DOI https://doi.org/10.32782/2415-8151.2024.31.2
UDC 625.7

TWO SOLUTIONS TO PROBLEMS: CONCRETE PAVEMENT DAMAGE AND REPAIR FROM THE PERSPECTIVE OF DESIGN OPTIMIZATION (BIM MODELING) AND MODIFIED CONCRETE MATERIALS

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Abstract. *With the rapid development of the global economy and the accelerated pace of global integration, the pressure on transportation is increasing in all countries of the world, including, of course, in Ukraine. The existing concrete often fails to meet the expected service life and quality, which means that roads have to be rebuilt as well as a lot of road repair work, which undoubtedly increases the government's financial expenditures and workload. There are a number of ways of solving these problems, the most frequently used and effective of which is the use of computer software for computational simulation of the road construction environment, monitoring and modification of concrete materials.* ***Purpose.*** *The goal of this paper is to start from the above two directions and propose two solutions to solve the problem of simulation of soil characteristics in road construction and optimization of road materials.* ***Methodology.*** *The research methodology is mainly based on theoretical research method and experimental method.* ***Results.*** *The article draws the following two results through theoretical analysis and experimental methods: a model for measuring soil characteristics using LIRA-SAPR software and the possibility and dosage of basalt fiber modified cement concrete.* ***Scientific novelty.*** *This article proposes for the first time a soil property modeling method based on the Winkler-Fuss and Pasternak soil models using the software LIRA-SAPR. For the first time, the performance of two specific basalt fibers from China and Ukraine were tested and verified the reinforcing effect and dosage of basalt fibers produced in Ukraine for concrete. Experiments have proven that adding 2% basalt fiber will make cement concrete have better performance.* ***Practical relevance.*** *The proposed modeling methodology helps to optimize the design to ensure structural stability and safety, and the in-depth knowledge of soil conditions helps to plan the construction phases more accurately, which helps to control costs and reduce delays. The response results of concrete modified with basalt fibers can be used in practical projects to enhance pavement strength.*

Key words: *BIM modeling, modified concrete materials, LIRA-SAPR software package, concrete pavement, soil basic characteristics, basalt fiber, pavement repair, cement, cement concrete, modifying additives, road construction, airfield construction.*

INTRODUCTION

As the total volume of traffic continues to rise, the loads and speeds of roads and the carrying capacity of vehicles increase and the number of vehicles increases, the need for newly constructed and rehabilitated roads in Ukraine continues to grow. Current roads need to be able to carry axle loads of 11,5–13,0 tons for heavy vehicles, whereas previously constructed roads had axle load standards of 6–10 tons, which makes the passage of heavy vehicles significantly lead to wear and tear and damage of roads [18].

In addition, design, materials, construction techniques and environmental conditions can also cause damage to concrete pavements [9]: due to temperature changes, design, long-term heavy load wear, etc., the pavement may develop cracks, cracked or dislocated joints, surface wear, structural damage and even settlement, uneven deformation and other problems [17].

Addressing concrete pavement distress and rehabilitation can be approached from several perspectives, covering a full range of considerations from design and material selection to construction techniques and maintenance strategies.

Design optimization: Future pavement problems can be predicted and reduced through accurate design using advanced design software and methods such as BIM. This includes, but is not limited to, proper drainage design, load considerations, and proper thickness and reinforcement design [3]; Modified concrete materials: Use high-performance, more durable modified concrete, such as high-strength concrete, fiber-reinforced concrete, or self-compacting concrete, to improve the crack and abrasion resistance of the pavement; Construction Technology Improvement: Advanced construction technology and equipment are used to ensure that the concrete is uniformly dense and reduce air porosity and irregular shrinkage, thus improving the overall quality of the pavement [20]; Preventive Maintenance: Regular road inspections and maintenance, such as filling cracks, sealing joints, and regular cleaning to minimize water and pollutant infiltration; Freeze-thaw cycle management: In areas susceptible to freezing and thawing, use freeze-thaw cycle-resistant concrete formulations and proper drainage systems to reduce freeze-thaw damage to pavements; Chemical Corrosion Control: In a chemically corrosive environment, use corrosion-resistant concrete additives and surface coatings to resist chemicals such as salts, acids, and alkalis; Load management: For roads carrying heavy traffic, reduce wear and tear on the pavement by limiting overweight vehicles and optimizing traffic flow; Applying new technologies: Explore and apply new technologies, such as intelligent sensing technology for monitoring the condition of pavements to detect and repair problems promptly; Environmental adaptability design: Considering the local environmental characteristics (e.g. temperature, humidity, rainfall, etc.), design concrete pavement adapted to the local environment [4].

This involves multifaceted and multidisciplinary topics, among which design optimization using software and modified concrete materials are two frequently used and effective methods. In this paper, we focus on proposing a technique for BIM (Building Information Modeling, now referred to as BIM) modeling of pavements for roads and a method for modifying concrete materials using basalt fibers.

ANALYSIS OF PREVIOUS RESEARCH

In recent years, with economic growth, countries around the world have been spending an increasing amount of money on road construction and maintenance, which accounts for a large proportion of national financial expenditures. Therefore, it becomes increasingly important for road pavements to ensure adequate structural and functional properties throughout their service life. In order to provide the longevity and quality of road pavements, it is necessary to refine the design of pavements on the one hand and, on the other hand, to adequately deal with complex monitoring and rehabilitation issues to ensure road performance and reliability [8].

BIM technology has continued to evolve over the decades since its introduction and has performed satisfactorily in all areas of civil engineering. Today, while BIM solutions have been widely utilized in many developed countries in the areas of architecture, structures, and electrical plumbing, BIM has not been able to take full advantage in the area of infrastructure (e.g., roads and sidewalks, etc.) [11].

BIM modeling integrates soil properties with building design and structure. Integrating soil data into a BIM model allows for a more accurate assessment of soil impacts on building structures, such as load-bearing capacity, settlement, and expansion. This helps optimize the design to ensure structural stability and safety. Understanding soil properties using BIM software can help identify and manage foundation risks, such as ground settlement or soil corrosion. This can prevent potential problems during the design phase and reduce future repair and retrofit costs [5]. A BIM system is also a platform for collaborative workflows, allowing multiple team members (e.g., engineers, designers, contractors) to access and use the same models and data. Integrating soil information improves collaboration and communication between teams and ensures that all parties involved clearly understand the project's soil conditions. It also means that BIM allows for construction planning and budget control: a deeper understanding of soil conditions helps to plan construction phases more accurately, including material selection, construction methods, and time management, which helps control costs and reduce delays.

Modeling and calculating the base characteristics of pavement soils is critical in the design, management, and monitoring of road pavements using BIM, which involves complex computational processes and solutions [2]. This paper proposes a solution for determining soil base characteristics using the LIRA-SAPR software package.

Also, as mentioned above, modified concrete materials are a key component in enhancing the quality of road pavements. Modified concrete can be used in a variety of ways, more commonly through the addition of additives and admixtures, but also through changing environmental conditions and mixing processes. Figure 1 lists a variety of methods for modifying concrete [16; 19].

By modifying concrete with the addition of fibers, modifiers, or other additives, concrete can often achieve better durability, compressive strength, flexural strength, and toughness to resist cracking, corrosion, and other types of damage, which is especially important for roads subjected to heavy traffic and extreme weather conditions, thus reducing the need for repairs and maintenance costs [6; 15]. In colder regions, modified concrete can be more effective in resisting damage caused by freeze-thaw cycles, thereby extending the life of the pavement. Certain modified concretes can also increase their resistance to corrosion by chemicals (e.g., road salt, fuel spills, etc.), which is critical to protecting structural integrity in harsh environments. In addition, concrete modification using environmentally friendly or recycled materials can help to reduce carbon footprints and minimize environmental impacts. For example, industrial wastes such as fly ash are used as part of the concrete composition [10; 13].

Concrete modification using various fibers is a standard method as it is cost-effective and less complicated to construct. Basalt fibers have already proved their effectiveness in practice in road construction in Georgia, USA, and have served as a basis for their extension to other parts of the country [14]. Unfortunately, this efficient pavement reinforcement technology has not been used in Ukraine. This paper will present a method and effectiveness of cement concrete modification using basalt fibers.

PURPOSE

The article aims to improve the problem of construction and rehabilitation of road pavements from two directions: design optimization (BIM modeling) and modified concrete materials (modification with basalt fibers). Regarding BIM modeling, we aim to provide solutions for soil-based characterization by LIRA-SAPR software using Winkler-Fuss and Pasternak models. Regarding the modification of concrete using basalt fibers, our goal is to test the physical and

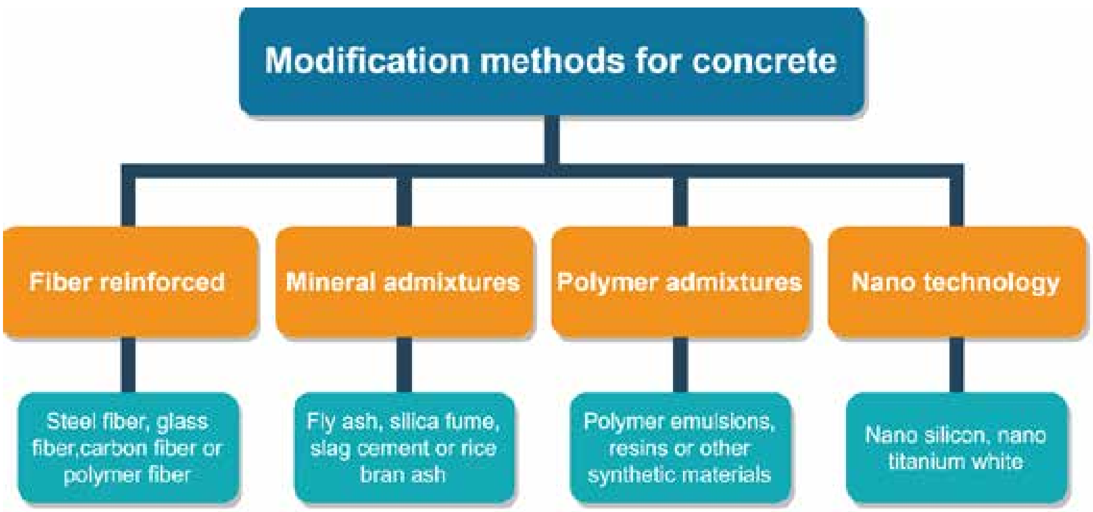

Fig. 1. Methods of modifying concrete

mechanical properties of two types of basalt fibers (made in China and made in Ukraine), and then experimentally explore whether cement concrete containing basalt fibers has higher strength and the most appropriate amount of basalt fibers to mix.

RESULTS AND DISCUSSIONS

The most common approach to calculating structures on an elastic base is the approach that considers the joint operation of the ground part of the structure with the groundmass. Thus, in the calculation model, both the ground part and the groundmass form a standard, finite-element model (Fig. 2). It should be taken into account that the soil massif is a nonlinear deformable medium consisting of layers with different properties.

Even though such models can be created and calculated with the help of the LIRA-SAPR program complex, and their calculation results will be the closest to reality, the volume of necessary calculations will be huge even for modern computers. Dimensions of the ground massif taken into account in the calculation should be such that the nature of boundary conditions in the area bounding this massif does not significantly impact. This is because the dimensions of the ground massif taken into account in the calculation should be such that the nature of boundary conditions in the area bounding this massif does not significantly impact the stress-strain state of the entire model. Since these dimensions are quite large and the problem is nonlinear, the time spent to obtain a solution will be very long.

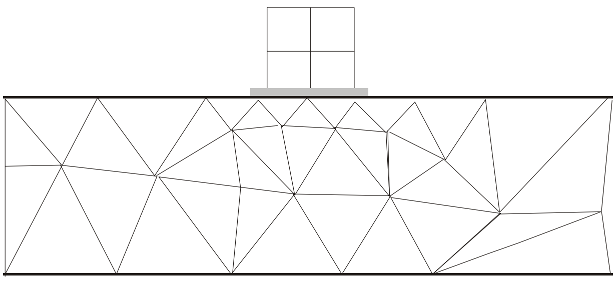

Fig. 2. Schematic diagram of the finite element model composed of ground part and soil massif

In this connection, simplified models of the soil foundation that allow for the replacement of a large soil mass with a limited number of parameters reflecting its properties in structural calculations are still relevant. In this connection, simplified models of the soil foundation that allow for the replacement of a large soil mass with a limited number of parameters reflecting its properties in structural calculations are still relevant. The soil models proposed by Winkler-Fuss and Pasternak provide a possibility of such replacement [1].

The SOIL subsystem realizes the soil foundation stiffness parameters calculation by different soil models.

The program performs the following operations:

– Formation of a spatial model in graphical mode soil following the specified engineering-geological conditions of the construction site;

– Specifying loads from projected and existing structures and arbitrarily applied loads;

– Determine the ground settlement field by the specified loads and geotechnical conditions;

– Calculate bedding coefficients of elastic (ground) foundation according to the Winkler-Fuss and Pasternak models.

To describe the construction site in the graphical mode, the base of soil characteristics is set, the coordinates and marks of wellheads are specified, and the characteristics of soil layers in each well.

Based on these data, a spatial model of the ground is formed, and the relief of the day surface is plotted using the wellhead marks. Assuming the ground structure is smooth enough.

The set parameters can be controlled by displaying geologic sections, which are lined up along a line segment drawn anywhere on a given construction site (Fig. 3).

On the given construction site there is an arbitrary polygonal contour of the foundation of the designed structure, as well as contours of the foundations of the buildings under construction and existing buildings.

Within each contour, the loads applied at the level of the basement elevation of the respective foundation are specified. The loads can also be set at any location on the site. The following types of loads are allowed: concentrated forces, uniformly distributed loads over the entire contour area and uniformly distributed loads over an arbitrarily defined contour (stamp). The following types of loads are allowed: concentrated forces, uniformly distributed loads over the entire contour area and uniformly distributed loads over an arbitrarily defined contour (stamp).

To perform calculations, triangulation of areas bounded by specified contours is performed. All necessary parameters are calculated in the nodes of the All necessary parameters are calculated in the nodes of the triangulation, the step of which can be controlled.

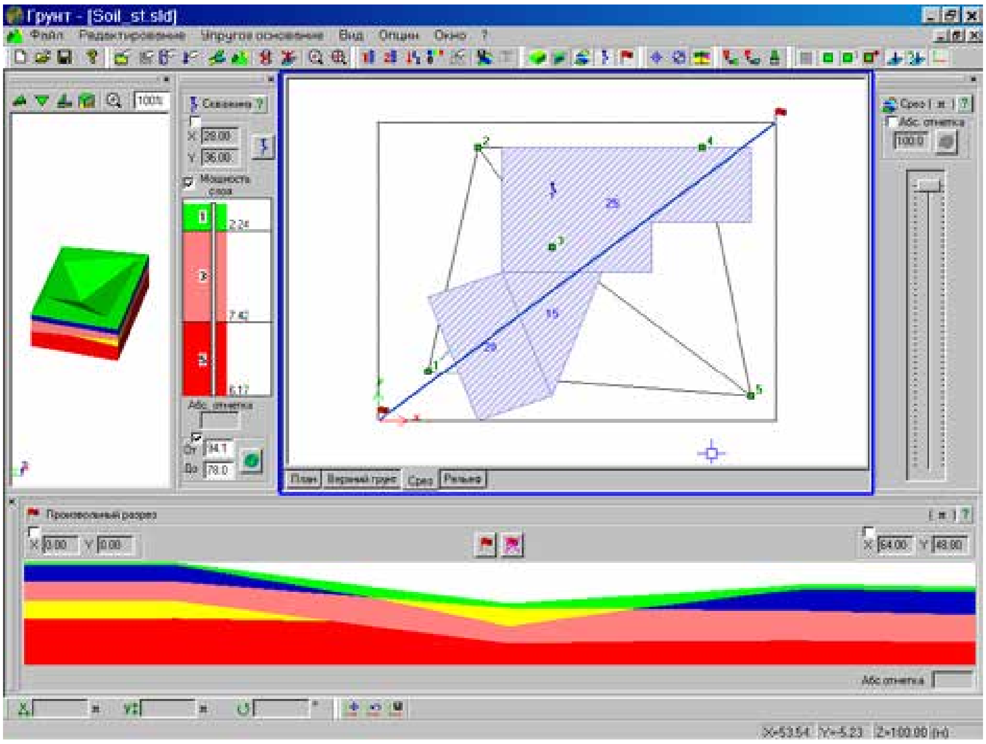

Fig. 3. Schematic diagram of geological section arrangement

In accordance with the applied loads, the ground settlement under the designed foundation is determined (Fig. 4). The provisions of the current norms for the design of foundations of buildings and structures are taken into account. The settlement is calculated by the layer-by-layer summation method using the scheme of a linearly deformed half-space (Boussinesq problem).

The settlement value is fixed upon reaching the boundary of the compressible thickness in accordance with the condition:

$$\sigma_{zp} = k\sigma_{zg},$$

where:

– $\boldsymbol{\sigma_{zp}}$ – additional vertical stress at depth $\boldsymbol{z = H_c}$;

– $\boldsymbol{\sigma_{zg}}$ – vertical stress from own weight of the soil;

– $\boldsymbol{H_c}$ – size of the boundary of the compressible thickness;

– $\boldsymbol{k}$ – coefficient determined by the relevant regulations depending on the type of soils and type of construction; as a rule, $\boldsymbol{k = 0,2}$.

The settlement at an arbitrary point in the projected foundation area is calculated using the following formula:

$$W = \sum_{1}^{n} \frac{\sigma_{zp,i} h_i}{E_i},$$

where:

$\boldsymbol{h_i}$, $\boldsymbol{E_i}$ – thickness and deformation modulus of the ***i-th*** soil layer, respectively; $\boldsymbol{N}$ – number of soil layers taking into account their fragmentation into sub-layers.

The calculation of bed coefficients $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ at an arbitrary point in the area of the designed foundation for Pasternak's two-parameter soil model (in the program – method 1) is carried out using the values of the deformation modulus $\boldsymbol{E_0}$ and Poisson's ratio $\boldsymbol{\mu_0}$ averaged for given soil layers:

$$E_0 = \frac{\sum_1^n \sigma_{zp,i} h_i}{\sum_1^n \frac{\sigma_{zp,i} h_i}{E_i}}; \quad \mu_0 = \frac{1}{H_c} \sum_1^n \mu_i h_i;$$

$$C_1 = \frac{E_0}{H_c\left(1 - 2\mu_0^2\right)}; \quad C_2 = \frac{E_0 H_c}{6\left(1 + \mu_0\right)}.$$

Standard draft value $\boldsymbol{S = 0,8 W}$.

Bedding factor $\boldsymbol{C_1}$ for the Winkler-Fuss soil model (in the program – method 2) at an arbitrary point in the area of the designed foundation is calculated by the following formula:

$$C_1 = \frac{q}{W},$$

where

$\boldsymbol{q}$ – stress under the foundation footing at the required point in its area.

The program results are used to plot the settlement fields, the boundaries of the compressible strata, and the Pasternak and Winkler-Fuss bedding coefficients (Fig. 5).

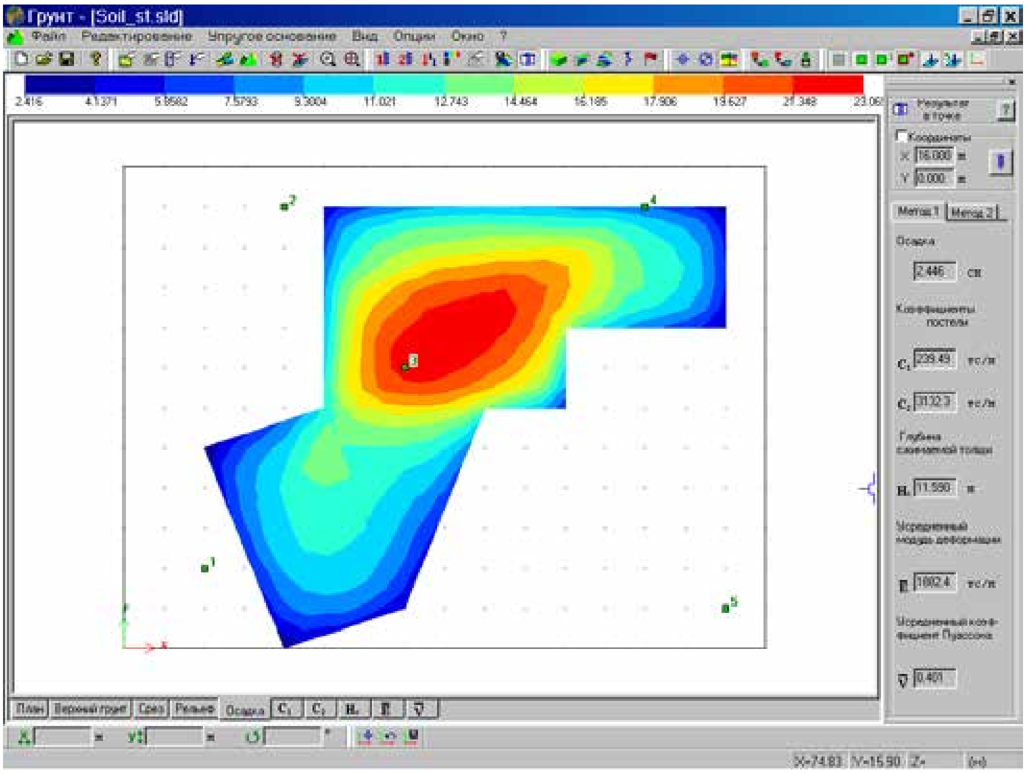

Fig. 4. Schematic diagram of the ground settlement under the designed foundation

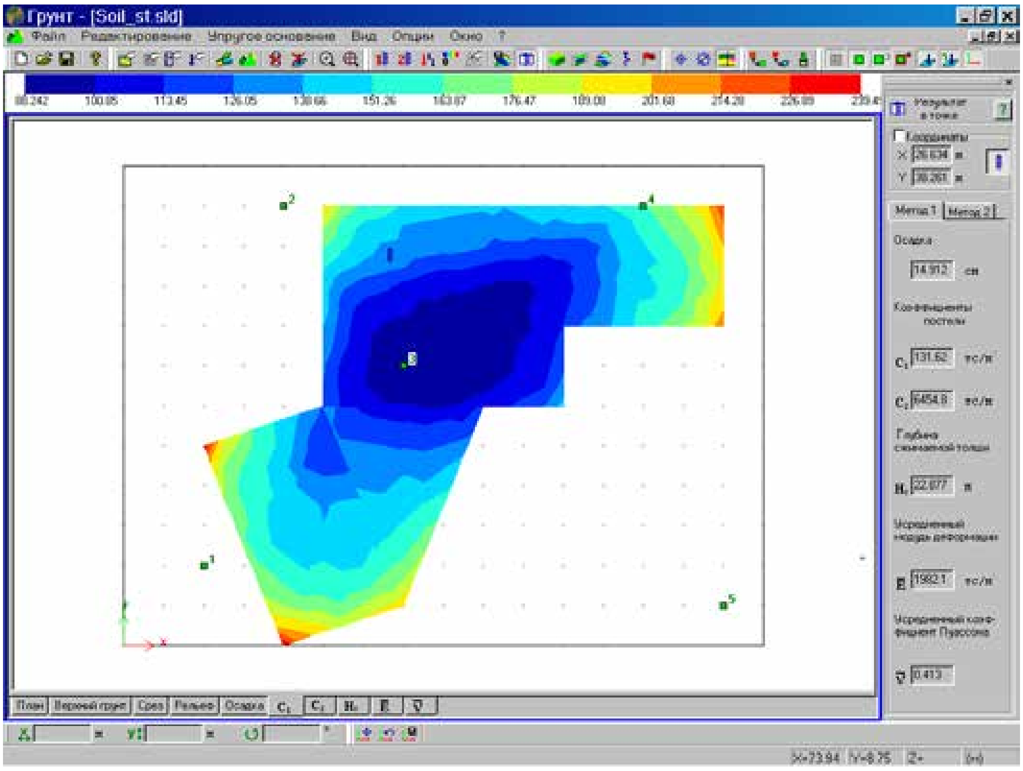

Fig. 5. Diagram of the settlement fields and the boundaries of the compressible strata

The soil foundation model generated by the program is exported to the LIRA-SAPR program complex, where it can be used in the calculation of foundations, foundation slabs, as well as road pavements.

The above is the modeling theory of soil base characteristics using the software LIRA-SAPR. The following part is about the modification of cement concrete using basalt fibers. In

Ukraine, cement concrete is the primary material used for constructing roads and airports, except for asphalt concrete. This material is also used to build bridges, tunnels, and other hydraulic structures.

From the literature review, it is clear that the introduction of basalt fibers into cement concrete and asphalt concrete mixtures is a pressing problem, the solution of which could expand the range of fiber additives in road mixtures, improve the transport and operational performance of roads with dispersed reinforcements, and reduce the cost of materials using basalt fibers [7; 12].

The client provided the research subject, Basalt Fiber, a high-quality microfiber made by melting basalt at temperatures of 1 600–1 650 °C and then pulling it into fibers. The appearance of basalt microfibers is shown in Figure 6.

Table 1 lists the chemical compositions used to produce basalt microfibers.

The physical and mechanical properties of basalt fibers are shown in Table 2.

Analysis of the data in Table 2 with the results of the tests to determine the possibility of using basalt fibers for dispersion (chaotic) reinforcement of cement-concrete mixtures showed that basalt fibers produced in China could not be used as a reinforcement additive due to their low mechanical strength.

Therefore, basalt fibers produced in Ukraine were used in subsequent studies.

The following materials for cement concrete were used in conducting the cement concrete study:

– Basalt fibers produced in Ukraine;

– Portland cement M 500 from the Amvroshevo plant with a normal density of 26%;

– Dniprovsky river sand, grain size modulus $M_к$ = 2,60, content of dust and clay particles – 2%, bulk density 1260 kg/m²;

– Crushed stone (5–20) mm from Gnevan quarry.

Chemical additives: plasticizing additive LST-E and air-entraining additive SNV.

Fig. 6. Structure of Microfine Basalt Fibers

Table 1

The chemical compositions used to produce basalt microfibers

Oxide Name	Fiber content (%), sample			
	1	2	3	4
Na_2O	1,48	1,54	1,66	1,48
MgO	1,29	1,24	1,19	1,09
Al_2O_3	23,67	20,48	21,59	18,10
SiO_2	47,08	36,97	46,51	35,37
K_2O	2,17	1,52	2,15	1,55
CaO	12,89	9,25	13,25	8,92
TiO_2	1,01	0,66	1,01	0,59
Mn_2	0,12	0,88	0,14	1,03
FeO_2	8,60	18,47	10,97	22,30

Table 2

Physical and mechanical properties of basalt fibers

Indicator name	Physical and mechanical properties		
	Basalt fiber (produced in China)	Basalt fiber (produced in Ukraine)	Glass fiber
Average fiber diameter, microns	150,0	160,0	200,0
Amount of non-fiber additives, %	2	2–3	Not more than 5
Density, g/cm^3	2,31	2,65	2,35
Operating temperature range,^{0} C	−269 – +900	−269 – +700	−60 – +400
Waterproofness %	99,8	99,6	99,1
Chemical resistance, %			
0,5N NaOH	96,4	93,4	90,3
2H NaOH	97,3	77,3	47,7
2H H_2 SO_4	98,5	98,5	72,5
Moisture absorption, %	Gundam 1.0	Gundam 1,0	10–15
Mechanical strength, Mpa	1 200	4 100	2 900
Elongation at break, %	2,6	3,1	2,8

Table 3

Compressive and tensile strength of concrete with basalt fiber added

№	Concrete sample name	Amount of fiber, % of concrete weight	Compressive strength (Mpa)		Flexural tensile strength (Mpa)	
			7 days	28 days	7 days	28 days
1	Control group	–	19,8	22,4	4,6	5,9
2	Contains basalt fibers	2,0	20,8	28,3	6,8	9,1
3	Contains basalt fibers	4,0	18,8	23,2	4,9	7,2

Concrete of the following composition was used in making the specimens:

Additive name	Adding amount
Cement M-500	650 kg
Sand	1 300 kg
Water	280 l
basalt fiber	2,0 and 4,0% by weight of concrete

The mixing of cement-concrete mixture with basalt fibers was carried out in a gravity mixer. Compaction of the mixtures was carried out in standard molds on a laboratory vibration table at a frequency of 3 000 vibrations per minute.

The physical and mechanical properties of the specimens were determined after 7 and 28 days of curing.

The 10 x 10 x 10 cm cube specimens and 10 x 10 x 40 cm beam specimens were tested under normal conditions at 7 and 28 days after curing, respectively, to determine the physical and mechanical properties of the concrete.

Basalt fibers of 4–5 mm in length and 160,0 μm in diameter were used in the preparation of cement-concrete mixtures with basalt fibers.

Studies of the concrete mixture with the addition of basalt fira were carried out to determine the compressive strength and tensile strength in bending.

Table 3 summarizes the results of the studies.

By analyzing the data in Table 3, we can conclude that the sample with 2% fiber content has higher compressive and flexural tensile strengths compared to the control sample and the sample with 4% fiber content. In other words, the addition of 2,0% basalt fibers to the concrete mixture is optimal.

CONCLUSIONS

In the results and discussion, we present a simplified model of soil foundations, which is helpful and practical for airport and road construction. Currently, the library of calculation programs for calculating bedding coefficients is open. In the near future, the program will be supplemented with calculation procedures for the Fedorovsky soil model.

In order to determine the possibility of using basalt fibers for dispersion (chaotic) reinforcement of cement-concrete mixtures, the results of the tests were analyzed, which showed that basalt fibers produced in China could not be used as a reinforcement additive due to their low mechanical strength. By analyzing the test results of cement-concrete mixtures with basalt fibers added, we can conclude that the samples with 2% added fibers have higher compressive and flexural tensile strengths than the control samples and the samples with 4% added fibers. In other words, the addition of 2,0% basalt fibers to the concrete mixture is optimal.

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АНОТАЦІЯ

Барабаш М. С., Шао Мейюй. Два рішення проблем: пошкодження та ремонт бетонного покриття з погляду оптимізації дизайну (BIM-моделювання) та модифікованих бетонних матеріалів.

Зі стрімким розвитком світової економіки та прискореними темпами глобальної інтеграції тиск на транспорт зростає в усіх країнах світу, зокрема, звичайно, і в Україні. Наявний бетон часто не відповідає очікуваному терміну експлуатації та якості, що означає потребу реконструкції доріг, а також багато ремонтних робіт, що, безперечно, збільшує фінансові витрати та навантаження держави. Існує низка шляхів вирішення цих проблем, найбільш поширеним і ефективним із яких є використання комп'ютерного програмного забезпечення для обчислювального моделювання середовища дорожнього будівництва, моніторингу та модифікації бетонних матеріалів. ***Мета.*** *Мета цієї роботи полягає в тому, щоб розпочати із двох вищевказаних напрямів і запропонувати два рішення для розв'язання проблеми моделювання характеристик ґрунту під час будівництва доріг і оптимізації дорожніх матеріалів.* ***Методологія.*** *Методологія дослідження в основному базується на теоретичному й експериментальному методах.* ***Результати.*** *У статті за допомогою теоретичного аналізу й експериментальних методів отримано два результати: модель вимірювання характеристик ґрунту за допомогою програмного забезпечення ЛІРА-САПР, можливість і дозування цементобетону, модифікованого базальтовим волокном.* ***Наукова новизна.*** *У статті вперше запропоновано метод моделювання властивостей ґрунтів на основі моделей ґрунтів Вінклера – Фусса та Пастернака з використанням програмного забезпечення ЛІРА-САПР. Уперше були перевірені характеристики двох конкретних базальтових волокон з Китаю й України та перевірено армувальний ефект і дозування базальтових волокон українського виробництва для бетону. Експерименти довели, що додавання 2% базальтового волокна покращить характеристики цементного бетону.* ***Практична значущість.*** *Запропонована методологія моделювання допомагає оптимізувати конструкцію для забезпечення структурної стабільності та безпеки, а глибоке знання ґрунтових умов дозволяє точніше планувати етапи будівництва, що допомагає контролювати витрати та скорочувати затримки. Результати реакції бетону, модифікованого базальтовими волокнами, можна використовувати у практичних проєктах для підвищення міцності тротуарів.*

Ключові слова: BIM-моделювання, модифіковані бетонні матеріали, програмний комплекс ЛІРА-САПР, бетонне покриття, основні характеристики ґрунту, базальтове волокно, ремонт покриття, цемент, цементобетон, модифікуючі добавки, будівництво доріг, будівництво аеродрому.

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Стаття подана до редакції 18.01.2024 р.

Barabash M., Shao Meiyu. (2024). Two solutions to problems: concrete pavement damage and repair from the perspective of design optimization (BIM modeling) and modified concrete materials. *Theory and practice of design. Architecture and construction.* 1(31). P. 15–24, doi: https://doi.org/10.32782/2415-8151.2024.31.2