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REINFORCEMENT OF COMPOSITE PIPELINES FOR MULTIPURPOSE TRANSPORTATION

Summary. The problem of monolithic behavior of a metal pipe and fiberglass safety cage has been considered in the article. The prestressed case does not only decrease the deformability of a pipe on-load but it also protects metal from corrosion. The ability to withstand the arising stresses has been investigated for both strip fiberglass reinforcement and the whole construction. It has been shown that the deformability of fiberglass depends on the kind of binder. The maximum strength value has been obtained while gluing glass fibers with butvar-phenolic glue. The calculated rupture strength coefficient of strip fiberglass reinforcement and the analysis of monolithic behaviour of metal and reinforcement proved the precondition as to the plasticity of a developed material. The process of force transmission between a steel pipe and fiberglass at ductile stage has been analyzed in the article. While forecasting the work of a pipe on-load, it is necessary to take into account nonlinearity of metal-fiberglass pipe properties.

1. INTRODUCTION

Pipeline transportation of oil, oil products, natural gas, water and other liquid and gaseous mediums is widespread. Besides, nowadays a more perspective direction of using of pipeline is being considered, namely – transportation of such materials as gravel, coal and many others by means of pipelines. Therefore, the construction materials, from which pipelines are erected, must be of increased strength and should have waterproofness, frost resistance, fire resistance, and resistance to chemical and electrochemical attack. The internal pressure, taken by the cylinder without plastic deformations, cannot exceed over $\frac{\sigma_y}{\sqrt{3}}$ no matter how much the thickness of cylinder walls is increased, where σ_y is the yield strength of the material. Low participation of external layers of a cylinder in taking loads is the reason of it. That is why, the increase in the external diameter of a cylinder does not lead to the correspondent increase in its strength. Manufacturing a fastened cylinder, which means that it consists of two or more concentric pipes, put one upon the other with draw, one can reach the decreasing of total stress in the internal part of a cylinder. It is not difficult to prove that with the given thickness of a cylinder wall, its resistance with the number of additional layers put on increases. The idea to form compound cylinder constructions was used in engineering while manufacturing high-strength products.

A similar effect can be reached by means of multilayer winding of prestressed steel wire, strip, on a cylinder. Even the first experiments on winding concrete pipes with prestressed steel wire, conducted in the last century, showed that manufactured in such a way, reinforced concrete pressure pipes are destroyed at higher load in comparison with unreinforced pipes. The investigations of a number of scientists showed that, brittle in usual conditions, construction materials obtain additional strength and plastic properties in the conditions of compressive three-dimensional stress at the expense of a steel coil or a pipe. Using this effect, named “a cage effect” later on, a number of ways to reinforce concrete was developed: concrete in the cage of a steel wire coil, concrete in a pipe, concrete with tubular steel reinforcement etc. High-strength indices of such constructions made it possible to decrease proper weight of constructions and save construction materials (steel, cement etc.). The development in the past decades of new high-performance composite fibrous materials, such as fiberglass, basalt fiber reinforced polymers, and carbon-filled plastics, proved to be quite perspective in the manufacturing of multilayer high-strength items and constructions [1, 2]. In combination with the winding method the using of such materials allowed creating a number of unique constructions consisting of a steel (or different) cylinder and a multilayer cage of unidirectional composite. Besides fibrous materials, polyethylene or ceramics are used as a cage [3, 4]. Pipes of polymer-reinforced concrete are becoming an attractive system for structural elements, designed for tough operating conditions [5-10]. In this case, the casing serves as a corrosion-proof element, reinforcement, holdback for concrete core, and formwork.

The analysis of the cases of pipelines premature failure indicates that one of the main reasons of their destruction is the impact of corrosion [11], including electrocorrosion [12]. One of the ways to increase the service life of pipeline systems is via both external and internal reinforcement of a pipeline with polymer composite materials, most importantly fiberglass. The construction of pipes with applied prestressed strength fiberglass with both external and internal layers is able to increase pipeline system’s rate of flow, and it protects them from external negative factors. The given type of reinforcement allows forming continuous coatings, casings etc. easily, by the method of winding. In this case, the coatings can have constant thickness or change along the length of a pipe being wound. The strip shape of reinforcement allows accomplishing multilayer application of fiberglass layer of a homogeneous structure to the fullest extent. The application of strip fiberglass reinforcement is also reasonable, because in this case, its specific properties, such as high tensile strength, corrosion resistance, are fully used. Fiberglass reinforcement is three times as light as steel, and its specific strength is 3.5-4 times higher. The urge to replace steel with a different material is caused by the fact that in a number of cases it is required to create a construction with high corrosion resistance and with antimagnetic and dielectric properties.

2. THE ANALYSIS OF PREVIOUS RESEARCH

Let us analyze the known solution on the reinforcement of tubular structures. According to the investigations [13-15], fiberglass reinforcement, which is recommended to use as a reinforcement element of reinforced concrete pipelines, has a number of advantages over the other types of reinforcement. Corrosion resistance is one of the main advantages of composite reinforcement. Other advantages include higher failure resistance, light weight (fiberglass is up to 9 times lighter than steel), chemical resistance, good elastic properties, frost resistance (up to -70°C), heat resistance (up to +100°C), low heat, and electrical conductivity. These peculiarities allow using this type of reinforcement in corrosive medium. The influence of the number of twisted fibers on mechanical properties of reinforcement with fiberglass concrete has been investigated in the work [13]. With the increase of volume content of fiberglass, modulus of elasticity is increased by 30%. The properties of reinforcement itself were investigated in the work by Muralidhar [14]. Linen cloth was used as the basis, and the composites were manufactured using the method of hand application. The obtained mechanical data showed that tensile and stiffness strength are the result of the synergy of fibers and a mold, whereas compressive and stiffness strength are provided by a reinforcing mold. The improved properties under tension and with lower volumetric fraction of fiber prove the opinion that hybrid composite blanks can have substantial advantages from the point of view of productivity, weight, and total cost. In the work by Abbasi and Hogg [15], concrete structures using plastic reinforced by fiberglass instead of re-bars improve strength in comparison with ordinary steel reinforcement because of corrosion resistance of re-bars. The given article considers the influence of aqueous and alkaline mediums on the adhesive strength between concrete and reinforcement as well as on the strength and rigidity of a plastic reinforcement bar in the range of various temperatures (20-120°C). The results obtained in this work can be used in the future together with thermal properties of the material to facilitate modeling long-term properties of composite reinforced concrete structures at elevated temperatures.

The reinforcement of pipes can be both internal (fiberglass re-bar [16]) and external (the layer of fiberglass on the surface of the structure). In the latter case, it is important to provide good adhesion between fibers, binder, and pipe surface. The strength of reinforced concrete elements has been improved in the work by Al-Bayati, Al-Mahaidi, and Kalfat [18] by using polymers reinforced with carbonic fiber with two methods of application, i.e. by adhesion by external reinforcement and near-surface assembly. Up to the present time, epoxy resin has been used as a binder to improve the flexure and shear strength of beams. As toxic vapors and low productivity in the conditions of high temperature are serious problems connected with the use of epoxy resin, a new glue on the basis of cement was used in the investigation [18] as an alternative to epoxy resin. The results show that the cement-based glue is less effective to improve twisting resistance than epoxy resin. Due to the absence of experimental data, polymeric bars are not recommended for the resistance to positive stresses in the shape of longitudinal reinforcement in columns or compressive reinforcement in flexural members. The results of the experimental program tests to investigate structural characteristics of 10 full-scale tubular concrete columns reinforced with carbonaceous polymer subjected to combined axial compressive loads and bending moments as well as under monotonous loading with various eccentricities have been presented in the articles [19,20]. The test results showed that carbon-filled plastic and reinforced concrete columns have similar behavior under peak loads. The failure of test specimens under various levels of eccentricity was not caused by the fracture of carbon-filled plastic bars on the tensile side but was more likely explained by gradual crushing of concrete with the consequent crushing of a bar on the compression side.

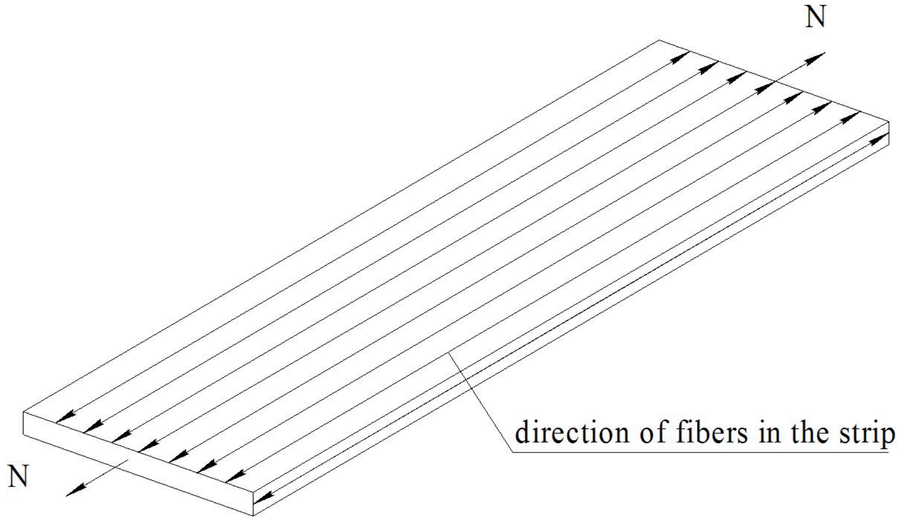
Composite materials in the methods of repair and reinforcement of the existing pipelines have become widespread. In particular, the use of carbonic fiber reinforced with polymer composite fibers for the reconstruction and strengthening of concrete pipelines under pressure is discussed in the study by Pridmore and Ojdrovic [21]. Different methods of repair and strengthening of steel pipes and culverts are considered here. To prevent corrosion and other damages from pipeline breaking, the area containing the damage must be strengthened. Laminates of polymer reinforced with carbonic fiber are used for this purpose. Although the use of nonmetal polymer composite materials reinforced with fiber to restore corrosion and other damages has increased recently, and the most widespread method of repairing trunk pipelines is installation of a steel lining fully surrounded by a cage of polymer-composite material. As it has been shown in the work of Hegger and Will [22], the choice of a free-form shell size and loading methods depends on the particular type of fiber impregnation (i.e. epoxy resin, styrene-butadiene caoutchouc, and unimpregnated fibers), as the binding properties greatly influence the behavior of the composition. Although the bendability of a solid cross-section can be calculated using the known laws, the situation with shell constructions is more complicated. In this case, the strength properties of a cross-section must be determined experimentally. It is obvious that their use in the construction is impossible without experimental investigations on establishing mechanisms of their deformation and destruction at hydraulic and mechanical loads. The conduction of experimental investigations will not only allow quantitatively comparing their results with the data obtained theoretically but also allow determining the degree of conformity of the accepted in calculations initial prerequisites and assumptions.

3. AIM OF THE WORK

The aim was to determine the mechanisms of strip fiberglass reinforcement (SFR) deformation at mechanical load with various type of a binder as well as the estimation of load-carrying capacity, rigidity, and fracture strength of metal pipes with fiberglass strip reinforcement. It is necessary to compare the values of bearing capacity of pipes reinforced with fiberglass shells determined by calculation and experimentally.

4. MATERIALS AND TESTING METHODS

An effective and constructive solution for reinforcement that makes it possible to use high initial mechanical strength of glass fibers to the maximum is a continuous strip structure in which untwisted initial threads are laid in plane parallel to each other along the active tensile force (Fig. 1). Their cross-direction strength is ensured by the binder.



N – tensile forces

Fig. 1. Schematic drawing of unidirectional fiberglass material (strip)

The samples of strips (SFR) in which glass fibers were pasted together with butvar-phenolic glue (BP), epoxy resin (ER), polyester-epoxy varnish (PEV), and polyester resin (PE) have been manufactured to be chosen as a reasonable type of binder. The investigation of stress-strain performance of strips was conducted after the production of each pilot batch. To determine short-time tensile strength of strip reinforcement, not less than 10 samples of each batch were subjected to test. The samples of strips were fastened in testing machines with special cylindrical clamps. The clamp consists of a steel cylinder with a tin band soldered to it which winds the cylinder 1-1,5 times. The end of a fiberglass strip was placed between the tin band and the surface of the cylinder. It was experimentally determined that one turn of a strip round the clamp was enough to fix it safely. To measure deformations, a measuring device consisting of two indicating gages with elongated legs was used.

The developed SFR were used while creating metal-fiberglass pipe construction, known as “pipe in pipe”; where external fiberglass pipe is on par with internal metal one in terms of strength properties. To check the obtained theoretical data, a batch of pipe samples has been produced and tested. The batch presented models of metal-fiberglass pipes with the diameter of 160mm; the main characteristics of which are given in Tab. 1. To wind a reinforcing fiberglass strip on pipes, a pilot-plant equipment is making it possible to carry out the application of a strip with various effort of its tension.

Pipes of this batch were tested regarding internal pressure by water with a plunger pump. The internal pressure was increased gradually by 1 MPa up to the design yield strength of a pipe material. On achieving plastic deformations in the core, the internal pressure was increased gradually by 0.5 MPa to destruction. To study the deflected mode of a pipe, resistance wire strain gauges were stick on fiberglass.

Table 1

Main characteristics of metal-fiberglass pipes (models) that are produced in a laboratory environment

No.	Name	Value
1	Pipe radius r, mm	80
2	Pipe wall thickness δ_1, mm	1.5
3	Thickness of a fiberglass strip to wind, mm	0.25
4	Thickness of a wound fiberglass shell δ_2, mm	1; 2; 3
5	Steel elasticity modulus E_1, MPa	$1.88\cdot10^5$
6	Steel yield strength σ_s, MPa	210
7	Steel ultimate strength σ_{us1}, MPa	660
8	Steel specific elongation at break ε_1, %	25
9	SFR elasticity modulus E_2, MPa	$4.1\cdot10^4$
10	SFR ultimate strength σ_{us2}, MPa	1000
11	SFR specific elongation at break ε_2, %	2.5

5. REULTS OF RESEARCHES

To estimate time dependence of SFR strength, the so-called long-term strength coefficient K_t was determined, which is the ratio of two strengths, corresponding to destruction points t_1 and t_2, measured in hours,

$$K_t = {F_{t_1}}/{F_{t_2}}. \tag{1}$$

Time t_2 corresponds to the life cycle of the material, and the value F_{t_1} is determined after a short-time standard test on monotonic loading. A long-term strength curve was drawn on the basis of stress rupture effect of a number of similar samples loaded with a constant gradually lowered loading. The curve had asymptotic pattern, and its asymptote pointed the value of SFR long-term resistance on the coordinate axis. The test period (base), which equals 6 months, was accepted. The tests were conducted on installations, which made it possible to keep the sample under long-tern constant loading during any time. A long-term strength curve of strip fiberglass reinforcement was drawn on the basis of the test results (Fig. 2). The SFR long-term strength coefficient equaled $K_t = 0{,}64$, which testifies the material plasticity.

SFR deformability is determined by the joint work of glass fibers and polymer binder. Strain and deformation for different types of binder have been determined in the following way. Analytical elasticity module of SFR in the direction of fiber orientation was determined from the following formula:

$$E = \frac{A_m}{A}E_m + \frac{A_c}{A}E_c = \left(E_m + \mu E\right)\frac{1}{1+\mu}, \tag{2}$$

where E_m and E_c are elasticity modules of polymer binder and fibers; A_m and A_c are cross-sections of polymer binder and fibers; $A = A_m + A_c$ is reinforcement cross-section; $\mu = \frac{A_c}{A_m}$ is reinforcement coefficient in the direction of fiber orientation.

The results of calculations are given in table 2.

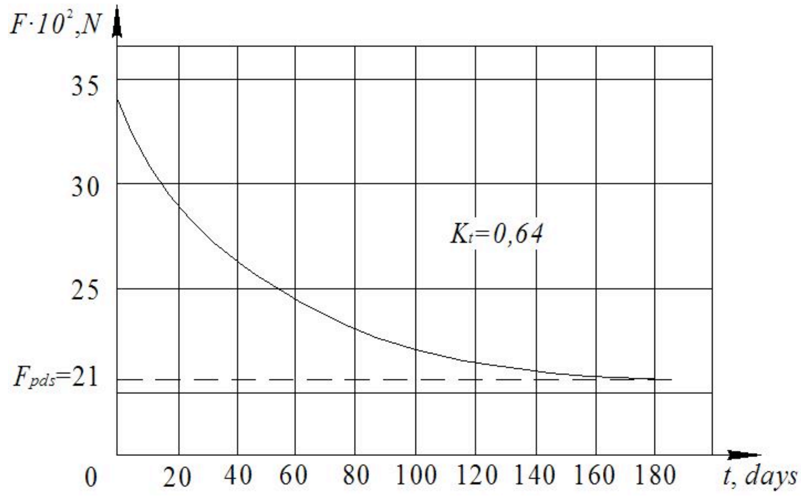


Fig. 2. Long-term strength curve of fiberglass reinforcement

Table 2

Characteristics of SFR and other strip fiberglass materials

Reinforcement type	Fiberglass composition	Fiber diameter, micron	Polymer binder	Strip width, mm	Strip thickness, mm	Binder content, % by weight	Tensile failure stress, MPa	Elasticity module, x $10^{4\ m}$ MPa
SFR (type1)	Aluminum-borosilicate	7…9	BP-4	15…20	0,2	15	1300…1400	4,7
SFR (type 2)	"	7…9	ER-20	20	0,2	20	1100	4,5
SFR (type3)	"	9…11	PEV	20	0,2	20	1000…1100	4,1
SFR-F (type4)	"	9…11	PE-933	20±2	0,2	22…25	800…900	4,0

As can be seen from Table 2, the largest elasticity module $4{,}7 \cdot 10^4$ MPa has the first type of reinforcement with BP-4 binder. This type of reinforcement has maximum tensile failure stress at minimal polymer consumption.

Steel stress in a pipe in a ring direction was determined from the formula:

$$\sigma_P = \frac{p \cdot r}{\delta}, \tag{3}$$

where p is internal pressure; r is a capacity radius; δ is wall thickness.

The deformation in steel pipe and shell in a ring direction was determined from the following formulas:

$$\varepsilon_p = \frac{\sigma_p}{E_p}\left[1 + \eta_P \left(\frac{\sigma_P}{R_p}\right)^{m_p}\right], \tag{4}$$

$$\varepsilon_s = \frac{\sigma_s}{E_s}\left[1+\eta_s\left(\frac{\sigma_s}{R_s}\right)^{m_s}\right], \tag{5}$$

where η_P, m_P and η_s, m_s are the nonlinearity parameters of respectively pipe steel and shell fiberglass; R_P, R_s - are temporary resistance of pipe steel and shell fiberglass, respectively; E_P, E_s are secant moduli of deformation of pipe steel and shell fiberglass.

Fig. 3 shows diagrams $\sigma_P - \varepsilon$ for strip fiberglass reinforcement and other unidirectional fiberglass plastics.

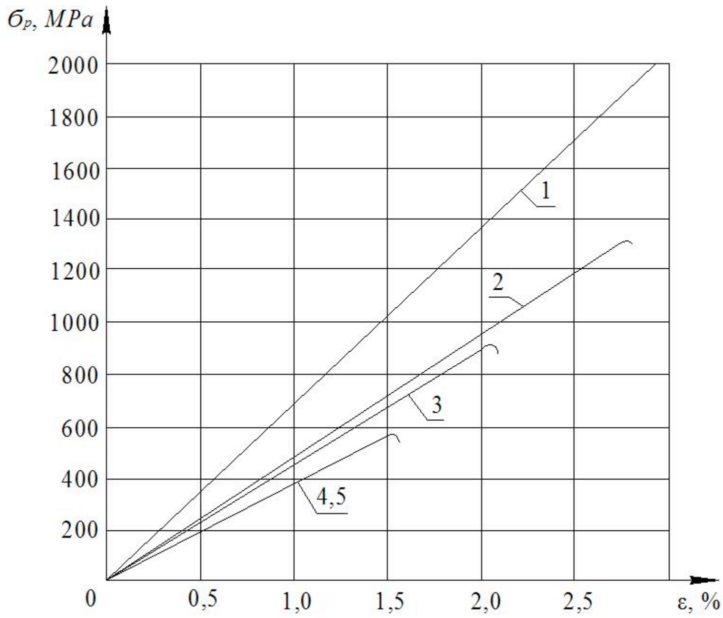


Fig. 3. Diagrams $\sigma_P - \varepsilon$ of glass fiber and unidirectional fiberglass plastics: 1 – glass fiber of aluminum-borosilicate composition; 2 – strip fiberglass reinforcement (SFR); 3 – fiberglass plastic bend SFR-F; 4,5 – fiberglass plastics REV and PE

As we can see, the obtained ultimate elongation of strip fiberglass reinforcement did not exceed 3%.

Due to small thickness and elasticity, SFR can be applied in a high-tech method of continuous reinforcement (winding) especially while creating solid corrosion-proof protective coatings for metal structures. The influence of the quantity of strip layers on the value of maximum pressure inside a pipe to fracture has been studies to design the thickness of the winding reasonably. Fig. 4 shows "pressure-versus-deformation" curves of pilot metal-fiberglass pipes (models).

6. DISCUSSION

As follows from the data in Fig. 4, pipes with a fiberglass winding withstand more pressure at the same value of deformation. The similar tests conducted in [23] for pipes with carbon-filled plastic winding showed lower results. Two winding layers made it possible to enlarge the failure pressure only up to 4 MPa. However as both our researches and [23] testify, multiple winding of a shell does not lead to multiple increase in strength. The reinforcement makes up to 20%. The identity of theoretical and experimental data testifies to the correctness of initial prerequisites and assumptions taken in calculations.

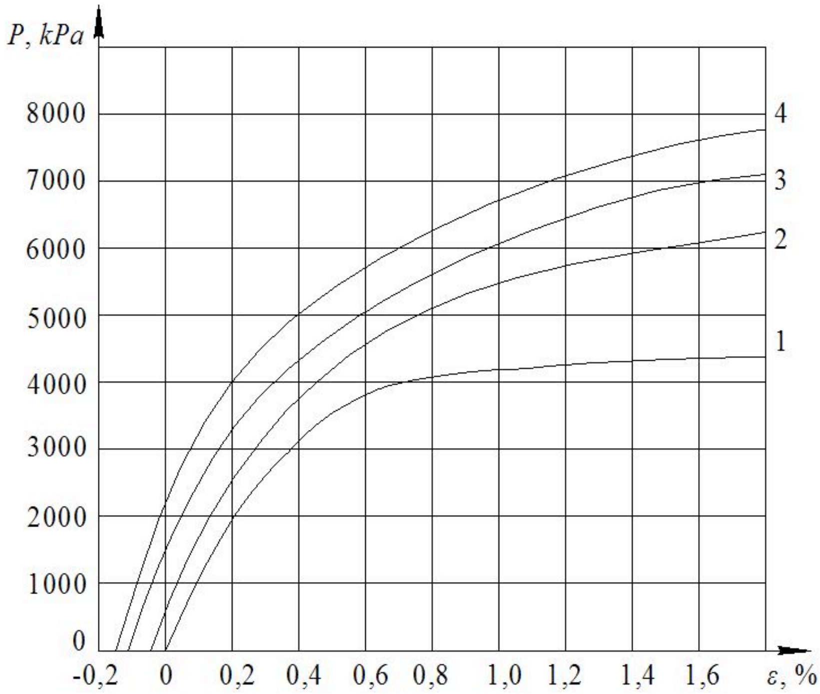


Fig. 4. „Pressure-deformation" dependence of pilot metal-fiberglass pipes (models) (*p* –internal hydraulic pressure; ε - pipe ring deformation): 1 – pipe without winding; 2 – 5 layers of winding; 3 – 10 layers of strip; 4 – 15 layers of strip

A batch of metal-fiberglass pipes (10 pieces) reinforced with fiberglass shells was manufactured under factory conditions to test them. Metal thin-wall cores of $\delta = 4$ mm in thickness had a diameter of 108 mm and width up to 1100 mm. Fragments of pipes are shown in Fig. 5. The winding of fiberglass shell was made on a pilot and experimental plant of a lathe type installed in the laboratory of composite materials.

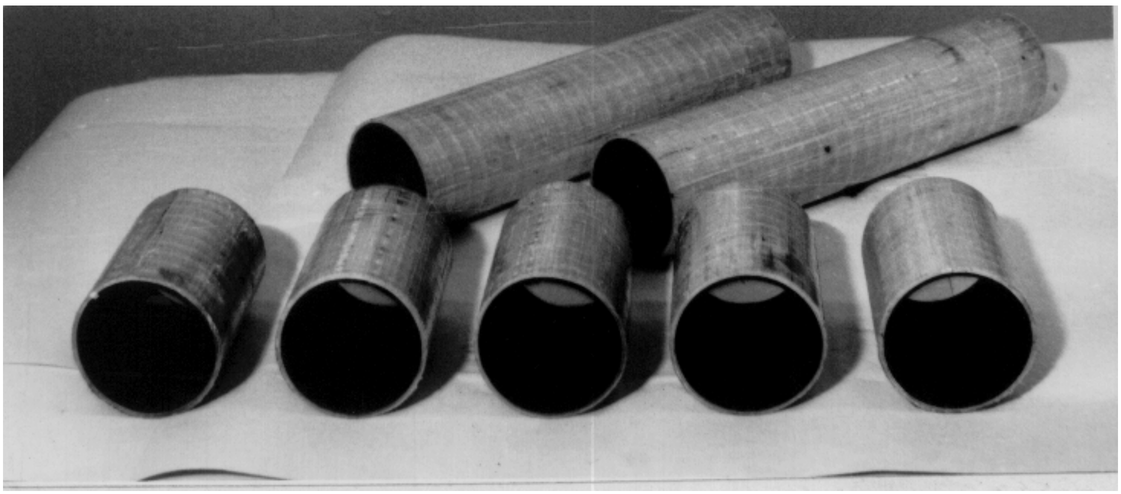


Fig. 5. Photo of metal-fiberglass pipe samples (fragments)

The winding of the samples was done under turned on tube sockets reaching the temperature of 105°C in a molding zone. Wound samples passed 8-hour cycle of polymerization on the same machine and under the same temperature conditions. The tests were conducted 0.5-3 months after their manufacturing. The sticking of wire strain gauges was made 2-3 days before the test. The repeated inspection and measurement of samples which did not reveal any changes of geometrical dimensions in the comparison with the initial ones had been carried out. The pipes produced according to the aforementioned technology were welded in a length of pipe. Pressure was increased gradually by 1 MPa. The pipeline was not brought to destruction. Maximum pressure corresponded to metal steel yield strength (σ_P = 216 MPa). Residual metal deformations, which are prohibitive under the conditions of operating conduit, began over that loading. The tests showed that with internal pressure being increased after the transit of steel into plastic stage of work, it was fiberglass plastic, behaving elastically, that took increase of strain. After the rupture of fiberglass reinforcement, all the pressure is transmitted to steel pipe which is destructed soon afterwards.

The tests also showed that stress condition of pre-stressed pipes was close to a design one. The greatest divergence of stress (up to 10% in a steel core) was observed in tested pipes in the area of transition of the material into plastic stage. The fracture pattern while testing an industrial sample of a metal-fiberglass pipe under factory condition is shown in Fig. 6. It is clear that a fiberglass shell is an obstacle on the way of longitudinal crack preventing its further movement.

Fig. 6. Fracture pattern of a metal-fiberglass pipe: 1 – fiberglass plastic; 2 – crack; 3 – metal

As our investigations has shown pipes of a new design at the expense of a fiberglass shell applied with prestress get additional supply of elastic energy that makes it possible to increase the strength of a core wall by up to 2 times. Fiberglass inhibits corrosive process on a steel pipe surface making the term of trouble-free operation of pipes 2-2,5 times longer.

7. CONCLUSIONS

Strip fiberglass reinforcement has all the necessary physics-mechanical properties and can be applied for spiral stressed reinforcement of metal pipes that allows creating a pipe structure to lay it in pipelines in places with enhanced aggressive action of ground water as well as in soils with substantial saturation of terrestrial currents. The application of fiberglass strengthening and protective shells is an efficient technique for pipelines coating. At that, it is not only possible to protect pipelines from corrosion but to increase their strength, as fiberglass plastic belongs to the type of high-strength anisotropic materials. While using a “metal-fiberglass plastic” pair, reinforced plastic is the first to be destroyed in a metal-fiberglass pipe. It can be explained by the fact that metal possesses greater plastic deformations with the development of which fiberglass plastic takes the main loading. Nonlinearity of deformation of only metal part was taken into account at calculations in the considered pipes. Fiberglass plastic was considered as an elastic material. However, in a general case, at the stage close to the destruction, all the fiberglass plastics are deformed nonlinearly. In these cases, it is necessary to take into account the nonlinearity of fiberglass plastic properties.

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