3 (gravel content) has the strongest influence on thermal conductivity: as the gravel content increases, desirability d_1 rises because thermal conductivity approaches the desired high value. In contrast, changes in temperature and time have virtually no effect on thermal conductivity (the y_1 curves are relatively flat), corresponding to the weak effects of $x_1 and\, x_2$ identified earlier **(Figure 4)**.

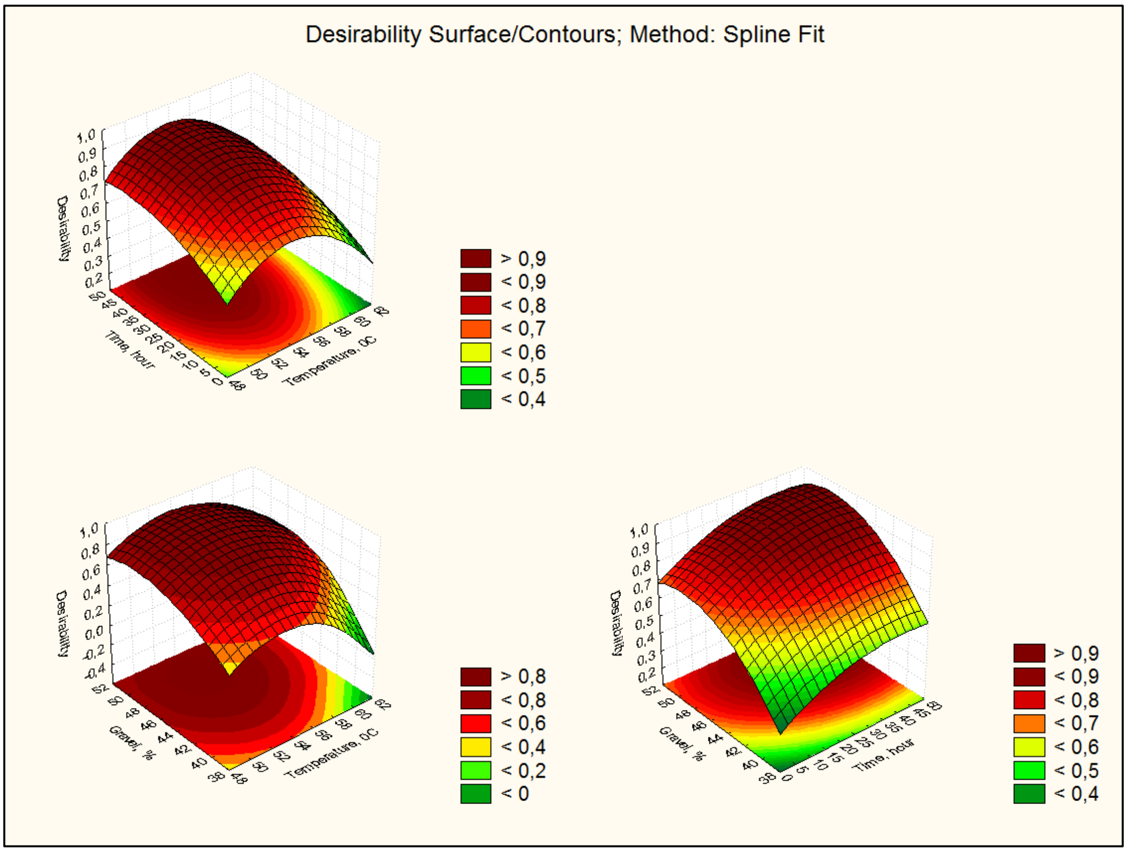

Figure 4 - 3D Surfaces of the Desirability Function D on Factor Combination Planes (author's materials)

4.2 Strength

Strength (y_2). Unlike y_2, for asphalt concrete strength, all three considered factors were significant. The greatest contribution to strength variation comes from bitumen content (x_3): as the percentage of bitumen increases, compressive strength rises monotonically. This is explained by the fact that higher bitumen content improves bonding between mineral particles and reduces overall porosity, leading to increased sample strength. The exposure time factor (x_2) also positively influences strength-extended thermal exposure (up to 48 hours) promotes structuring of the bitumen film and additional material hardening, especially at elevated temperatures. A pronounced nonlinear effect of time was observed: the strength gain slows down when moving from 25 h to 48 h. Temperature (x_1) showed a smaller but still statistically significant effect: moderate increases in processing temperature also contributed to strength improvement; however, this effect appears in combination with other factors. ANOVA revealed a high statistical significance of x_3 and x_2 ($p < 0.001$) and a somewhat weaker but still significant effect for x_3 and x_1 ($p \approx 0.04$). In **Figure 6**, the steepness of the main effect curves can be seen: the curves for x_3 and $x_2$have a pronounced slope, while for **x_1** the slope is less steep. Thus, the strength of the mixture is primarily determined by bitumen content and thermal exposure, especially when bitumen content is sufficiently high.

Factor Interactions. The y_2 model revealed certain interactions; for example, the effect of temperature (x_1) becomes more pronounced at high bitumen content (x_3)-apparently, increasing the temperature accelerates structuring within the bitumen-rich mixture. Meanwhile, the interaction between x_1 and x_2 turned out to be insignificant: increasing exposure time at higher temperatures was practically equivalent to that at lower temperatures, meaning the effects are essentially additive.

The quadratic terms in the y_2 model indicate the presence of an optimum: excessive bitumen content may slightly reduce strength due to excessive softening of the structure; however, within the studied range of 5-6%, this was not observed (strength continued to increase up to the highest tested x_3 level).

For y_1, the quadratic term for x_3 showed a slight curvature of the $\lambda(x_3)$ relationship, which is associated with the fact that, at high gravel content, the increase in thermal conductivity starts to slow down (once it reaches the thermal conductivity level of the mineral aggregate itself, further increases in gravel content have little effect) **(Pengyu & Hao, 2022)**.

The modeling results are summarized in graphical form in **Figures 5-8**. **Figure 5** shows the effect of each factor on strength (main effect profiles), while **Figure 2** shows the effect on thermal conductivity. **Figures 7-8** illustrate the 3D desirability surfaces-combinations of factors that simultaneously optimize both responses. The optimum region is found at relatively high values of x_3 (bitumen ~6%) and x_2 (~40-48 h), and moderate x_1 (~55°C); in this region, a compromise is achieved between maximum strength and sufficient (not too high) thermal conductivity of the material.

It should be noted that targeted modification of asphalt concrete's thermal conductivity is possible through adjusting porosity and mix composition-for example, by introducing porous fillers or special additives. However, this may lead to a reduction in strength, so optimization is required. The developed models and response surfaces help identify a balanced combination of properties.

ANOVA; Var.:Strength, MPa4; R-sqr=,97944; Adj:,96402 (Spreadsheet10)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=1,475655
DV: Strength, MPa4

Factor	SS	df	MS	F	p
(1)Temperature, 0C L+Q	63,6496	2	31,8248	21,5666	0,000599
(2)Time,hour L+Q	201,0240	2	100,5120	68,1135	0,000009
(3)Bitumen, % L+Q	257,3415	2	128,6707	87,1957	0,000004
Error	11,8052	8	1,4757		
Total SS	574,1088	14			

Figure 5 - ANOVA Analysis of Strength (author's materials)

Figure 5 presents the ANOVA table for the strength model (y_2). Unlike thermal conductivity, all three factors for strength were statistically significant (p < 0.001). The largest contribution to strength variation is made by bitumen content (factor x_3): F = 87.20, p ≈ 0.000004. The influence of exposure time (x_2) was also highly significant (F = 68.11; p ≈ 0.000009). Temperature (x_1) had a somewhat smaller but still significant effect (F = 21.57; p ≈ 0.0006). The high R^2 (≈0,979) and adjusted R^2 (≈0,964) indicate that the selected model describes the variability of strength in the experiment well.

Effect Estimates; Var.:Strength, MPa4; R-sqr=,97944; Adj:,96402 (Spreadsheet10)
3 3-level factors, 1 Blocks, 15 Runs; MS Residual=1,475655
DV: Strength, MPa4

Factor	Effect	Std.Err.	t(8)	p	-95,% Cnf.Limt	+95,% Cnf.Limt	Coeff.	Std.Err. Coeff.	-95,% Cnf.Limt	+95,% Cnf.Limt
Mean/Interc.	8,35976	0,353087	23,6762	0,000000	7,54554	9,17398	8,35976	0,353087	7,54554	9,17398
(1)Temperature, 0C(L)	1,39975	0,858969	1,6296	0,141840	-0,58104	3,38054	0,69988	0,429484	-0,29052	1,69027
Temperature, 0C(Q)	-4,02208	0,632184	-6,3622	0,000218	-5,47990	-2,56426	-2,01104	0,316092	-2,73995	-1,28213
(2)Time,hour(L)	-1,55275	0,858969	-1,8077	0,108272	-3,53354	0,42804	-0,77637	0,429484	-1,76677	0,21402
Time,hour(Q)	-7,40049	0,635154	-11,6515	0,000003	-8,86516	-5,93583	-3,70025	0,317577	-4,43258	-2,96791
(3)Bitumen, %(L)	0,80950	0,858969	0,9424	0,373568	-1,17129	2,79029	0,40475	0,429484	-0,58564	1,39514
Bitumen, %(Q)	8,42835	0,641237	13,1439	0,000001	6,94966	9,90705	4,21418	0,320619	3,47483	4,95352

Figure 6 - Estimated Factor Effects for the Strength Model (author's materials)

Figure 6 presents the effect estimates for the coefficients of the strength model. Unlike thermal conductivity, significant nonlinear (quadratic) factor effects are observed for strength. The quadratic effect of bitumen content is particularly large: Effect = +8.4285, p ≈ 0.000001, 95% CI [6.95; 9.91]. The positive sign of the quadratic term for x_3 indicates that the dependence of strength on bitumen content has a curved shape with an extremum (minimum) near the center of the factor's range; in practice, strength maximizes when the bitumen content deviates from the plan center.

Similarly, the significant negative quadratic effect of exposure time (Effect = -7.4005; p ≈ 0.000003) indicates a curved influence of x_2 (strength decreases at too long or too short exposure times, peaking at an intermediate value). The quadratic effect of temperature is also statistically significant and negative (Effect = -4.0221, p ≈ 0.0002), indicating the presence of an optimal temperature range for mixture hardening.

The linear components of the factors for strength are less significant: for example, the linear effect of bitumen content is small (Effect = +0.8095, p ≈ 0.374) compared to the quadratic term-this suggests the presence of an optimum strength at a certain bitumen content. The linear effect of exposure time (-1.5528, p ≈ 0.108) is also less pronounced than the quadratic, and the temperature effect (+1.3998, p ≈ 0.142) is close to the threshold of significance.

Overall, the coefficient estimates confirm the conclusion that strength exhibits a pronounced extremum in the region of central factor levels, especially in relation to bitumen content and exposure time (**Zicheng et al., 2022**).

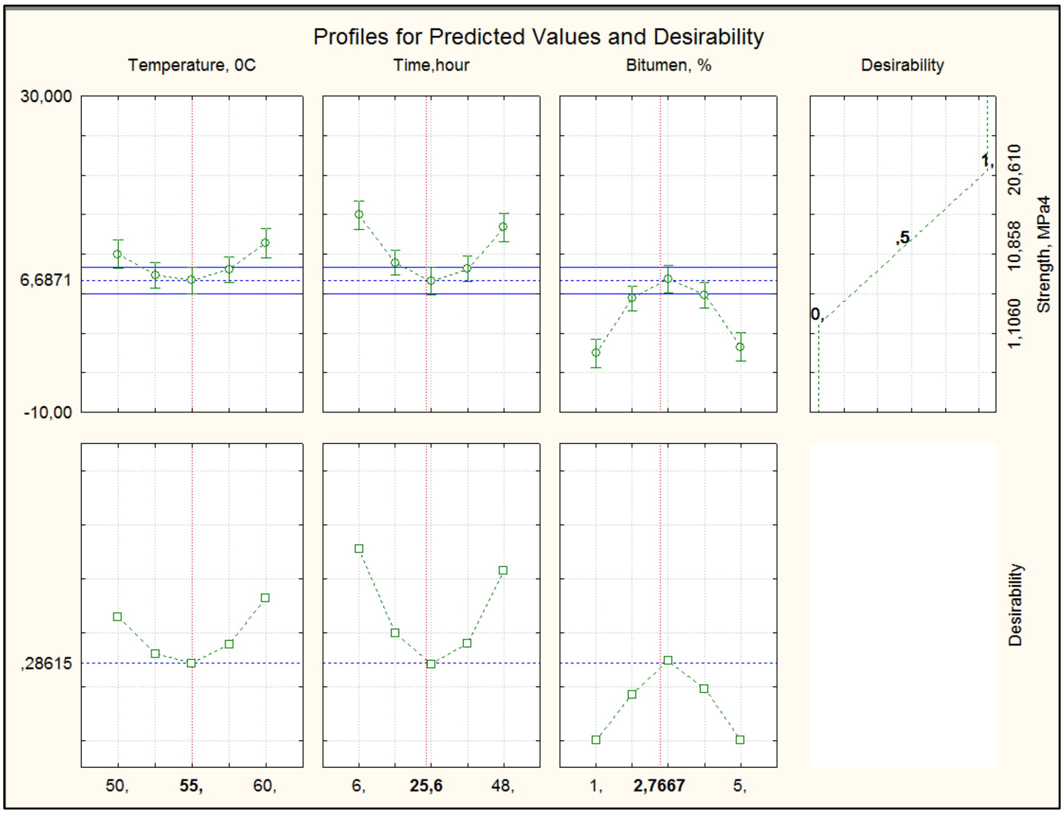

Figure 7 - Response and Desirability Profiles for Strength (y_2) as a Function of Factors ($x_3 - x_1$) (author's materials)

Figure 7 similarly presents the profiles for strength and the desirability function d_2. In this case, factor **x₃** (bitumen content) has a decisive impact on strength: when bitumen content is too low or too high, strength decreases and the desirability coefficient d_2 drops. The maximum desirability is achieved at an intermediate bitumen content (~4-5%), which corresponds to the optimal strength value. Exposure time (d_2) also plays a significant role: as time increases from 6 to ~25 hours, strength rises, increasing d_2; however, further increases in exposure time up to 48 hours may lead to a slight reduction in strength (a nonlinear effect). Temperature (x_1) influences strength to a lesser extent, with the d_2 optimum occurring around 55°C. Thus, the profiles confirm that to achieve maximum strength, a moderate temperature, sufficient exposure time, and optimal bitumen content are required (**Jiaqi et al., 2022**).

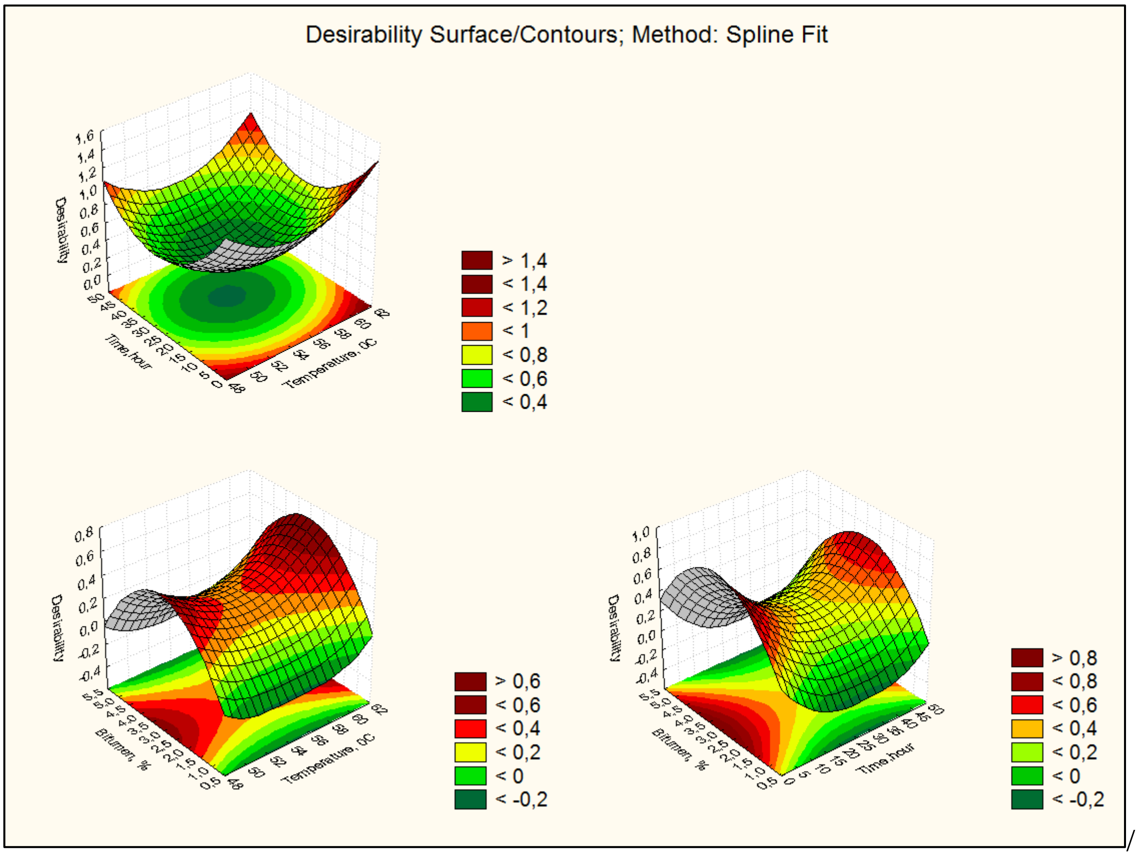

Figure 8 - 3D Surfaces of the Desirability Function D on Factor Combination Planes [author's materials].

The overall desirability function D reaches a maximum value close to 1 in the region of optimal parameters. Figure 8 shows the 3D surfaces and desirability contours in the factor coordinate planes: (a) temperature-time, (b) temperature-bitumen content, (c) time-bitumen content. The color scale reflects the level of D (from dark green for D < 0.7 to dark red for D > 0.9). It can be seen that the D > 0.9 region is formed at temperatures around 55°C, exposure times of approximately 25-30 hours, and bitumen content around 4-5%. In particular, the optimal combination of factors for maximizing D corresponds to the following values: temperature ~55°C, time ~26 h, bitumen content ~4.5% (with fixed gravel content as part of the mix). Under these parameters, high strength (~11 MPa) is achieved with satisfactory thermal conductivity (~0.85 W/m·K), corresponding to $D \approx 0.95$. Thus, the use of the desirability function made it possible to determine a compromise region that satisfies both quality criteria.

5 CONCLUSIONS

1. The strength of the asphalt concrete mixture depends primarily on bitumen content (within the studied range of 5-6% by mass) as well as on the duration of thermal exposure at a given temperature. Increasing the binder content and exposure time leads to higher strength; the effect of compaction temperature is less significant, although raising the temperature to 60°C slightly improves strength.
2. The thermal conductivity of asphalt concrete is mainly determined by the mineral content (gravel) and the mixture's porosity. Denser, gravel-rich mixtures have higher thermal conductivity. The influence of other factors (temperature and preparation time) is statistically insignificant for the thermal conductivity of the dry material. However, water saturation significantly increases its thermal conductivity, which should be considered during service.
3. Three-factor modeling using a Box-Behnken design and analysis of variance (ANOVA) made it possible to quantitatively assess factor effects and identify nonlinear dependencies. Regression

response equations, factor influence profiles, and property optimum regions were constructed. The use of the desirability criterion showed that optimizing the mixture to achieve maximum strength with acceptable thermal conductivity is accomplished with increased bitumen content (~6%) and sufficient thermal strengthening time (>40 h).

4. The thermal analysis confirmed that reducing the thermal conductivity of the asphalt concrete layer decreases the frost penetration depth of the subgrade, which is beneficial for preventing frost heave. The determination of the design soil moisture content (considering the type of moisture exposure) showed that even in arid conditions, moisture in the frost zone can reach 65-80% of the soil's liquid limit, which, in the absence of sufficient insulation, may cause heaving. The results obtained can be used in the design of asphalt concrete mixtures with specified characteristics and in comprehensive pavement design calculations for frost resistance.

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