Basalt fiber concrete as a new construction material for roads and airfields

K Kravuskina\textsuperscript{1,3}, T Khymryk\textsuperscript{2} and A Bieliatynsky\textsuperscript{2}

\textsuperscript{1} Department of modern technologies, DP DerzhdorNDI, Peremohy av., 57, Kiev, 03113, Ukraine
\textsuperscript{2} Department of airports and highways reconstruction, National Aviation University, Komarova av., 1, Kiev, 02156, Ukraine

\textsuperscript{3} Email: ekrayushkina5@ukr.net

Abstract. The presence of reinforcing fibers in concrete in terms of their optimal content increases density, uniformity and reduces the risk of cracking which allow predicting the increased dynamic resistance, frost resistance, abrasiveness and durability of both cement and asphalt concrete. This article presents the results of experimental studies of the physical-mechanical properties of cement and asphalt concrete reinforced with basalt fiber during which technological indicators of impact on the strength and durability of concrete (fiber content in mixtures, the ratio of fiber length to the size of the largest coarse aggregate) were selected, statistical analysis and optimization of the research results. To justify the choice of basalt fiber, the results of research on the determination of its chemical composition of the fiber and physico-mechanical characteristics are shown. The optimal sizes of basalt fiber, which is introduced into the mixture, are also determined. It was concluded under what conditions the studied characteristics of concrete reinforced with basalt fiber reach their maximum value with the corresponding ratios of technological indicators.

1. Introduction

In Ukraine, asphalt and cement concrete are the main structural materials for highways and airfields. Dispersed reinforced concrete – fiber concrete – is one of the perspective structural materials which allow compensating such shortcomings of cement concrete as low tensile strength, high brittleness during fracture and of asphalt concrete, such as formation of cracks, waves, ruts during operation.

Road and airfield surface must withstand repeated cyclic traffic loads, resist the stresses that occur on the surface due to changes in temperature and humidity, withstand the stresses caused by deformations due to frost heaving of the soil base, so ensuring their durability and reliability is an urgent task.

In Ukraine, the main type of surface is cement and asphalt concrete. The riding qualities of cement and asphalt concrete can be improved by introducing basalt fibers into the mixture which will contribute to the elimination of the negative impact of the concentration of stresses from vehicles on these pavements during operation.

Significant reserves of basalt are available in Ukraine, the treatment of which is completely developed which makes this material accessible and economical for application.
In recent years, the use of basalt threads as fibers for the dispersed reinforcement of cement and asphalt mixtures has begun.

2. Basalt fiber experimental research
Depending on the diameter, basalt fibers are divided into: microthin with a diameter of less than 0.6 μm; ultrathin 0.6 - 1.0 μm; superthin 1.0 - 3.0 μm; thin 9 - 15 μm; thickened 15 - 25 μm and coarse with a diameter of 50 - 500 μm.

The appearance of basalt fiber is shown in Figure 1.

Figure 1. The structure of basalt fiber: a - microthin; b - coarse

The chemical composition of basalt rock is given in Table 1.

| Name of oxide | Content, % by weight |
|---------------|----------------------|
| SiO₂          | 46.5 – 51.5          |
| Al₂O₃         | 15.0 – 19.0          |
| MgO           | 4.0 – 10.5           |
| CaO           | 7.5 – 11.5           |
| FeO+Fe₂O₃     | 8.0 – 12.0           |
| K₂O+Na₂O      | 3.0 – 6.0            |
| TiO₂          | 0.3 – 2.5            |
| Cr₂O₃         | 0.02 – 0.05          |
| MnO           | < 0.1                |
| Other         | Up to 100            |

Physical-mechanical properties of basalt fiber are shown in Table 2.

The fiber is obtained by cutting a basalt thread which is obtained from a melt of basalt crumb at 1450-1550°C by pulling it through special filters with segments of 4-5 mm length.

The fiber length of 4-5 mm was selected as a result of analysis of the study results which show that the best strength indicators for cement and asphalt concrete are typical for this length which can be explained by the increased surface of adhesion with the cement stone and the structuring of bitumen in mixtures.

The results of numerous tests confirm the possibility of using fibers of thin (8 μm) and coarse (160 μm) thread. However, studies have established that the smaller diameter of the basalt fiber, the greater decrease in its strength in the cement medium is, especially in the first 3-6 months after introduction and arrangement in the pavement. It is positive that the process of strength reduction has a fading nature, it
occurs in glass and metal fibers, but for basalt fibers this process is less typical (Figure 2).

Table 2. Physical-mechanical properties of basalt fiber.

| Value                              | Physic-mechanical properties of basalt fiber |
|------------------------------------|---------------------------------------------|
| The average fiber diameter, µms   | 160.0                                       |
| The amount of non-fiber additives, % | 2 – 3                                       |
| Density, g / cm³                   | 2.65                                        |
| Application temperature range, °C  | -269 – +700                                  |
| Water resistance, %                |                                             |
| Chemical resistance, %             |                                             |
| 0.5H NaOH                          | 93.4                                        |
| 2H NaOH                            | 77.3                                        |
| 2H H₂SO₄                           | 98.5                                        |
| Hygroscopicity, %                  | Up to 1.0                                   |
| Mechanical strength, MPa           | 1,800-4,100                                 |
| Modulus of elasticity, Mpa         | 110-120                                     |
| Elongation at fracture, %          | 3.1                                         |

Figure 2. Comparative dependence of the strength loss over time of fibers of different origin in the hardening medium of Portland cement.
3. Experimental studies of cement-concrete and asphalt-concrete mixtures with the addition of basalt fiber

Basalt fiber of 4-5 mm length, diameters of 160.0 μm in the amount of 2.0 and 4.0 % by weight of cement concrete was used to carry out studies of the cement-concrete mixture with fiber. Concrete was prepared using Portland cement PTs-500 with a conventional density of 26 % - 650 kg, river sand with a fineness modulus of $M_k = 2.60$ with content of dusty and clay particles - 2%, crushed stone of fractions (5-20) mm, plasticizing and air-entraining additives produced by “Stachema” (Slovenia).

The cement-concrete mixture was mixed with basalt fiber in a gravity mixer.

Studies determined the positive impact of basalt fiber orientated perpendicular to the workload on the physical and mechanical characteristics of fiber concrete. The workload is achieved by vibrocompaction of fiber concrete under the influence of a magnetic field.

Studies were carried out to determine the impact of the flowability of the concrete mixture on the efficiency of fiber orientation, the results of which are given in Table 3. The necessary flowability of the concrete mixture was provided by the selection of the content of the “Stachema” superplasticizer. The fiber content in all concrete mixes was constant and amounted 40 kg/m$^3$. Orientation of basalt fiber occurred as a result of the action of a magnetic field which was created by an electromagnet on the mounted laboratory vibratory platform.

Table 3. The results of the impact of the flowability of the concrete mixture on the efficiency of fiber.

| №  | water-cement ratio | Content of the "Stachema" superplasticizer | Flowability of the mixture, cm | Tensile strength under compression at the age of 7 days, MPa | Tensile strength under compression at the age of 28 days, MPa |
|----|--------------------|------------------------------------------|-------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| 1  | 0.30               | 0.25                                     | 7                            | 4.1                                                      | 5.2                                                      |
| 2  | 0.30               | 0.35                                     | 14                           | 5.2                                                      | 6.5                                                      |
| 3  | 0.30               | 0.55                                     | 21                           | 6.7                                                      | 7.9                                                      |
| 4  | 0.30*              | 0.54                                     | 21                           | 3.9                                                      | 5.3                                                      |

Figure 3. Diagram of the impact of consumption of cement, fiber and water cement (W/C) ratio on tensile strength of fiber concrete under compression at the age of 3, 7 and 28 days. C - cement consumption, kg/m$^3$; F - fiber consumption, kg / m$^3$; W/C - water-cement ratio.
As follows from the data in Table 3, the use of concrete mix with \( \text{OK} = 7 \) cm, compacted by vibration, gave an insignificant impact of increasing the tensile strength of concrete under compression which can be explained by the insufficiently expressed effect of fiber orientation in low flowable concrete mixes. Increasing the flowability of the mixture from 7 to 21 cm allows significant improving the orientation impact and increasing the tensile strength under compression by 1.6 times at the age of 7 days and by 1.5 times at the age of 28 days during reinforcing with fiber under the influence of vibration.

Considering the above mentioned, to determine the physical-mechanical properties of fiber concrete, the studies were carried out with samples compacted on a vibratory table with an oscillation frequency of 3000 oscillation/min.

Physical-mechanical properties were determined after hardening of the samples on the 7th and 28th day.

Two technologies of introduction of basalt fiber into the cement-concrete mixture were used. First: fiber is introduced into the premixed mixture of cement, water and fillers in the last turn. Second: fillers and fiber are mixed first, and then cement, water and additives are added.

Studies of the concrete mixture with basalt fiber were carried out with the determination of compressive strength \( (R_{\text{compression}}) \) and tensile strength at bending \( (R_{\text{bending}}) \).

The research results are shown in table 4-5.

### Table 4. The physical-mechanical properties were determined after hardening of the samples.

| №   | Name of concrete samples | The amount of fiber, % by weight of concrete | Compressive strength, MPa, at age | Tensile strength at bending, MPa, at age |
|-----|--------------------------|--------------------------------------------|----------------------------------|----------------------------------------|
|     |                          |                                            | 7 days                          | 28 days                                |
|     |                          |                                            |                                 |                                        |
|     |                          |                                            |                                 |                                        |
| 1   | Reference                | -                                          | 19.8                            | 22.4                                   |
| 2   | With basalt fiber       | 2.0                                        | 20.8                            | 28.3                                   |
| 3   | With basalt fiber       | 4.0                                        | 18.8                            | 23.2                                   |
|     | First technology        |                                            |                                 |                                        |
| 4   | Reference                | -                                          | 19.9                            | 22.2                                   |
| 5   | With basalt fiber       | 2.0                                        | 20.9                            | 28.4                                   |
| 6   | With basalt fiber       | 4.0                                        | 18.6                            | 23.3                                   |
|     | Second technology       |                                            |                                 |                                        |

When analyzing the data of table 4, we can conclude that the samples with two percent of fiber have higher compressive and tensile strength at bending than the reference samples and the samples with fiber in the amount of 4%. That is, 2.0% (by weight of concrete) is the optimal amount of basalt fiber added to a cement-concrete mixture.

Physical-mechanical properties of cement concrete with basalt fiber are shown in Table 5.

When analyzing the data of Table 5, it is obvious that the introduction of basalt fiber improves the quality and durability of cement concrete. Due to the formation of a dense, strength concrete structure, water absorption indicators are decreased, and water and frost resistance indicators are increased.

The impact of basalt fiber on the improvement of the physical-mechanical properties and performance of asphalt concrete was studied on hot mixtures of B type and cold mixtures. The function of the fiber as a regulator of the viscosity of bitumen and reinforcing filler is to reduce the total porosity of asphalt concrete and reduce the number of large pores which positively impacts on its strength and water resistance.
Table 5. The physical-mechanical properties of cement concrete with basalt fiber.

| №  | Name of concrete samples | The amount of fiber, % by weight of concrete | Coefficient of frost resistance after the number of cycles | Water resistance, MPa | Water absorption, % |
|----|--------------------------|---------------------------------------------|--------------------------------------------------------|-----------------------|---------------------|
|    |                          |                                             | 100  | 200  | 300  |                                             |                        |
| 1  | Reference                | -                                           | 0.840| 0.760| 0.710| 4.8                                         | 5.3                    |
| 2  | With basalt fiber        | 2.0                                         | 0.960| 0.910| 0.830| 8.0                                         | 2.1                    |
| 3  | With basalt fiber        | 4.0                                         | 0.901| 0.860| 0.792| 8.0                                         | 2.3                    |
| 4  | Reference                | -                                           | 0.850| 0.750| 0.680| 4.3                                         | 5.5                    |
| 5  | With basalt fiber        | 2.0                                         | 0.980| 0.880| 0.840| 7.5                                         | 2.4                    |
| 6  | With basalt fiber        | 4.0                                         | 0.890| 0.840| 0.790| 7.0                                         | 2.7                    |

Note: Samples were studied on frost resistance after 100, 200, 300 cycles of freezing and melting in 5 % solution of NaCl.

Asphalt concrete is a complex system of structural elements of different sizes. The presence of these components and the various degree of their arrangement contributes to the sorption of water and capillary steam condensation in the pores. In addition, it is known that sometimes in asphalt mix bitumen does not completely cover aggregate particles, exposing separate open sections. This confirms the intensity of the interaction of steam with a partially hydrophobic material increasing adsorption on a hydrophilic surface and facilitating the penetration of steam through the film.

The studies carried out by the weighted static “desiccation” method allow obtaining the isotherms of adsorption and desorption of steam in mixtures with basalt fiber and without it. (figure 4).

![Figure 4. Isotherms of steam sorption: (a) without fiber introduction; (b) with fiber introduction](image)

When analyzing figure 4, it is seen a significant decrease in the sorption of steam in a mixture with the introduction of basalt fiber. This shows that there is a change in porosity and the adhesion of bitumen with the surface of the aggregate grains is improved. Consequently, moisture accumulation in the asphalt...
pavement which occurs due to sorption of steam moisture from the air and the road foundation by large pores will be difficult due to the presence of fiber.

Thus, moisture will not condense in dispersive reinforced asphalt concrete, that is, the negative impact of water on the peeling of the bitumen layer from the surface of aggregate particles, reducing its destructive impact on the structure of bitumen and acceleration of the aging of the binder are prevented.

A decrease in the number of macropores leads to the approximation of individual grains in the mixture, the increase of the viscosity and strength of bitumen films due to the decrease in the thickness of its interlayer between particles and a gradual significant increase in the strength of asphalt concrete.

In asphalt concrete, as well as in cement concrete, the optimal length of fiber is 4-5 mm and the fiber diameter of 160 µm.

Thinner fibers create processing difficulties during mixing and distributing the fiber (clumping) in the mixture.

The studies were carried out with hot fine-grained asphalt mix of “B” type and cold asphalt mix. Basalt fiber was introduced to replace the filler in an amount of from 0.5 to 2.0% by weight of the filler (Table 6).

Table 6. The studies were carried out with hot fine-grained asphalt mix of “B” type and cold asphalt mix.

| Mix type                                      | Average density, g/cm³ | Water saturation, % | Swelling, % | Compressive strength, MPa | Tensile strength at bending, MPa | Water resistance coefficient, K_w |
|----------------------------------------------|------------------------|---------------------|-------------|---------------------------|---------------------------------|----------------------------------|
| Fine-grained asphalt of “B” type with limestone filler (reference) | 2.36                   | 2.13                | 3.17        | 2.6                       | 1.4                             | 10.5                             | 4.8                             | 0.90                           |
| Fine-grained asphalt of “B” type with basalt fiber in amount of, % |                        |                     |             |                           |                                 |                                  |                                 |                                |
| 0.5                                          | 2.35                   | 2.52                | 0.79        | 3.8                       | 1.9                             | 9.6                              | 4.9                             | 0.92                           |
| 1.0                                          | 2.34                   | 3.44                | 1.21        | 4.2                       | 3.2                             | 10.3                             | 5.2                             | 0.90                           |
| 2.0                                          | 2.32                   | 4.21                | 2.07        | 4.6                       | 3.8                             | 10.9                             | 6.6                             | 0.86                           |

When analyzing the data of table 6, it becomes obvious that the physical and mechanical properties are improved by the introduction of a dispersion-reinforcing additive - basalt fiber.

Particular attention should be paid to a significant increase in strength under compression at a temperature of 50 °C which indicates a sufficient rutting resistance on road pavement during hot weather.

Laboratory studies of cold asphalt mix were carried out using aggregates that were also used for hot dense fine-grained asphalt of “B” type; bitumen of SG 70/130 grade with a modifying additive Wetfix-BE was used.

The research results of the physical and mechanical properties of cold asphalt mix dispersed-reinforced with basalt fiber are shown in Table 7.
Table 7. The research results of the physical and mechanical properties of cold asphalt mix with basalt.

| Value                                      | Reference sample without fiber | Asphalt mix type | With fiber in amount of 1 % | With fiber in amount of 2 % |
|--------------------------------------------|--------------------------------|------------------|----------------------------|-----------------------------|
| 1 Porosity of mineral skeleton, % by volume| 19.0                           | 18.5             | 18.0                       |                              |
| 2 Residual porosity, % by volume           | 9.5                            | 8.0              | 7.5                        |                              |
| 3 Water saturation before heating, % by volume | 7.8                            | 6.0              | 6.0                        |                              |
| 4 Swelling before heating, % by volume, not more than | 1.5                            | 1.2              | 1.2                        |                              |
| 5 The limit of compressive strength MPa, at a temperature 20°C before heating, not more than | 2.5                            | 3.8              | 4.0                        |                              |
|                                             | after heating, not more than    | 3.2              | 4.5                        | 4.6                          |
| 6 Water resistance coefficient              |                                |                  |                            |                              |
|                                             | before heating, not more than   | 0.70             | 0.76                       | 0.76                         |
|                                             | after heating, not more than    | 0.85             | 0.88                       | 0.90                         |
| 7 Compression by the number of impacts, not more than | 9.0                            | 8.5              | 8.5                        |                              |

Analysis of the data of Table 7 shows that dispersed reinforcement increases the strength of the cold asphalt mix in comparison with unreinforced mix by 40-45% before and after heating, while the values of water saturation and swelling are reduced.

4. Conclusions
1. Laboratory studies to determine the possibility of using basalt fiber for dispersed (chaotic) reinforcement of cement and asphalt concrete mixtures showed that the material can be effectively used as a reinforcing additive and this will lead to an improvement in the physical and mechanical properties of dispersed reinforced materials.
2. The introduction of basalt fiber into the cement concrete mixture can improve physical and mechanical characteristics (increasing the compressive strength by 20%, tensile strength at bending by 20% - 25%, frost and water resistance by 15 - 20%, as well as abrasion).
3. During the studies the optimal amount of fiber injection which is 2.0% by weight for cement concrete and 1.0% by the amount of filler for hot and cold asphalt concrete was established. Fibers provide three-dimensional hardening compared to traditional reinforcement, which provides two-dimensional hardening.
4. Introduction of basalt fiber into the hot asphalt mix will provide crack resistance of the pavement (the possibility of reflected cracking is reduced) and formation of asphalt concrete structure resistant to temperature fluctuations due to increase in the number of contacts between aggregate grains which will increase the shear resistance of asphalt concrete. Therefore, the hot dense disperse-reinforced asphalt mixture has higher tensile strength at bending, higher shear resistance and an improvement of quality and increase of the pavement service life of both roads and runways of airfields by 1.5 times can be predicted.
5. Studies for determining the physical and mechanical properties of cold asphalt mix showed that the cold asphalt mix disperse-reinforced with basalt fiber does not compress and has the increased compressive strength (by 40-45% more than the reference cold asphalt mix). The value of the coefficient of water resistance is within normal limits and higher than for conventional mixture. All the obtained research results indicate high durability of asphalt concrete when basalt fiber is used.
6. The improvement of physical and mechanical properties indicate the positive impact of basalt fiber on the structure of asphalt concrete which occurs during mixing with bitumen and the change in the viscosity of the binder in the neighboring layers. This will prevent the peeling of the binder from the surface of the fibers and will prevent the penetration of water during repair, operation and construction.

7. An important factor is the possibility of using cold asphalt mixture disperse-reinforced with basalt fiber for emergency road repairs which is carried out in difficult weather conditions – at low temperature and high humidity, to ensure uninterrupted traffic during the year.

8. They are not subject to electrochemical corrosion, unlike conventional reinforcement which are electrical conductors and may be subject to cathodic effect.

9. The economic efficiency of the use of materials dispersed-reinforced with basalt fiber is due to increase of the service life of road pavement, possibly reducing the thickness of the top layer, as well as reducing the repair and road maintenance costs due to the durability of concrete reinforced with basalt fiber.

References

[1] Dzhigiris D and Makhova M 2002 Basics of the production of Basalt fibers and products (Moskow: Teploenergetik)
[2] Makhova M and Grebenyuk N 1980 Dispersed reinforcement of Portland cement with basalt fibers Cement 2 94-99
[3] Veselovskyi R and Savitskiy N 2006 The study of the strength of the system "metal substrate-reinforced polymer pavement" at bending and tension Coll. of scientific works of PSASA
[4] Dzhigiris D and Makhova M 1989 Basalt fiber materials XVII scientific and technical information and economics of industry of building materials
[5] Bazhanov Y 1987 Concrete technology (Moskow: Higher School)
[6] Gigineshvili D 1988 The numerical and analytical method of potential for the calculation of structures made of composite materials taking into account the destruction mechanics (Varna: Sofia: BAN)
[7] Kholmyansky M and Kurilin V 2005 Steel-fiber concrete with an amorphous grid (Moskow: Concrete)
[8] Talantanova K and Tolstenev S 1999 Composite - steel fiber concrete in road construction (Vilnius: Highways)
[9] Mikhailov K and Evgeniev I 1990 The use of metal reinforcement in concrete (Vilnius: Highways)
[10] Aavik A and Paabo P 2006 Assessment of pavement structural strength by the falling weight deflectometer The Baltic journal of road and bridge engineering 15 228-234