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CURRENT PROBLEMS AND PROSPECTS OF APPLICATION OF PRODUCTS BASED ON CONTINUOUS BASALT FIBER

The progress of science and technology significantly depends on the success in creating new materials. Composite materials are a heterogeneous structure formed by a combination of reinforcing elements and isotropic binder (binder) material, currently widely used in various fields of technology. but for the economy is more important mass application. For this purpose, more thorough and long-term research and experimental implementations are carried out, which require significant intellectual and material costs. Development of structural elements using basalt fiber began in NDIBV since 1987. and experimental samples of prestressed concrete structures with basalt-plastic reinforcement. Research to identify the interaction of cement with basalt fiber and the design of effective concrete structures using basalt reinforcement. Concrete beams with basalt reinforcement were successfully tested. Unfortunately, the results of research have not been widely implemented. Therefore, this article is devoted to the problems of mass introduction into construction practice of various types of composite materials, including basalt reinforcement. The advantages and disadvantages of composite reinforcement in comparison with steel are discussed. During the theoretical and experimental studies, both positive and negative aspects of the use of basalt reinforcement were identified. So experiments have shown that basalt fiber loses strength in the environment of Portland cement stone. But this shortcoming has been overcome by the efforts of scientists, it is important to use certain defects of basalt fibers for specific conditions. There are the following main types of basalt fibers:

1) basalt continuous fibers with a diameter of 8 - 11 microns, 12 - 14 microns, 16 - 20 microns with a fiber length of 25 - 50 mm and more;

2) staple short fibers with a diameter of 6 - 12 microns and a length of 5 - 10 mm and several diameters;

3) basalt superthin fibers with a diameter of 0.5 - 1 microns with a length of 10 - 50 mm;

4) coarse basalt fibers with a diameter of 100 - 400 microns.

To create structures with certain properties for specific conditions, appropriate basalt fibers are selected. According to the research results, recommendations and normative documents have been developed. Suggestions for measures to improve and successfully widely use composite elements for reinforcement of concrete structures.

Keywords: basalt, composite materials, basalt fiber, Continuous basalt fiber, basalt plastic reinforcement (BPR), Experimental products based on continuous basalt fiber, prestressed reinforced structures*.*

1 Introduction. The basis of composite reinforcement is a material which is formed from different fibers: glass, basalt, aramid, carbon, zirconium, aluminosilicate, aluminmagnezial etc. and usually with binding based on thermosetting synthetic resin which cures under the influence of the temperature or irreversible chemical reaction converted into a solid, infusible and insoluble material with the three-dimensional network structure.

The first continuous basalt thread was obtained in Kiev in the research laboratory of basalt fiber (NILBVI) by Dimitri Dzhigiris and Maria Makhova [1] in the mid-70s of the last century. To obtain a continuous filament, basalts were used, brought from Georgia from the Marneuli deposit, see Table 1. They also investigated the suitability of obtaining a continuous filament from a basalt deposit located on the territory of Georgia, see Table 1.

Continuous basalt fiber is a unique product obtained from basalt rock using a special melt technology. Basalt fiber surpasses other types of mineral fibers in many respects: thermal resistance, sound and heat insulation properties, vibration resistance, wear resistance, resistance to aggressive chemical environments, etc.

Due to high cost of composite reinforcing elements as a whole, for the mass application of composite reinforcement in construction, the most suitable are glass and basalt fiber [1-8]. One of the most important features of composite materials is a significant anisotropy of mechanical properties. Therefore, the use of composite materials makes it necessary to determine the rational schemes of reinforcement and distribution of the material in the structure taking into account its loading conditions. In comparison with steel reinforcement, basalt plastic reinforcement (BPR) is more lightweight (3.3-3.5 times), greater strength (2.5-3.0 times stronger), has significantly higher corrosion resistance (12-15 times), the heat shield and dielectric properties, it is non-magnetic and radio transparent [2, 3, 8, 11].

High specific strength of the material is implemented with short-time loading in the direction of reinforcement. Under loads that cause high levels of stress in the bonding adhesive, material loses its benefits to a large extent. Thus, the composite materials have a number of specific features that require the development of special methods of design and calculation.

2 Main part. The growth of production of continuous glass fibers is being constrained by the growing deficiency of raw materials (soda ash, boric acid, sulfate, etc.), as well as high technical requirements and others. It is well known for the fact that the limiting factor in the widespread use of fiberglass structures is a relatively high cost, low limit of fire resistance, low modulus of elasticity and others.

In this regard, in recent decades production of other fibers, instead of glass, has intensively been expanded. There are currently several technological processes of continuous fibers (roving) of the widespread eruptive rocks - basalt, which do not require any additives [1, 8, 11].

In Georgia there are no deposits of iron ore, therefore, steel and all metal products are mainly imported from abroad, which significantly increases the financial costs of construction and installation works. On the other hand, there are huge reserves of basalt, from which you can get high-quality fiber, that naturally causes a great interest to the basalt technologies.

Continuous basalt fiber production technology with the single-stage method has good prospects for the use and distribution, but not all of basaltic rocks may be suitable for production of continuous basalt fiber.

There are several careers on the territory of Georgia (Marneuli, Akhaltsikhe, Chiatura, Bolnisi and others), from which the raw materials high-quality fibers are obtained. The volume of found raw materials only in these careers is estimated at many millions of cubic meters. The basalt fiber obtained from these quarries has a high initial strength and durability.

The chemical composition of the investigated basalt quarries in Georgia, which are suitable for the production of continuous super thin fiber, is given in Table 1.

Table 1

The chemical content of the investigated basalt quarries in Georgia

Studied deposits of basalt rocks in Georgia	Oxides, %										
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3+Fe	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	SO_3
Marneuli	**51.11**	**0.92**	**15.5**	**10.45**	**10.22**	**6.36**	**4.64**	**4.64**	**0.3**	**0.5**	**-**
Akhaltsikhe	44.99	1.88	14.82	9.86	11.98	9.81	3.03	1.67	0.1	-	-
Aspindza	46.28	1.57	12.06	12.08	9.22	11.67	2.09	0.58	1.06	0.32	0.1
Bakuriani	59.06	1.16	17.54	7.26	4.86	2.94	3.7	1.62	0.71	0.93	0.12
Okami	53.41	0.63	20.38	8.29	7.85	2.56	3.75	1.07	0.73	0.32	0.1
Chiatura	46.39	-	14.84	12.08	10.08	8.82	4.18	4.18	-	-	0.25

BPR “Stress-strain” diagram obtained with this method of production is substantially rectilinear to failure (see Fig. 1). However, the data are experimental and subject to further refinement, taking into consideration the content of the fiber. The essential fact is that the diameter affects the temporary resistance value of the BPR, thinner reinforcement, the greater its strength.

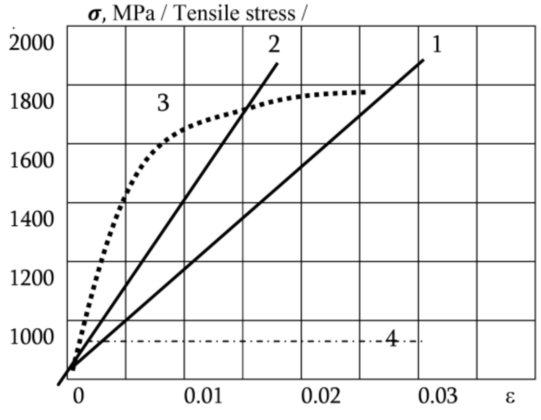

Fig. 1. The dependence of the relative elongation ε of the stressed $\boldsymbol{\sigma}$ for:
1. BPR;2. Cold-drawn steel; 3. High-strength cable; 4. Steel with high yield stress

The experimental studies of basalt and of other fibers in the concrete confirmed the decrease of fibers’ strength in time. The results of experimental studies in high humidity conditions and the alkaline environment of concrete show a significant strength reduction of basalt, glass and other types of fibers (Fig. 2) [8].

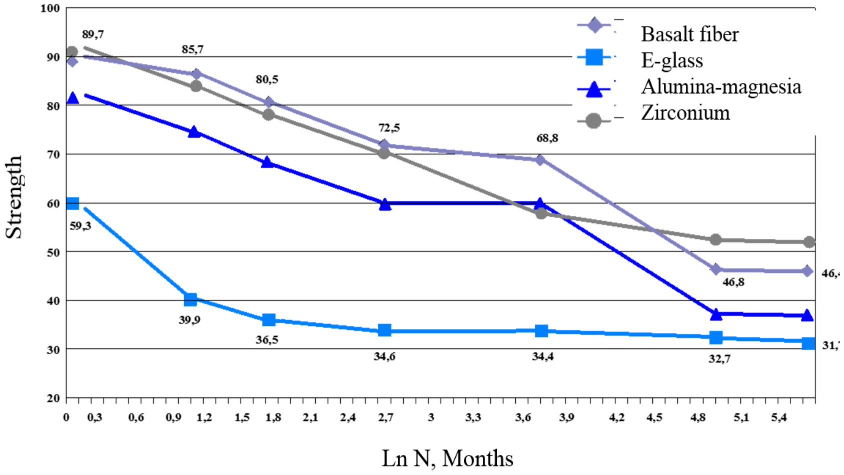

Fig. 2. Comparative time dependence of the strength loss of basalt and other fibers types in a hardening portland cement

Experiments show other features of behavior of composite reinforcement in the concrete. For example, the strength and modulus of elasticity of composite reinforcing elements are decreased with increase of the rod diameter [2, 4, 6]. The tensile strength of polymer composite reinforcement decreases significantly during the process of being in concrete, while the modulus of elasticity changes significantly [3].

Concrete and composite reinforcement (of glass, basalt, carbon, zirconia and other fibers) are rheologically active materials, therefore the bearing bearing capacity, the nature of the distribution of forces, deformability and crack resistance of concrete structures, reinforced with composite, significantly depend on the model of combined work during the long-term load action.

The tensile strength of basalt plastic reinforcement (BPR) at T = 20°C is 12000-18000 MPa and depends on the composition and percentage of binder in the product (which is typically 25-30%). Some other typical parameters:

- product density 1.95-2.2 g/cm^3;
- product elasticity modulus at 20°C ranges between 75000-90000 MPa;
- index of thermal conductivity of the product depends on many factors and can vary within 0,04-0,1Wt/m*K;
- linear expansion coefficient (0.5-0.7)x10^{-5}, at t =200°C;
- product melting point is determined on parameters of the binder and varies widely from 1800°C to 6000°C; initial softening temperature of the fibers is 6200°C, the softening temperature - 6350°C;
- basalt fiber melting temperature range from Marneuli quarries is 1150-11800° C; at a temperature of 12000°C fiber begins to char;
- special surface finishing is not required, the color of the product can vary from perfectly-black to light brown depending on the type of used binder.

Basic physical, mechanical and technical characteristics of BPR and AIII reinforcement are shown in Table 2:

Table 2

Characteristics of BPR and AIII reinforcement

Name	Value of the indicator		Note
	BPR	AIII reinforcement	
Temporary tension resistance, kg/cm^2	$1.2x10^4$-$1,8x10^4$	3650-3800	
Modulus of elasticity, kg/cm^2. Tension- Compression-	 $(0.7-0.9)x10^6$ $(0.4-0.5)x10^6$	 $2x10^6$ $2x10^6$	
Poisson's ratio	0.22-0.26	0.3	
Corrosion resistance increasing (times): In an acidic environment- In salt solutions- In hydrogen sulfide environment-	12-15 9-12 15-20	1 1 1	
Coefficient of linear expansion, grad^{-1}	$(58-85)x10^{-7}$	$(111-150)x10^{-7}$	
Volume weight, kg/cm^3	1.9-2.1	7.8	Lighter than steel by 3.7-4.1 times

The composite rebar in comparison with steel one has a number of disadvantages:

- low modulus of elasticity;
- low fire resistance and durability at high temperatures;
- inability to manufacture the bent reinforcing rods of composite reinforcement at the construction site;
- inefficiency and sometimes impossibility to use it in compressed zone of concrete;
- most of fibers, which form the basis of the composite reinforcement, lose strength in hardening Portland cement;
- during the long-term loading the nonlinear deformation of glass and basalt composite reinforcement is observed even at load level 0.25-0.4 of breaking point. This makes it necessary to take it into account in calculations;
- the higher cost comparable with the cables of high-strength steel (ropes);
- compressive strength of composite reinforcement is much lower than the tensile strength;
- the virtual absence of plastic deformations in the composite reinforcement, low elongation at break - about 2%, which means an increased risk of brittle failure.

Due to the low elasticity modulus of composite reinforcement, the concrete structural elements may be destroyed in bending conditions. This character of destruction of the same section of the bent concrete structure with steel reinforcement is not possible. For this reason, high strength characteristics of composite reinforcement in most cases, remain unused.

The most effective area of application of composite reinforcement (BPR, in particular) in accordance with their features (high strength and low deformation modulus) is in prestressed concrete structures [3-6,9,10]. However, clamps used for prestressed steel may not be applied since a composite (and basalt plastic) rebar strength in that case is determined by the strength characteristics of the polymer binder which is significantly less than tensile strength of fiber [8, 9, 10, 11]. This circumstance makes it necessary to develop a special type of clamp for realization of prestressing. The value of controlled stress in composite reinforcement should be taken not more than 50% of ultimate stress.

In view of the foregoing, before the use of composite rebar in ordinary and prestressed structures it is necessary to carry out a number of investigations to assess the efficiency of local composite materials, including:

- the influence of solar radiation and sea humid climate on the behaviour of concrete structures reinforced with composite reinforcement;
- the influence of the rheological properties of the binder polymer on the contact surface between the composite reinforcement and concrete;
- the influence of stress regime, especially under sign variable loads, which is very important in seismic zones and under dynamic effects;
- the influence of creep and shrinkage of concrete and interaction features on the contact surface, taking into account long-term strength of the composite reinforcement and different types of concrete.

One of the most important features of composite materials is a significant anisotropy of their mechanical properties. Therefore, the use of composite materials makes it necessary to determine the rational schemes of reinforcement and the material distribution in the cross section taking into account the relevant loading conditions.

Bond strength of composite reinforcing thin rod with the concrete depends on the structural features of the production process, the mechanical characteristics of the rod and the environment, however, when designing should take into account that the interlaminar shear strength of the polymer is provided with a relatively weak component. The strength of the connection between a composite reinforcing thin rod and concrete depends on the structural features, of the production process, mechanical characteristics of core and environment. And during design it should be considered that the interlayer shear strength of the polymer is ensured by a relatively weak binder component.

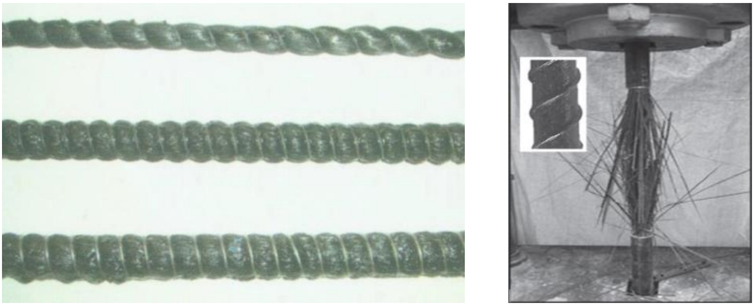

Fig. 3. 4mm, 6mm and 8mm diameter rebars made of basalt fiber; tension test results of rebars made of basalt fiber

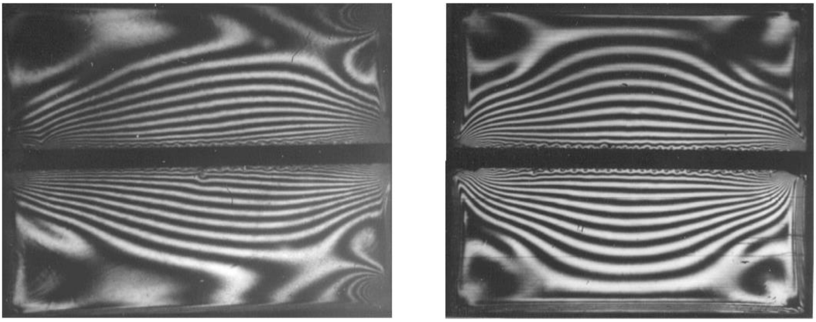

Fig. 4. Distribution of stresses in concrete in contact zone with BPR: in normal concrete (left); in expanding concrete (right). Figure 4, shows the experiment results- distribution of stresses in concrete in the contact zone with BPR (*author's development*)

The tension elasticity modulus of the composite reinforcement $\mathbf{E_{r.sp}}$ (including basalt plastic) can be calculated by the formula:

$$\mathbf{E_{r.sp} = E_aF_{st} + E_sF_s}\,, \tag{1}$$

where E_a and E_s – the tension elasticity modulus of the fiber and a binder, accordingly; F_{st} and F_s – volume content of glass (basalt) and binder in the composite.

The elastic stresses in composite reinforcement:

$$\boldsymbol{\sigma}_{\mathbf{r.sp}} = \mathbf{V_1E_1\varepsilon_1 + V_2E_2\varepsilon_2}, \tag{2}$$

where V_1 and V_2 – volume content of glass and binder in the composite, accordingly; E_1 and E_2 – the elasticity modulus of fiber and binder; ε_1 и ε_2 –deformation of fiber and binder.

The Poisson ratio **m** of the composite reinforcement in longitudinal and transverse directions are different. For BPR **m** varies in longitudinal direction within 0.25-0.35 depending on type of binder.

Prestressed concrete structures reinforced with BPR, should be calculate for both groups of limit states: strength, cracking and deflections. Calculations of members with BPR are based on the following provisions: sections remain plane; stress diagram in the compressed zone has a parabolic shape at extreme edge of the compression stresses that are equal to calculated resistance at compression $\mathbf{R_c}$. If the edge compression stress is $\mathbf{0.7R_c}$ or less, the diagram is simplified to the linear one.

The chosen diagram form of compression stresses and the magnitude of the boundary stresses depends on technological and structural factors. Reinforcement of the compressed concrete zone using any type of composite reinforcement is not economically justified. From our opinion, an obstacle in the practical use of all the positive features of BPR is the insufficient study and reflection in the existing regulations [12-27] and, most important, the absence of studies and an appropriate normative basis for the effective application of basalt plastic reinforcement in conditions of Georgia, the local deposits of basalt, its properties for the local realization in construction, especially under seismic loads, as well in offshore structures, under solar radiation, low temperatures and in other conditions.

With the aim of large-scale application of continuous basalt fiber in construction, we have made various products: I-beams, channels, angles, brake pads, pipes of different diameters and purposes, etc. see Fig. 5. Elements for the construction of roofs of any buildings and structures, and practically, for any climatic region, have also been manufactured.

Fig. 5. Experimental products based on continuous basalt fiber, manufactured in Tbilisi

3 Conclusion. It’s completely impossible to replace the steel reinforcement by the composite one in the modern concrete products. But it’s expedient and effective the use of composite reinforcement in certain conditions instead of steel. Primarily we are talking about chemical resistance, radio transparency and dielectric properties of the composite reinforcement.

Thus, it’s appropriate to apply the composite reinforcement to the following construction sites: in structures exposed to aggressive environments, causing corrosion of steel reinforcement; in road-transport infrastructure; in concrete prefabricated and monolithic structures on elastic foundation (foundations, roads, airfield slabs etc.); in water treatment plants; for reinforcing the masonry; in structures operating under conditions of high electromagnetic fields and the potential difference; in tunnels, soil and bank revetment structures; in prestressed structures; during reconstruction, restoration of buildings and structures.

In our opinion, in order to expand the area of the composite reinforcement application in the construction activity, it is necessary to perform the following:

- develop standards and norms with calculation requirements of composite reinforcement taking into account its mechanical properties and methods of control, based on local materials and conditions including extreme conditions;
- prepare specifications on different types of periodic profile of composite reinforcement taking into account types and classes of concrete;
- work out standard solutions to ensure the required level of fire resistance of concrete structures reinforced with composite reinforcement;
- compile an inventory of composite construction materials and technologies necessary for preparation of normative documents;
- standardize the typical solutions of the bent rebar elements and work out the rules for their manufacture, quality control etc.

What will be the new technical solutions in the direction of wider application of composite reinforcement for concrete reinforcement, unfortunately, still has no clear answer. However, practice requires that they should be studied in greater detail, which offers vast scope for theoretical work and creative research. Success largely will depend on the creation and discovery of new types of fibers, binders and their joint application for conventional or special types of concrete, and especially for concretes made with the use of expanding cements.

Conclusions:

1. To design prestressed reinforced structures of basalt-plastic reinforcement, proposed technology requires no special gripping devices that are inconvenient for service and also tend to damage the reinforcement at bar tightening zone. According to the proposed technology, transfer of tensile forces is due to the shear stresses that arise when expanding of stressing cement occurs and develops along the contact line reinforcement-concrete;
2. The results of the proposed methods and the methods of SNIP 11-21-85 and computer modeling to determine the stress-strain state of structures differ by an average of 15%;
3. The use of self-stressing cement or low-energy expansion and a minimum diameter of BPR (6.5mm) to design a pre-stressed structure should be considered ineffective, because destruction of the beams occurred before reaching the limit values of BPR;
4. A substantially rectilinear relationship σ-ε (stress-strain) of the BPR to tensile fracture retains prestressed position when cracking occurs and to the destruction of concrete beams, additionally, reduces the deformation parameters of construction elements;
5. High technical and deformation performance of concrete elements reinforced with basalt reinforcement determine the feasibility of using such structures for earthquake-resistant and special buildings and structures;
6. The numerous studies that are conducted prove that the sticking coefficient of concrete to BPR is less than the sticking coefficient of concrete to the steel reinforcement. Therefore, improving factor of the bonding of BPR with concrete should be given greater role and attention;
7. Basalt reinforcement and other products do not corrode, which leads to an increase in the service life of concrete;
8. The specific gravity of basalt plastic reinforcement and basalt composites is 4 times less than that of steel, which leads to a decrease in the weight of the frame, the cost of handling and transportation costs.
9. The studies carried out show the promise of large-scale application of continuous basalt fiber for various areas of both the technical industry and for construction.

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Сучасні проблеми та перспективи застосування продукції на основі безперевного базальтового волокна

Від успіхів у створенні нових матеріалів істотно залежить прогрес науки і техніки. Композиційні матеріали являють собою неоднорідну структуру, утворену поєднанням армуючих елементів і ізотропного в'яжучого (сполучного) матеріалу, в даний час широко використовуються в різних областях техніки.Відомі різного роду нові композитні матеріали з досить цікавими корисними властивостями і навіть мають певні впровадження на практиці, але для економіки має більш вагоме значення масове застосування.Для цього проводяться більш ретельні і довготривалі дослідження і експериментальні впровадження, які потребують значних інтелектуальних і матеріальних витрат.Розробка конструктивних елементів із застосуванням базальтового волокна почалась в НДІБВ починаючи з 1987 р. Почав створюватись *композиційний матеріал базальтофібробетон та експериментальні зразки попередньо напружених бетонних конструкцій з базальто-пластиковою арматурою. Дослідження з метою виявлення взаємодії цементу з базальтовим волокном і конструювання ефективних бетонних конструкцій із застосуванням базальтової арматури. Успішно пройшли випробування бетонні балки з базальтовою арматурою. Нажаль результати досліджень широкого впровадження не набули. Тому дана стаття присвячена проблемам масового впровадження в будівельну практику різних видів композиційних матеріалів, у тому числі базальтової арматури. Обговорюються переваги та недоліки композитної арматури в порівнянні зі сталевою. За час проведення теоретичних і експериментальних досліджень було виявлено як позитивні, так і негативні сторони застосування базальтової арматури. Так експерименти показали, що базальтове волокно втрачає міцність в середовищі портландцементного каменя. Але цей недолік був подоланий зусиллями вчених, має велике значення використання певних вадів базальтових волокон для конкретних умов..Існують наступні основні види базальтових волокон:*

1) базальтові неперервні волокна діаметром 8 – 11 мк, 12 – 14 мк, 16 – 20 мк довжиною волокна 25 – 50 мм і більше;

2) штапельні короткі волокна діаметром волокон 6 – 12 мк і довжиною 5 – 10мм та кілька діаметрів;

3) базальтові супертонкі волокна діаметром 0,5 – 1 мк довжиною 10 – 50 мм;

4) грубі базальтові волокна діаметром 100 – 400 мк.

Для створення конструкцій з певними властивостями для конкретних умов вибираються відповідні базальтові волокна. За результатами досліджень напрацьовані рекомендації і нормативні документи. Висловлено пропозиції щодо заходів щодо вдосконалення та успішного широкого застосування композитних елементів для армування бетонних конструкцій.

Ключові слова: базальт, композиційні матеріали, базальтове волокно, суцільне базальтове волокно, базальтопластичне армування (БПР), експериментальна продукція на основі суцільного базальтового волокна, попередньо напружені армовані конструкції.

Посилання на статтю

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