PriMera Scientific Engineering
Volume 2 Issue 6 June 2023
ISSN: 2834-2550

Dispersion-Reinforced Asphalt Concrete in Road Construction

Type: Research Article
Received: April 27, 2023
Published: May 24, 2023

Citation:
Krayushkina Kateryna. "Dispersion-Reinforced Asphalt Concrete in Road Construction". PriMera Scientific Engineering 2.6 (2023): 45-53.

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Abstract

A wide variety of destructions and deformations of the pavement, such as rutting, waves, fatigue cracks, is shown by the experience of operating roads with asphalt concrete pavements. The actual service life of road structures is often much lower than the standard. The service life of asphalt concrete pavements of roads in Ukraine is 5-7 years instead of 12 before overhaul.

Thus, a decrease in the service life generally leads to a deterioration in the transport and operational condition of the road network.

Bitumen is one of the materials most susceptible to changes in asphalt mixes.

In the world practice of road construction, the opinion is firmly established that a radical way to improve the quality of bitumen is their modification with polymers. However, the introduction of polymer additives into petroleum bitumen is not always able to provide the required performance of asphalt concrete in terms of shear resistance at high positive temperatures, crack resistance at low temperatures, and fatigue life when exposed to long-term dynamic loads.

The compositions and technologies for the production of technological complex-modified road asphalt mixtures for the construction of non-rigid pavements of increased durability based on basalt fiber have been developed at the National Aviation University.

Keywords: asphalt concrete; dispersed reinforcement; basalt fiber; crack resistance; shear resistance

Introduction

Experience in the operation of roads with asphalt concrete pavement shows that the actual service life of road structures is often much lower than the standard.

In operational conditions, non-rigid pavements on public roads have recently been subjected to a significant increase in axial loads (load on the axle of a car over 80 kN (up to 110 kN)) and the intensity of the impact of road transport (more than 15 thousand cars per day). As a result, the upper layers of the pavement are subjected to the action of normal and tangential, as well as shock loads in the contact areas of the vehicle wheel with the coating. Also the effect of solar radiation, rain, snow and temperature.

This leads to a wide variety of destruction and deformation of the coating: rutting, waves, fatigue cracks. In addition, during the production process, temperature control in thermal bunkers, transportation to the place of laying in the pavement layers and under operating conditions in the pavement of a non-rigid road pavement, aufalto-concrete mixtures undergo aging. This leads to the fact that the service life of asphalt concrete pavements of roads in Ukraine is 5-7 years instead of 12 before major repairs.

Thus, a decrease in service life generally leads to a deterioration in the transport and operational condition of the road network, requires an annual increase in the volume of repair work, accumulating "underrepair" of roads over the years.

In the world practice of road construction, the opinion is firmly established that a radical way to improve the quality of bitumen is their modification with polymers. For this purpose, thermoplastics (polyethylene), thermoplastic elastomers (copolymers of the styrene-butadiene-styrene type), elastomers (natural and synthetic rubbers), rubber, sulfur, polyolefins, mineral powder and fibrous waste from industrial production are used.

However, the introduction of polymer additives into petroleum bitumen is not always able to provide the required performance of asphalt concrete in terms of shear resistance at high positive temperatures, crack resistance at low temperatures, and fatigue life when exposed to long-term dynamic loads. This is due to the fact that in asphalt concrete mixtures prepared according to traditional technology, the connection between the particles of mineral material and the strength of the conglomerate is provided mainly by the deformation properties of the adsorption-solvation layers of the asphalt binder. At the same time, the connection of each material particle is carried out only with a number of other particles that surround it (short-range connection). There is no connection of a mineral particle with particles that are separated from it by rows of other particles (long-range order connection).

Therefore, to increase the durability of asphalt concrete pavements, it is necessary to solve a number of problems: to ensure the resistance of asphalt concrete to cracking in the autumn-winter-spring period, to increase its resistance to shear loads in the summer period, along with an increase in fatigue life.

The compositions and technologies for the production of technological complex-modified road asphalt-polymer-sulphur concrete mixtures for the construction of non-rigid pavements of increased durability have been developed at the National Aviation University. An analysis of world experience indicates that one of the effective ways to increase the durability of asphalt concrete pavements is dispersed reinforcement of asphalt concrete mixtures. This allows you to simultaneously reduce the likelihood of cracks in the coating and improve their deformation and strength characteristics. The uniform distribution of dispersed reinforcement (polymer, basalt, asbestos-chrysotile fibers) leads to a uniform distribution, primarily of tensile stresses due to chaotic pinching and interweaving of reinforcing fibers with particles of the mineral core. Due to the high tensile strength of microfibers, crack growth is significantly slowed down. Each mineral particle, first of all, micro- and mesostructures of road asphalt concrete, will be structured with fibers, for example, chrysotile asbestos, containing on its surface adsorption-solvation layers of a bitumen-polymer sulfur binder. This will create a strong spatial frame, which will significantly increase the tensile strength of dispersed-reinforced asphalt-polymer concrete, shear resistance, crack resistance and fatigue life of non-rigid pavements.

This method of reinforcement makes it possible to increase the resistance to dynamic loads, significantly reduce the formation of fatigue cracks, and increase the ultimate strength in bending and shear. At the same time, the technological properties of reinforced asphalt concrete mixtures, as well as the deformation and strength characteristics of asphalt concrete with a complex-modified structure, have not been sufficiently studied.

In an asphalt concrete mixture, about 80...90% of the total surface of mineral materials is the surface of grains with a particle size of less than 0.071 mm. The calculation of the number of particles of different fractions shows that the number of particles less than 0.071 mm is also within the same limits. Consequently, 80…90% of all contacts occur between particles smaller than 0.071 mm. With a fiber length of the dispersed reinforcement of 20 mm, a particle with a size of 0.071 mm due to the presence of dispersed reinforcement will be associated with 282 particles.

Considering that two or more rows of particles are located along the fiber, at least 564 particles will be connected by one segment of the fiber. And since each segment of the reinforcing fiber can be in contact with two or three other fiber segments, the total number of particles bound by these fibers can reach 1,700. Thus, the bond coefficient in the case of dispersed reinforcement will be within 1,500. At the same time, in asphalt concrete, obtained by traditional technology, it is equal to six. It is the increase in the number of bonds between particles, in our opinion, that makes it possible to significantly improve the deformation-strength characteristics of dispersed-reinforced asphalt concrete. The above theoretical considerations additionally explain the reasons for the increase in the strength characteristics of dispersion-reinforced asphalt concrete mixtures, which were established by many foreign and domestic researchers, including A. E. Merzlikin, A. V. Akulich, Ya. N. Kovalev.

Thus, when using dispersed reinforcement from mineral fibers, wedging of mineral particles of asphalt binder, asphalt mortar, and even crushed stone grains is possible when the diameter of the fibers of the dispersed reinforcement exceeds the thickness of the oriented bitumen layer on the surface of these mineral particles. This fact leads to the fact that the particles of the mineral material are in contact with each other not through the oriented layer of bitumen, but through the layer of bulk bitumen, which leads to a decrease in the strength characteristics of bitumen-mineral mixtures at positive temperatures. This can also play a positive role, since the presence of some excess of bulk bitumen reduces the intensity of aging of the asphalt concrete pavement. These features of the structure formation of dispersed-reinforced asphalt concrete mixtures must be taken into account when designing their composition.

A very important factor influencing the processes of asphalt concrete structure formation is the adhesion of the binder to the components of the asphalt concrete mixture. With the introduction of pieces of chemical fibers into the asphalt concrete mixture, the necessary adhesion of petroleum bitumen to the surface of dispersed reinforcement is not always ensured. To increase adhesion, the fibers of dispersed reinforcement are treated with surfactants, which complicates the technology for the production of asphalt concrete mixtures. An increase in the adhesion of oil bitumen to the surface of the reinforcement can be achieved by forming the fibers of the dispersed reinforcement directly in the composition of the asphalt concrete mixture. To do this, it is necessary to introduce a fiber-forming polymer in the form of a melt or solution into the asphalt concrete mixture during its production through filters. In this case, the formation of reinforcing fibers and the creation of a spatial reinforcing lattice occurs directly in the mixer. This technology of dispersed reinforcement makes it possible to increase the length of dispersed reinforcement without the appearance of lumps. Part of the fibers in the process of mixing the fiber-forming polymer with a mineral material treated with bitumen will break. However, the resulting segments of the reinforcing chemical fibers will have a greater length than in the case of introduction of finished cut chemical fibers into the mixer.

A large number of types of fibers are known: mineral, basalt, diabase, metal, cellulose, fiberglass, synthetic. All these types of fibers differ in their nature, size, application features and effect on the properties of the material. The main technical characteristics of various types of fibers currently used for the production of composite building materials are given in Table. 1.

Dispersed reinforcement of asphalt concrete mixtures with synthetic fibers makes it possible to create a spatial lattice of dispersed reinforcement in asphalt concrete, improve the distribution of stresses in asphalt concrete from a moving load due to a more perfect spatial lattice of dispersed reinforcement, and thereby increase the durability of the asphalt concrete pavement. At the same time, it should be noted that one of the main determining factors that make it possible to increase the physical and mechanical properties of asphalt concrete is the optimally selected composition of the asphalt concrete mixture.

According to the results of research, the main problem of using fibers from various fibers in asphalt concrete mixtures is the lack of technology (method) for introducing fibers into the composition of the mixture. In Ukraine, dispersed reinforcement of asphalt concrete mixtures has not been widely used. Since the main problem is the uniform distribution of fibers in the mixture, as well as the lack of proven technology for the production of micro-reinforced asphalt concrete. But there is some experience in using this technology in our country.

Fiber	***Density, g/cm^3***	***Elastic modulus, MPa***	***Tensile strength, MPa***	***Elongation at break, %***
Polypropylene	0,9	3500-8000	400-700	10-25
Polyamide	0,9	1900-2000	720-750	24-25
Polyethylene	0,95	1400-4200	600-720	10-12
Acrylic	1,1	2100-2150	210-420	25-45
Nylon	1,1	4200-4500	770-840	16-20
Viscose heavy duty	1,2	5600-5800	660-700	14-16
Polyester	1,4	8400-8600	730-780	11-13
Cotton	1,5	4900-5100	420-700	3-10
Карбоновое	1,63	280000-380000	1200-4000	2,0-2,2
Carbon	2,0	200000-250000	2000-3500	1,0-1,6
Glass	2,6	7000-8000	1800-3850	1,5-3,5
Asbestos	2,6	68000-70000	910-3100	0,6-0,7
Basalt	2,6-2,7	7000-11000	1600-3200	1,4-3,6
Steel	7,8	190000-210000	600-3150	3-4

Table 1: Characteristics of the types of fibers used.

Despite the difficulties associated with the lack of experience in the use of fibers in road surfaces, it is obvious that this direction needs to be fully developed and eventually come to the widespread use of micro-reinforced road surfaces. For road bridges, this technology may be the most in demand, since as a result of irregularities formed on the roadway, dynamic effects arise that adversely affect the performance of artificial structures.

At the National Aviation University, tests were carried out on dispersed-reinforced asphalt concrete with the addition of basalt fiber (BF) to determine the optimal length and consumption. Tests were carried out to compare asphalt concrete with the use of BF and asphalt concrete without micro-reinforcement.

Basalt fiber (BF) is obtained by melting basalt rocks - continuous basalt fibers (CBF) have high strength characteristics, chemical, corrosion and thermal resistance to temperature extremes and alternating loads, low cost. Due to this, CBF provide high building properties to materials made on their basis, namely: fibers, meshes and solid fabrics, non-woven geotextiles, reinforcing bars, the use of which in road construction makes it possible to increase the resistance of asphalt concrete pavements to the influence of traffic loads and natural and climatic factors, increase the time between repairs and resources of different structural layers, reduce the cost of construction and repair of roads.

To obtain BF with optimal properties, a complex mathematical model of the production process was developed and unified differential equations were obtained that take into account heat transfer, fluidity, fiber stretching both before the separation of elementary threads and after their separation (primary and secondary stretching).

The solution of the corresponding differential equations made it possible to obtain such calculation equations.

To determine the BF temperature in any local section (x) in a dimensionless form, the following dependence is proposed:

$$V(x) = \frac{t_f - t(x)}{t_f - t_0} =$$
$$= exp\left[-\sqrt{2\pi}\left(\frac{\lambda_{\varepsilon 0}}{C_0\rho_0} \cdot \frac{L}{Q} \right) \frac{\overline{\lambda_z}}{\overline{\rho}\overline{c}\nu_2} \cdot Re^{\frac{1}{2}} \left(\frac{L}{r_{00}} \right)^{\frac{1}{2}} \left(\overline{W} - \overline{U}(x)^{\frac{1}{2}} \int_0^{\overline{x}} \sqrt{\overline{r}}(x) d\overline{x} \right) \right] \quad (1)$$

Where Re is the average value of the BF tensile strength; $\overline{W}$ - thermodynamic work of adhesion; W is the work of cohesion;

$$\mathrm{Re} = \frac{U_0 r_{00}}{\nu_2} \quad (2)$$

$$\overline{W} = \frac{W}{U_0} \quad (3)$$

$$\overline{U}(x) = \frac{U(x)}{U_0} \qquad \overline{r}(x) = \frac{r(x)}{r_{0z}} \quad (4)$$

$$\overline{x} = \frac{x}{L} \quad \overline{\rho_z} = \frac{\rho_z}{\rho_{zo}} \quad \overline{\lambda_z} = \frac{\lambda_{zo}}{\lambda_z} \quad \overline{\nu_z} = \frac{\nu_{zo}}{\nu_z} \quad \overline{\rho} = \frac{\rho}{\rho_o} \quad \overline{c} = \frac{c}{c_o}$$

Index “g” - gas; “o” - BF; another index “o” - initial value; $\overline{U}(x)$- pulling speed; $\overline{r}(x)$- BF radius in the drawing area; L - length of the stretching section; $Q = \pi r_{oo}^2 U_o$ - material consumption for BF; Wг - gas flow rate; tf - gas flow temperature; t(x) - BF temperature; C - heat capacity; ρ - density; ν - viscosity; λ - thermal conductivity.

The continuity equation has the form:

$$r^2(x)\overline{U}(x) = 1 \quad (5)$$

The calculation of the pulling speed is carried out by intervals:

$$\overline{U}(\frac{i+1}{k}) = \overline{U}(\frac{i}{k}) + \frac{\overline{U'}\left(\frac{i}{k}\right)}{1!}\left(\frac{1}{k}\right) + \frac{\overline{U''}\left(\frac{i}{k}\right)}{2!}\left(\frac{1}{k}\right)^2 + \ldots\ldots \quad (6)$$

i=0, 1, 2, …….. (k-1)

For the initial section $\overline{U}(0) = 1$;

$$\overline{U'}(0) = \frac{2}{3}\frac{\sigma_0}{\eta_0 r_{00}} \cdot \frac{L}{U_0} \cdot \frac{\sigma_0}{\overline{\eta}\overline{r}}; \frac{\sigma}{\overline{\eta}\overline{r}} = 1 \quad (7)$$

σ - surface tension; η - viscosity; T- BF stiffness.

In what follows, it is taken into account when determining $\overline{U}(\frac{i+1}{k})$ meaning $\overline{U}(\frac{i}{k})$ based on the previous interval.

$$\overline{U'}(\frac{i+1}{k}) = \frac{2}{3} \cdot \frac{\sigma_0}{\eta_0 r_{00}} \cdot \frac{L}{U_0} \cdot \frac{\overline{\sigma}}{\overline{\eta}\left(\overline{T}\left(\frac{i}{k}\right)\right)\overline{r}\left(\frac{i}{k}\right)}; \quad (8)$$

$$\overline{U''}(\frac{i+1}{k}) = \frac{4}{9}F \cdot \frac{\overline{\sigma_z}}{\overline{\eta}_z\left(\overline{T}\left(\frac{i}{k}\right)\right)}\overline{U}\left(\frac{1}{k}\right) - \frac{1}{\overline{\eta}\left(\overline{T}\left(\frac{i}{k}\right)\right)} \cdot \frac{d\overline{\eta}}{d\overline{T}} \cdot \frac{d\overline{T}}{d\overline{x}} +$$

$$\overline{U''}\left(\frac{i+1}{k}\right) = \frac{4}{9}F \cdot \frac{\overline{\sigma_z}}{\overline{\eta}_z\left(\overline{T}\left(\frac{i}{k}\right)\right)}\overline{U}\left(\frac{1}{k}\right) - \frac{1}{\overline{\eta}\left(\overline{T}\left(\frac{i}{k}\right)\right)} \cdot \frac{d\overline{\eta}}{d\overline{T}} \cdot \frac{d\overline{T}}{d\overline{x}} +$$
$$+ \frac{R_{eo}}{3} \cdot \frac{\overline{\rho}\overline{U}\left(\frac{i}{k}\right)}{\overline{\eta}\left(\overline{T}\left(\frac{i}{k}\right)\right)} \cdot \frac{2}{3}F\frac{\overline{\sigma}}{\overline{\eta}\left(\overline{T}\left(\frac{i}{k}\right)\right)}\overline{U}^{\frac{1}{2}}\left(\frac{i}{k}\right) +$$
$$+ \frac{1{,}328}{3\sqrt{2}}\left(\frac{L}{r_{oo}}\right)^{\frac{3}{2}}\sqrt{R_{ez}}\left(\overline{W} - \overline{U}\left(\frac{i}{k}\right)\right)^{\frac{3}{2}}\overline{U}^{\frac{1}{2}}\left(\frac{i}{k}\right) \tag{9}$$

where; $F = \frac{\sigma_0}{\eta_0 r_{00}} \cdot \frac{L}{U_o}$; $R_{eo} = \frac{\rho_0 U_0 t}{\eta_0}$

F - force of interaction that causes the onset of deformation.

The calculation algorithm is as follows:

1 cycle: $$\overline{r} = 1; t\left(\overline{x}\right) = t\left(\frac{1}{k}\right); \overline{\eta} = \overline{\eta}\left(\frac{1}{k}\right); \overline{U} = \overline{U}\left(\frac{1}{k}\right) \tag{10}$$

2 cycle: $$\overline{r} = \sqrt{\frac{1}{\overline{U}\left(\frac{1}{k}\right)}}; t\left(r\left(\frac{1}{k}\right)\right); \eta\left(t\left(\frac{1}{k}\right)\right); \overline{U} = \overline{U}\left(\frac{2}{k}\right) \tag{11}$$

3 cycle: $$\overline{r} = \sqrt{\frac{1}{\overline{U}\left(\frac{2}{k}\right)}}; t\left(r\left(\frac{2}{k}\right)\right); \eta\left(t\left(\frac{2}{k}\right)\right); \overline{U} = \overline{U}\left(\frac{3}{k}\right) \tag{12}$$

As a result, BF was obtained with optimal dimensions - chopped into segments with a diameter of 13-18 microns and a length of 15 - 30 mm, which were accepted for further studies of dispersed reinforcement of asphalt concrete. The fiber is suitable for dispersed (volumetric) reinforcement of asphalt concrete of various types. BF, with thorough mixing, is evenly distributed in the mixture throughout the volume in different directions in such a way that each cm3 of asphalt concrete contains from 20 to 30 pieces of BF, which significantly increases its strength in bending, compression, impact and crack resistance, especially to the formation of reflected cracks.

The general view of the basalt fiber (BF) is shown in fig. 1, reinforced sample in fig. 2.

Figure 1: Basalt fiber with a diameter fibers 13-18 microns, length 15-30 mm.

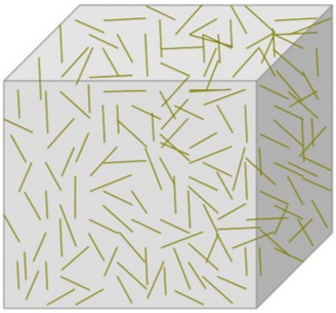
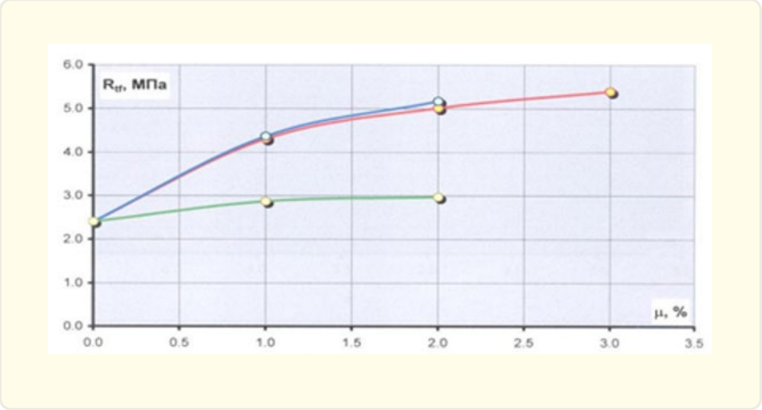


Figure 2: Dispersed (volumetric) reinforcement of asphalt concrete.

Results have been obtained that show an increase in the ability of asphalt concrete with BF to resist rutting and cracking.

The determination of the dependence of the tensile strength in bending of hot fine-grained asphalt concrete type “A” on the length of the fiber is shown in Figure 3.



Rice. 3 Dependence of tensile strength in bending of asphalt concrete type “A” reinforced with basalt fiber (BF).

1 (red) - BF 24 mm long;
2 (blue) - 12 mm;
3 (green) - 30 mm;

The research results are shown in table 2.

Asphalt concrete	***Average density, g/cm³***	***Water saturation, %***	***Compressive strength, MPa, at a temperature***			***Breaking strength at 0°C, MPa***
			0 °C R_0	***20 °C R_{20}***	***50 °C R_{50}***	
Control mix	2,37	3,7	2,6	1,4	5,9	4,0
Experienced mixture	2,38	3,0	4,3	2,0	6,3	4,2
Requirements DSTU B V.2.7-119		1,5-4,0	No more 13	No less 2,5	No less 1,3	4,0-6,5

Table 2: Indicators of the physical and mechanical properties of a hot mix of dense fine-grained asphalt concrete (type B, grade I) with the use of a BF.

It can be seen from the results of the research that the BF 24 mm long is most suitable for reinforcing asphalt concrete. The content of BF 24 mm long should be within 2-3% of the weight of mineral materials (crushed stone, sand, mineral powder). With such reinforcement, the tensile strength in bending increases by 1.8-2.5 times, the compressive strength by 37-40% and a possible increase in crack resistance by 2.0-2.5 times, which will prevent the formation of rutting on the coating and increase service life of roads.

BF can be used in the preparation of hot and cold types of asphalt concrete. The technology of adding BF can be both to the mineral powder (separate) and directly to the mineral part of the mixture (joint) does not affect the physical and mechanical properties of asphalt concrete.

Preparation of hot asphalt concrete occurs at t 140-150 °C, cold at t - 95-100 °C. The mixing time of hot and cold mixtures with separate technology is 14-15 minutes, with joint technology 10-12 minutes.

The introduction of BF improves the physical and mechanical properties of cold asphalt mixes, prevents their caking, such mixes have increased compressive strength (70-80% more than the reference cold asphalt mixes). The value of the coefficient of water resistance is within the normal range due to the fact that when mixing fibers with bitumen, boundary layers are formed that prevent the bituminous binder from peeling off the surface of the fibers and the penetration of water during operation.

This makes it possible to use cold asphalt-concrete mixtures dispersed-reinforced with basalt fiber for emergency road repair, which is carried out in difficult weather conditions - low temperature and high humidity, to ensure uninterrupted and safe traffic throughout the year.

The economic efficiency of using asphalt concretes of various types dispersed-reinforced with basalt fiber arises due to an increase in the service life of pavements, a possible decrease in the thickness of the top layer, as well as a reduction in the cost of repair and maintenance of roads.

Dispersed reinforcement of asphalt concrete mixtures leads to the following advantages of structure formation. Due to the dispersed reinforcement, the characteristics of asphalt concrete increase, including shear resistance at positive temperatures, the intensity of crack formation at negative temperatures decreases, which leads to an increase in the service life of asphalt concrete pavements.

Conclusion

Dispersed reinforcement of asphalt concrete mixtures, in addition to the advantages indicated above, which are characteristic of the process of reinforcement with discrete segments, leads to the following advantages of structure formation. As a result of an increase in the length of a piece of dispersed reinforcement, an increase in the number of particles bound by one of its pieces is ensured.

The adhesive bond between the dispersed reinforcement formed in the composition of the asphalt concrete mixture and the bitumen film is improved. The nodes of the spatial reinforcing lattice are not from separate discrete segments of chemical fibers, but represent a chemical fiber that diverges in different directions from one point. The strength of the spatial lattice in this case does not depend on the strength of the adhesive bond between the adsorption layer of bitumen and the fiber, but on the strength of the chemical fiber itself. Due to the fact that the strength characteristics of chemical fibers are very high, the strength characteristics of the resulting composite also increase. Using this technology, any polymeric waste from thermoplastics and even polymers soluble in organic solvents can be processed into dispersed reinforcement, followed by their condensation after fiber formation.

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