Mechanical Properties of a New Composite Sleeve for Pipeline Repair

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This paper outlines the results of a series of experiments designed and conducted by the authors in order to determine the mechanical properties of a new composite material used for manufacturing the sleeves for the consolidation or reinforcement of the zones with local surface defects (flaws) in transport pipelines. The analysis and interpretation of the results allowed the authors to: assess the effectiveness of the new composite in repairing pipelines with local metal loss defects; establish the most effective way of preparing the pipeline surface for the application of the new composite sleeve; and to emphasize the correlation between the elastic properties of composites and the consolidation or reinforcement effect on the corroded or damaged pipelines following the application of composite sleeves.

Keywords: pipeline maintenance, composite sleeve or wrap, mechanical properties of composites

Pipelines repairing with coatings made of composite materials represents a modern maintenance technology applied to pipelines which transport crude oil, liquid petroleum or petrochemical products and natural gas. This technology allows in-service repair of pipelines and repairing the pipelines with local defects (metal loss, grooves, gouges, notches, scratches, pittings, dents, cracks, etc.), and due to the arguments summarized in Table 1, it is preferred to the use of the traditional repair technologies [1].

Composite wrap repair has the structure shown in the figure 1, and its achievement requires three stages: a) pipeline preparation for repair, which consists of cleaning the pipeline surface using an appropriate procedure and of polishing, grinding or sandblasting operations in order to round the edges and smooth the flaws profile, to eliminate the possible micro-cracks initiated on the flaws and to transform the flaws in long-radius curvature grooves, with reduced effects of mechanical stress concentration; b) pipeline external configuration rehabilitation, which consists of filling the outside flaws using a polymeric filler; c) pipeline mechanical strength rehabilitation, which consists of applying a composite wrap for reinforcement in the flaws area.

This paper presents the results of the experimental program carried out in order to determine the mechanical characteristics of the multiple layers wraps obtained from fiber glass cloth impregnated with a polymeric resin manufactured according to the original recipe of a research team from ICECHIM Bucharest [2,3]. Due to the production method used, it can be considered that these wraps are made of a multilayer composite material – MCM, in which the reinforcement component consists of layers of fiber glass fabric, and the matrix is the polymeric material used to impregnate the fabric.

The polymeric material used to produce the wraps is conceived as a modified polymeric system with flexibilisators with small molecular weight (that ensures the viscosity level required to apply the material by brushing) and with mineral fillings (which increase the material thixotropy and prevent its flowing during application) [2,3]. The fabric used for wrap reinforcement is a fiberglass roving fabric having the texture shown in figure 1.

Experimental part

The experimental program had the following objectives:

- definition of the preparation methods used for the pipeline surface to be repaired in order to obtain the best adhesion of the multilayer composite material wrap;
- determination of the detachment strength by shear of the multilayer composite material wrap on the steel pipe on which was applied;
- determination of the tensile mechanical characteristics of the multilayer composite material wrap.

In order to carry out the experimental program 10 samples of multilayer composite material applied on support plates processed from a steel flat bar for manufacturing pipes for pipelines have been made, each sample having the configuration and the sizes shown in figure 2.

Table 1
COMPARISON BETWEEN DIFFERENT
REPAIRING TECHNOLOGIES
FOR TRANSPORT PIPELINES

Criterion	Repairing Technology		
	Cut out and replace	Welded steel sleeve	Composite wrap repair
Production loss [a)]	Major	Minor	None
Labour force required	Large	Large	Small
Labour skill level	High	High	Moderate
Welding	Substantial	Substantial	None
Radiography required	Yes	Yes	None
Heavy equipment required	Major	Major	None
Time scale	Major	Major	Minor
Price	High	High	Reasonable

a) because the pipeline is taken out of service or due to some modifications in the mode of operation of the pipeline while performing maintenance works

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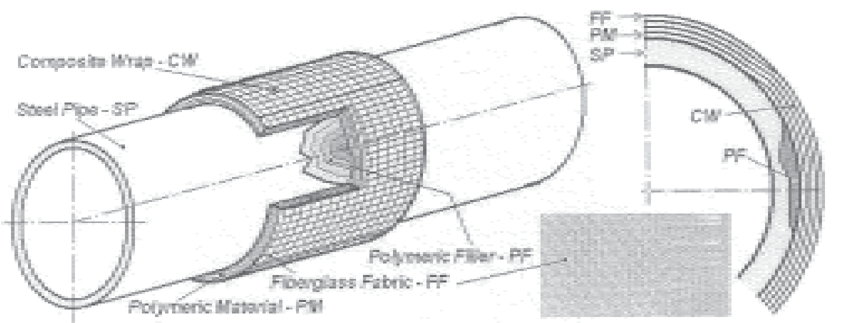

Fig. 1. The structure of the repairs carried out using composite wraps

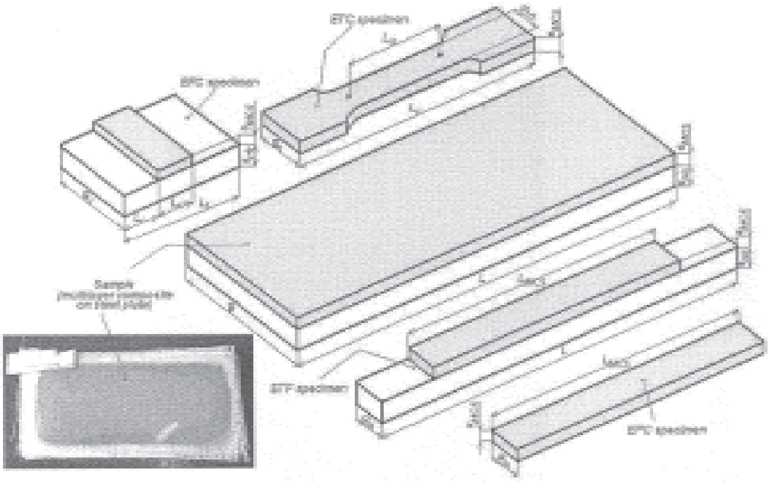

Fig. 2. The form and the dimensions of the steel plate type samples with composite material wrap

The flat bar used to manufacture the support plates for the samples was made of S235 steel; by means of tensile testing (in accordance with SR EN 10002-1) of a specimen taken from the flat bar the conventional stress – strain curve – $CSSC_S$ has been obtained and the following mechanical characteristics of the steel have been determined: the modulus of elasticity (Young's modulus) E_S = 200 GPa, the yield strength (the tensile stress required to produce the total elongation of 0.5% of the gage length as determined by an extensometer) $R_{t0,5S}$ = 301 MPa, the ultimate tensile strength R_{mS} = 368 MPa and the elongation percentage at failure A_S = 25%.

The steel support plates were processed on the active areas, on which the multilayer composite material wrap was subsequently applied, using various technological processes and regimes, in order to have areas with different configurations of the micro-irregularities and different values of the roughness: a) the plates for the samples marked P1 were processed by grinding, in order to ensure a roughness of the surface R_z = 0.8 μm; b) the plates for the samples marked P2 were processed by finishing shaping, in order to provide a surface with a roughness of R_z = 6.3 μm; c) the plates for the samples marked P3 were processed by rough shaping, in order to provide a surface with a roughness of R_z = 50 μm; d) the plates for the samples marked P4 were processed by sandblasting using a normal semi-friable corundum, at the pressure of 0.5 MPa; e) the plates for the samples marked P5 were processed by sandblasting with corundum, normal and semi-friable, at a pressure of 0.9 MPa. After processing on the active areas, the thickness of the steel support plates was s_S = 8 mm.

On the active surface of each of the 10 support plates one multilayer composite material wrap has been applied, as follows:

- the necessary amount of reactive polymer modified with flexibilisator and mineral filling has been prepared;
- the fiberglass woven fabric required to make the wrap has been prepared, under the form of tapes with dimensions slightly larger than the dimensions of the surface on which the wrap is to be applied;
- the surface prepared for applying the wrap has been degreased using organic solvents;
- the modified reactive polymer has been mixed with the required amount of catalyst and the mixture has been homogenized for 5 min; this mixture has been brushed on the active surface of the basic plate and over it the first strip of fiberglass fabric has been applied; this operation has been repeated several times, by applying the strip of fiber glass fabric and its brushing with modified reactive polymer; a multilayer composite material wrap (modified reactive polymer, reinforced with fiberglass fabric) with 14...15 layers of fiber glass fabric with the total thickness s_C = 4.5...4.8 mm resulted.

The total 3D-dimensioning of the resin used to produce multilayer composite material wraps on the samples thus obtained was followed by DSC calorimetric analysis and FT-IR spectroscopy (Fourier Transform Infrared Spectroscopy). The results of the experimental testings carried out are summarized in [3]; after 7 days, the polymeric system used as matrix for the composite material used to make the wraps was completely hardened, this fact being shown both by the exothermic reaction configuration, on which the heat effect can no longer be practically seized upon, and by the disappearance of the absorption bands specific to the unhardened polymer in FT-IR analysis.

From the samples taken the following types of specimens have been processed:

- ETF marked specimens, for detachment strength determination of the multilayer composite material from the support plate in the case of plate tensile loading;
- EFC marked specimens, for detachment strength determination of the multilayer composite material on the basic plate in the case of a shear loading at the interface

between the multilayer composite material and the support plate;

- ETC marked specimens, for tensile mechanical characteristics determination of the multilayer composite material;

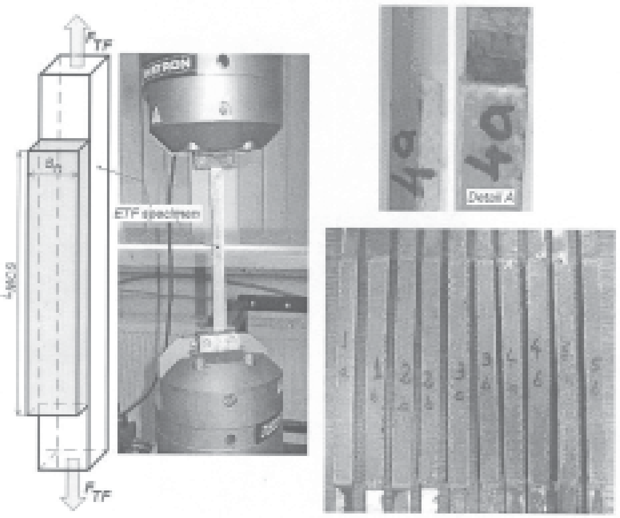

Fig. 3. ETF specimens testing method

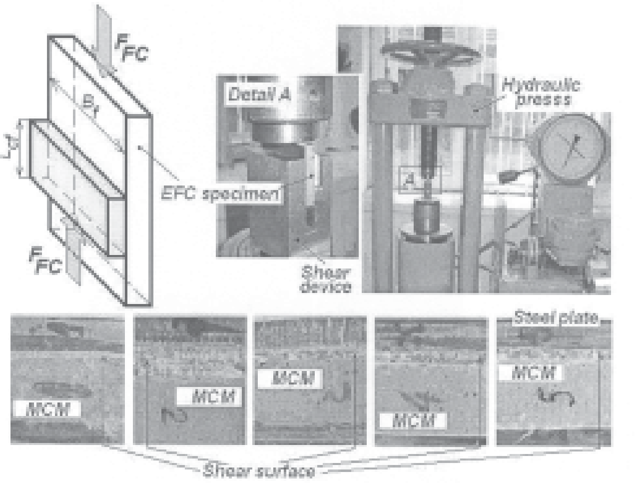

Fig. 4. EFC specimens testing method and the aspect of the specimens tested

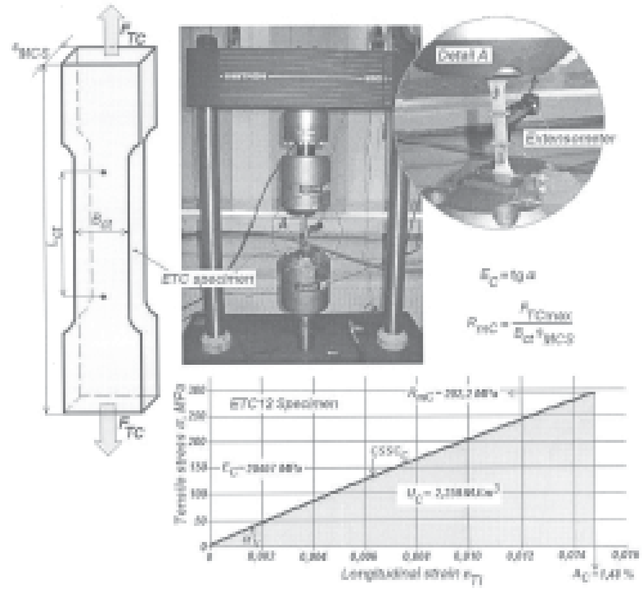

Fig. 5. ETC specimens testing method

- an EPC marked specimen, taken from the multilayer composite material of the P2 sample, to determine the Poisson's ratio of the multilayer composite material.

As can be seen in figure 3, the ETF specimens were tested on an INSTRON 8801 machine, by applying a monoaxial tensile stress on their steel support. The test has been carried out in order to determine the tensile force intensity F_{TF} at which the multilayer composite material detachment from the steel support has been produced, to calculate the detachment strength $\tau_{TF} = F_{TF} / L_{MCS}B_{ft}$ and to select the steel support active surface processing technology for which t_{TF} is maximum.

As can be seen in figure 4, the EFC specimen were tested on an LOSENHAUSENWERK – LOS Press with the capacity of 600 kN, by applying a shear force on the steel-multilayer composite material interface of the specimen. During the test the shear force intensity F_{FC} to which the multilayer composite material detachment from the steel support occurred has been determined, on this basis the detachment strength by shearing $\tau_{FC} = F_{FF} / L_{cf}B_f$ has been calculated and the steel support active surface processing technology for which τ_{FC} is maximum has been selected.

As shown in figure 5, the ETC specimens were tensile tested on an INSTRON 8801 machine, in accordance with SR EN ISO 527-4 provisions, in order to obtain conventional stress - strain curve – $CSSC_C$ and to determine the following mechanical characteristics of the multilayer composite material: modulus of elasticity (Young's modulus) E_{MCM}, ultimate tensile strength R_{mC}, elongation percentage at failure A_C and toughness U_C, defined as the specific energy consumed for composite tensile breaking (area of the surface under the $CSSC_C$).

As shown in figure 6, the EPC specimen, on which one X – rosette with 2 measuring grids type strain gauge was applied, was tensile tested on an INSTRON 8801 machine, in accordance with SR EN ISO 527-4. During this test, using a SPIDER 8 data acquisition system, the deformations ε_{Ta} on the axial direction (tensile force direction of application) and ε_{Tt} on transversal direction have been measured; on this basis the values of the multilayer composite material Poisson's ratio $\mu_C = -\varepsilon_{Ta} / \varepsilon_{Tt}$ have been calculated. The results have been validated by applying the methodology from ASTM E 132, which states, as it can be seen in figure 6, the plotting on the same diagram of the statistical regression (A_S

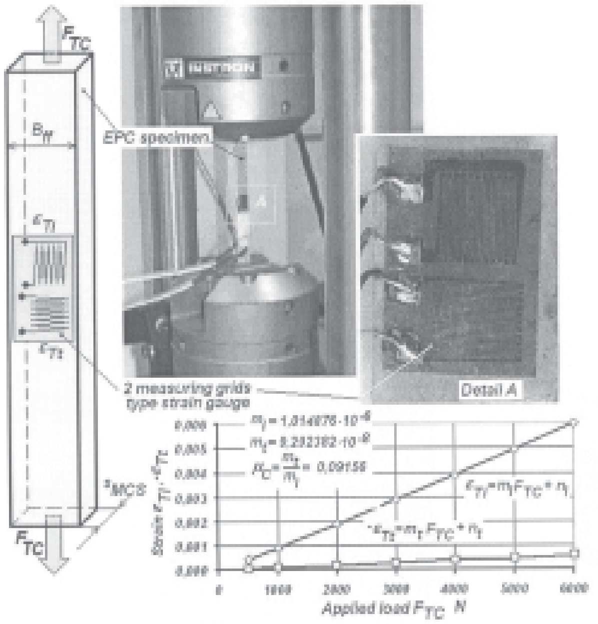

Fig. 6. EPC specimens testing method

Table 2
THE RESULTS OF THE ETF SPECIMENS TESTING FOR MCM ADHESION TO STEEL DETERMINATION

Sample	Specimen mark	L_{ct}, mm	B_{ft}, mm	F_{TF}, N	τ_{TF}, MPa	Comments
P1	ETF 11	170.1	15.2	18000	7.0	Spontaneous detachment of the composite material
	ETF 12	173.2	15.2	17100	6.5	
P2	ETF 21	171.2	15.5	23900	9.0	
	ETF 22	171.3	15.3	24900	9.5	
P3	ETF 31	172.5	15.1	32500	-	Progressive detachment of the composite material, with the occurrence of plastic deformations in the steel support
	ETF 32	173.0	15.1	33000	-	
P4	ETF 41	170.2	15.1	35000	-	
	ETF 42	170.8	15.1	36000	-	
P5	ETF 51	171.5	15.4	36500	-	
	ETF 52	173.0	15.2	37000	-	

Table 3
THE RESULTS OF THE EFC PIECES TESTING FOR MCM ADHESION TO STEEL DETERMINATION

Sample	Specimen mark	L_{cf}, mm	B_{ff}, mm	F_{FC}, N	τ_{FC}, MPa
P1	EFC11	18.9	56.2	7540	7.1
	EFC 12	19.9	59.5	8760	7.4
P2	EFC 21	23.7	54.8	11430	8.8
P3	EFC 31	19.8	57.3	14180	12.5
P4	EFC 41	20.8	58.1	16070	13.3
P5	EFC 51	20.1	58.0	17370	14.9

straight lines $\varepsilon_{Tl} = f(F_{TC})$ and $\varepsilon_{Tt} = g(F_{TC})$, the determination of the slopes m_l and m_t of these straight lines and the calculation of the Poisson's ratio value with the equation $\mu_C = m_t / m_l$.

Results and discussions

The ETF specimens testing led to the results summarized in table 2. Only the MCM from the specimens taken from samples P1 and P2, with the smooth active faces (having low roughness), detached spontaneously, simultaneously in all the areas from the contact surface with the support, before the occurrence of plastic deformations of the steel support; for these specimens the force intensity F_{TF} could be determined and the τ_{TF} detachment strength was calculated. MCM on the specimens from the other samples detached progressively, with the occurrence of plastic deformations of the steel support in each interface area; therefore, certain F_{TF} values could not be determined and the τ_{TF} values could not be calculated for these specimens. The ETF specimens testings outline that a higher roughness of the active surface of the steel supported could lead to higher adhesion in MCM wrap application.

The EFC specimens testing led to the results summarized in table 3. The F_{FC} shearing force values were determined and the steel support MCM shear detachment strength values were calculated. Based on these it was established that the steel support active surface sandblasting determines the best adhesion of the MCM applied, ensuring the maximum values of the τ_{FC} shear detachment strength.

The rough planning of the active surface of the steel support is not recommendable, since it determines small irregularities in the direction of progress of the planning tool and, consequently, the MCM adhesion degree will depend on the relative position of the small irregularities as compared to the stress direction of the system steel support – MCM wrap; moreover, rough planning is difficult to be performed on the outer surface of the pipelines in repair.

The ETF specimens testing led to the results summarized in table 4 and in figure 6. The analysis of these results outlined the following aspects regarding the mechanical characteristics of the MCM: a) the $CSSC_C$ configuration leads to the finding that MCM has a linear elastic behavior at the monoaxial tensile stress; b) the mechanical resistance of the MCM (R_{mC} = 268.5…318.6 MPa) is of same magnitude of the support plates steel resistance (R_{mS} = 368 MPa); c) the elongation percentage at failure of the MCM (A_C = 1.32…1.60 %) is low, much lower than the one of the support steel plates

Table 4
MECHANICAL CHARACTERISTICS DETERMINED BY TENSILE TESTING OF THE ETF SPECIMENS

Sample from which the MCM was taken	Specimen mark	Tensile characteristics of the MCM			
		E_C, MPa	R_{mC}, MPa	A_C, %	U_C, MJ/m^3
P1		22659	318.6	1.32	2.077
	ETC 12	20467	292.2	1.48	2.259
P2	ETC21	18535	268.5	1.32	1.772
	ETC22	17878	304.8	1.60	2.416
P3	ETC 31	17480	278.2	1.52	2.219
P4	ETC 41	19444	298.0	1.43	2.188
P5	ETC 51	20457	301.5	1.38	1.968

Table 5
THE RESULTS OF THE TENSILE STRESS TEST OF THE EPC SPECIMEN

Tensile force F_{TC}, N	Axial force in specimen σ_{aC}, MPa	Specific deformation ε_{Ta}	Specific deformation ε_{Tt}	Poisson's ratio μ_C
500	6.8	$4.253194 \cdot 10^{-4}$	$-4.462796296 \cdot 10^{-5}$	0.104928
1000	13.5	$9.015712 \cdot 10^{-4}$	$-9.613826923 \cdot 10^{-5}$	0.106634
2000	27.1	$1.886661 \cdot 10^{-3}$	$-1.957703986 \cdot 10^{-4}$	0.103766
3000	40.6	$2.881662 \cdot 10^{-3}$	$-2.948004098 \cdot 10^{-4}$	0.102302
4000	54.1	$3.886472 \cdot 10^{-3}$	$-3.902050000 \cdot 10^{-4}$	0.100401
5000	67.6	$4.924342 \cdot 10^{-3}$	$-4.790704945 \cdot 10^{-4}$	0.097286
6000	81.2	$6.007137 \cdot 10^{-3}$	$-5.557010667 \cdot 10^{-4}$	0.092507
Average value of Poisson's ratio of the MCM:				**0.101118**

Table 6
COMPARISON BETWEEN THE MECHANICAL CHARACTERISTICS OF THE MCM AND OF OTHER COMPOSITE MATERIALS USED FOR PIPELINE REPAIRING

Composite material	Reinforcement material	Mechanical characteristics of the composite material*		
		E_C, GPa	R_{mC}, MPa	A_C, %
MCM	**Fiberglass**	**17.5 ... 22.7**	**265 ... 315**	**1.32 ... 1.60**
Perma Wrap	Fiberglass	34.0 … 38.0	580 …620	1.00 … 1.10
Fiba Roll	Fiberglass	7.9 ... 8.7	86 ... 72	2.60 ... 3.10
Clock Spring	Fiberglass	33.8 ... 34.5	630 ... 650	1.06 ... 1.36
TDW RES-Q Wrap	Carbon fiber	68.8	1028	-

* measured in the direction corresponding to the pipeline circumference when applying the composite material wrap

= 25 %); d) the modulus of elasticity (Young) of the MCM (E_C = 17.5...22.7 GPa) is much lower (8.8...11.4 times lower) than the one of the support steel plates (E_S = 200 GPa).

The EPC specimen testing outlined the results summarized in table 5. The average value obtained for Poisson's ratio of the MCM analyzed is μ_f = 0.1. As it can be seen when examining the diagram from figure 6, the same value has also been obtained by applying the method recommended by ASTM E 132. Considering the fiberglass woven fabric type used for reinforcement and the value of volume fraction of fibers in the MCM ($\nu_f \cong 0.5$), the results obtained for Poisson's ratio of the composite material are completely compliant with those of other composite materials which have a structure similar with the MCM [4-6].

The mechanical characteristics of the MCM have been compared with those of other composite materials used for pipeline repairing [4-13]. The results of this comparative analysis, summarized in table 6, underline the fact that the MCM analyzed in this paper has the mechanical characteristics of the best fiberglass reinforced composite materials existing at the moment. Higher values (than those provided by the MCM) of the mechanical resistance and of the modulus of elasticity can be obtained only by the tetra axial fiberglass woven fabric reinforcement of the composite material, by increasing the volume fraction of fibers and, especially by the use of carbon fiber fabric. Applying one or several of these solutions leads however to the increase of the cost of the pipeline repairing wrap.

The experimental programme results interpretation process has been finalized by analyzing the extent to which the mechanical characteristics of the MCM (and of the other pipeline repairing composite materials) fit for the purposes in which these materials are used. Since the composite materials wraps are applied on damaged steel pipelines and have to be adequate for them, compensating for the decrease of their supporting capacity caused by the presence of the local defects, it is necessary that the deformation continuity condition is permanently fulfilled at the steel pipeline and composite material wrap interface, meaning that the specific deformations of the steel pipeline have to be equal to the deformations of the composite material wraps [14]. The fulfilling of the above condition determines an inconvenient distribution of the mechanical stresses in the pipeline composite material repaired area, the $k_{\sigma r}$ ratio between the intensities of the stresses in the steel pipeline and in the wrap used for repairing being maintained at the level $k_{\sigma r} = \frac{\sigma_{eS}}{\sigma_{eC}} = \frac{E_S}{E_C}$ ·. It results that the pipeline consolidation effect by the composite wrap application, which characterizes the efficiency of the use of these wraps in pipeline repairing, primarily depends on the elastic properties of these materials compared with the elastic properties of the pipe steel (metal); this idea will be developed in a future paper.

Conclusions

The multilayer composite material – MCM whose mechanical characteristics have been determined and analyzed in this paper is used for the steel pipeline repairing wraps. The reinforcement component of the MCM is made of fiberglass multilayer fabric, and the matrix is a polymeric material made according to the original recipe of a research team at ICECHIM Bucharest.

The experimental research has underlined the fact that the MCM wraps have a good adhesion to the steel pipeline surface in repair only if, before application, the surface is sandblasted and degreased with organic solvents.

The experimental research brought forward that the MCM has the mechanical characteristics of the best fiberglass reinforced composite materials existing at the moment. The MCM's quality can be improved and the effectiveness of the repairs made by the use of wraps from this material can be made more effective only by the use of technological solutions leading to the increase of the modulus of elasticity of the MCM or to the ensuring of a more reasonable structure of the MCM wraps.

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