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Strength Testing and Ring Stiffness Testing of Underground Composite Pressure Pipes

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Abstract. The paper presents issues related to the production and testing of filament-wound glass fibre reinforced epoxy pipes. At the beginning, a strength analysis of a pipe embedded in the ground subjected to loads from ground pressure and passing vehicles was carried out. Based on the calculations, composite pipe samples were manufactured by winding, and then tested using a universal testing machine. During the tests, the ring stiffness and strength of a pipe wall structure were studied, and the latter was characterised by a variety of materials in its radial cross-section (various reinforcing fibres such as glass, basalt, carbon).

Introduction

The research area studied in this work concerns the behaviour of a pipe (culvert) embedded in the ground at the appropriate depth. Therefore, considerations taken into account concern two objects: the composite pipe (material, technology, properties) and the soil (type, properties).

Polymer matrix composites which include, among others, glass-, carbon,- basalt fibre- and organic fibre- (Kevlar) reinforced polymer matrix composites, form the largest group among the fibre composites used. A significant class of reinforced plastic products includes pipes and tanks produced as a result of filament winding. In many technical fields, they effectively replace products manufactured out of traditional construction materials. However, in order to obtain optimal strength properties of such a product manufactured out of polymers, the winding process should be designed in such a way that the load is transferred via the reinforcing fibres. As these materials behave in a particular way under load, it is important to know the mechanics behind strain and the methodology for verifying basic properties of these materials [2, 6].

When designing structures embedded in the ground, the main issue concerns the determination of the size and distribution of loads acting on their external surface. These difficulties result from the random character of the factors affecting the operation of the structures buried in the ground. An important element here is the analysis of all these factors and matching the right parameters of the manufactured product to the load [4].

Determining the pipe embedment depth

Determining the load exerted onto a pipe by the overburden requires the determination of a pipe burial depth. This depth is also crucial when determining live (transport) loads, as these loads functionally decrease with an increased burial depth. It should be underlined here that the trench width and materials used for filling should also be specified. Most of these parameters are governed either by the national- or industry standards:

– bedding for pipelines can be made of crushed stone, sandstone, gravel or sand. The bedding material used should meet the requirements of the PN-EN 13043: 2004 standard;
– soil compaction index at the pipeline foundation level should be $I_s \geq 0.97$ according to Proctor impact compaction test. In case of lower compaction values, additional soil improvement should be done via cement or lime soil stabilization;
– the burial depth of pipelines should be such that the thickness of the soil layer above the pipe equals at least 0.9 m;
– backfill in the pipe zone (area immediately surrounding the pipe) should only consist of easily compacted soil, e.g. sand, sand or gravel. The height of the pipe zone should reach from the bottom of the trench to a level of 0.3 m above the top of the pipe. The width of the pipe zone should be equal to the width of the trench (at least four times the pipe diameter);
– the minimum distance on each side of the pipe from the trench/pipe shoring should be 0.3 ÷ 0.5m, depending on the external diameter of the pipe, while in the case of mechanical soil compaction, the distance from the pipe to the trench shoring should be at least 0.4 ÷ 0, 5m, regardless of the diameter of the trench [4].

Based on these guidelines, a bedding of a pipe in a trench was designed. Dimensions dependent on the diameter of the pipe were determined for the outer diameter of the pipe d_e = 150mm. Fig. 1 presents the designed pipe placed in the trench.

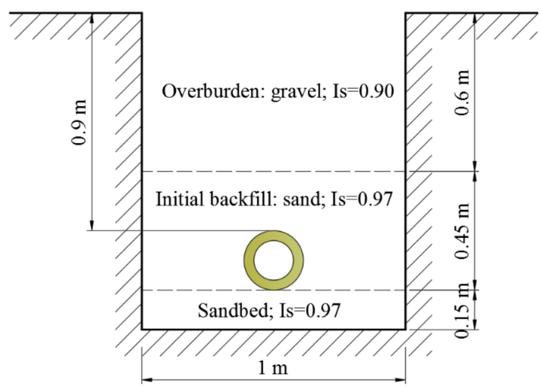

Fig. 1. Pipe embedded in a trench with compaction zones marked

Guidelines for the pipe-soil system

Along with the progress of civilization, the development of sewer networks and road networks, as well as the issues of sewer pipes, transmission pipes and culverts became of significant interest for the engineers. The emergence of new materials and technologies meant that composite materials were being used more and more often. These materials are characterized by high strength and very good resistance to structural degradation in environments, such as soil. Therefore, pipes made of composite materials, especially continuous fibre (glass, carbon) reinforced composites in a polymer (polyester resin, epoxy resin) matrix are most often used as lines and pipelines for gas transmission. Strength calculations of the structure of such pipes usually focus on determining the appropriate wall thickness due to the internal pressure of the gas within the pipeline.

In the case of pipelines laid in the ground, the dominant load on the pipe may include external loads caused by the impact of the ground, of ground water and overburden load. Such load pattern occurs when there is no internal pressure in the pipe, e.g. during pipeline maintenance.

The correct calculation of pipe stress and loads requires qualifying the pipe to the appropriate group of appropriate elastic properties.

The cables are divided into three groups, which result from the PN-EN 805: 2002 and PN-EN 476: 2011 standards:

1) rigid pipes – those for which the relative deformation of the wall is ~ 0%. This includes pipes made of traditional materials, e.g. concrete, stoneware, cast iron. These pipes are an independent static system and do not cooperate with the soil medium;
2) semi-rigid pipes – those for which minor relative wall deformations (~ 0.5%) are allowed. Apart from these materials being capable of withstanding high mechanical stress, soil compaction parameters are important as well. This group includes pipes made of glass fibre reinforced epoxy resins (duroplastics): GRP-EP, GRP-UP;
3) flexible pipes – for which relative deformation (< 5%) is allowed. These pipes "cooperate" with the soil and together they form a static system. These include pipes made of PVC-U, PE and PP, among others.

On the basis of the guidelines above, filament fibre composite pipes analysed in this work can be classified as belonging to the semi-rigid pipe group.

Determination on the pressure

When analysing the load distribution impacting both the plastic- and pipes made of traditional materials, it should be noted that it is not the same. Traditional (rigid) pipes are practically non-deformable, therefore the stress arising from the load concentrates in the upper and lower parts of the pipe. The resultant bending stresses in the walls are unfavourable from the perspective of the durability of the pipe.

When the plastic pipe is under load, the stress in the upper and lower part of the pipe decreases, while the lateral stress increases. The deforming pipe exerts pressure on the soil and causes passive earth pressure, which in turn reduces the bending stress within the pipe wall. The force with which the soil around the pipe is able to resist the pressure of the pipe depends on the size of the vertical load and the type of soil, as well as its compaction [5].

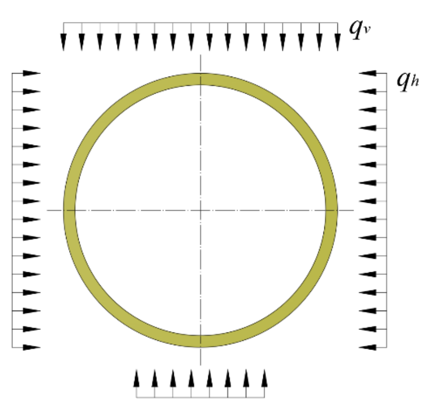

Fig. 2. Diagram of loads impacting the pipe embedded in the trench

Fig. 2. shows the distribution of pressures impacting the pipe embedded in the soil, assuming that the pipe is rigid or semi-rigid (relatively inelastic, e.g. a polyethylene pipe).

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According to the diagram, the following load components act on the pipe:

1) vertical earth pressure q_v:

$$q_v = p_v + p_t \, , \tag{3.1}$$

where:
p_v – dead load (soil load),
p_t – live load (traffic load);

Taking the theory of embankment for calculations, the formula for dead load assumes the following form:

$$p_v = \frac{5}{3}(\gamma \cdot H) \, , \tag{3.2}$$

where:
γ – unit weight of bedding material and initial backfill (for sand γ=19.5kN/m^3);
H – height of soil cover over top of pipe (acc. to Fig. 1.1, H=0.9 m),

therefore:

$$p_v = \frac{5}{3} \cdot 19.5 \cdot 0.9 = 29 kPa \tag{3.3}$$

Depending on the embedment depth, live load is calculated based on PN-85/S-10030 standard. Assuming that the embedment depth is 0.9 m, live load would equal the following:

$$p_t = 52 kPa \tag{3.4}$$

Therefore the total vertical earth pressure will equal:

$$q_v = 29 + 52 = 81 kPa \tag{3.5}$$

2) horizontal earth pressure q_h:

$$q_h = q_v \cdot K_0 \, , \tag{3.6}$$

where:
K_0 – coefficient of active earth pressure at rest.
horizontal earth pressure is calculated with K_0 equal 0.5,
Therefore:

$$q_h = 74 \cdot 0.5 = 37 kPa \, . \tag{3.7}$$

Manufacture of test samples

The test samples were manufactured out of three types of composite by using continuous filaments in the form of roving, wound on a suitable core. The exact properties of glass fibres [8], basalt fibres [9] and carbon fibres [10] are given in Table 1.

Epolam 5015 epoxy resin and AXSON Epolam 2016 hardener were used in the composite matrix. The properties of the cured resin are given in Table 2 [11].

The test samples were manufactured by winding the fibre strands around the core. A specially prepared core was mounted to the winder handle, on which fibre strands were being wound. The core had been constructed in such a way that it was possible to fabricate several samples as part of a single manufacturing process. The core was fitted with sliding steel rings which formed a plane of resistance for the manufactured samples. The fibre was unwound from a roving spool, and then supersaturated in a tub with liquid resin and then goes through a supersaturation system.

Table 1. Physical and mechanical parameters of fibres used

Property	**ER 3005 (Krosglass) fibreglass**	**BCF 13-1200-KV12 (Basfibre) Basalt fibre**	**UTS 5631 12K (TohoTenax) Carbon fibres**
Flexural modulus [GPa]	73	85	240
Tensile strength [MPa]	3400	2900	4800
Poisson ratio [–]	0.21	0.26	0.285
Elongation at break [%]	3.5	3.1	1.8
Density [g/cm^3]	2.55	2.75	1.79
Linear density [tex]	1200±7%	1200	800
Monofilament diameter [µm]	10÷15	13	6.9

Table 2. Properties of Epolam 5015 (Axson) resin

Property	**Value**
Flexural modulus [GPa]	2.9
Tensile strength [MPa]	73
Elongation at break [%]	7
Poisson ratio [–]	0.35
Hardness [Shore D15]	84
Mixing ratio [by weight]	32
Density at 25°C [g/cm3]	1.12÷1.16
Pot life (on 500 g) at 25°C [min.]	360÷450
Glass transition temperature [°C]	82
Brookfield viscosity at 25°C [mPa.s]	400÷500

Five rings were manufactured from each composite for the research purposes. The geometrical parameters of the samples taken are shown in Table 3, while Fig. 3 presents the samples prepared for testing.

Table 3. Geometric parameters of samples adopted for testing

No.	Sample material (composite)	Average wall thickness e [mm]	Sample width [mm]
1.	Epoxy/glass fibre (ES)	3.91	25
2.	Epoxy/basalt (EB)	3.90	25
3.	Epoxy/carbon (EW)	4.46	25

Fig. 3. Manufactured samples

The examination of the actual strength properties of the manufactured structures was conducted and included investigation of the fibre volume ratio in the entire composite, as the strength of the composite is mainly determined by the reinforcing fibres contained in it.

The determination of fibre volume ratio was done by analysing the content of the surface occupied by the fibres in relation to the entire surface of the structure in microscopic images, assuming that the fibres have a circular cross-section, they are packed in the matrix in a hexagonal lattice, and that the matrix and fibre reinforcement exhibit isotropic properties. The determination of fibre content was carried out via image analysis.

Fig. 4. shows examples of microscopic images of the composites analysed, while Table 4 provides a list of fibre volume ratios in individual structures.

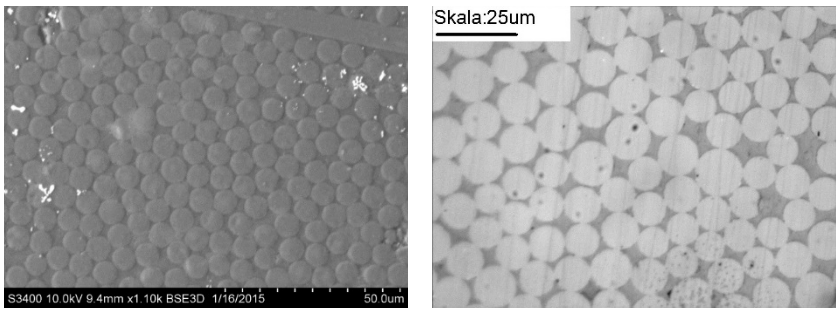

Fig. 4. Sample photos of the EW composite microstructure taken with magnification of 1100 (left) and ES composite taken with magnification of 1000 (right)

Table 4. Volume ratio of the reinforcing fibres within the manufactured composite

Composite type	**Fibre volume ratio [%]**	**Resin volume ratio [%]**	**Void volume ratio [%]**
Epoxy/glass fibre composite	65.5	23.6	10.9
Epoxy/basalt composite	63.9	22.3	13.8
Epoxy/carbon composite	61.9	25.8	12.3

Table 5. Effective strength properties of composites

Properties	**Epoxy/glass fibre composite**	**Epoxy/basalt composite**	**Epoxy/carbon composite**
E_1 [GPa]	48.8	55.4	149.7
$E_2 = E_3$ [GPa]	12.1	11.8	12.3
G_{12} [GPa]	4.5	4.3	4.4
G_{23} [GPa]	4.3	4.2	4.3
ν_{12} [–]	0.25	0.29	0.31
ν_{23} [–]	0.39	0.40	0.42

Then, knowing the strength properties of fibres and resin (Table 1 and Table 2), as well as the fibre volume ratio in the composite (Table 4), the effective strength properties of the composites were determined using the homogenization method. These properties are listed in Table 5. Eshelby's inclusion [3] was used for calculations, assuming that:

- the material consists of a matrix and reinforcing fibres;
- materials are homogeneous and linear elastic

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– the fibres have a circular cross-section and are evenly distributed;
– there are no voids or discontinuities in the composite.

Strength testing

Structural elements produced out of composite materials are subjected to rigorous strength and qualification tests. This approach is dictated on the one hand by the complexity of the material structure and, on the other hand, by high load values during operation. For determining strain and stress distributions in isotropic materials, analytical and numerical computational methods have been developed and are still developing rapidly. They are also used to elaborate models of anisotropic and orthotropic materials, however, reliable determination of the mechanical properties needed for these models is problematic and costly. Therefore, approval of any structures made of composited has to be preceded by thorough experimental testing, in accordance with the relevant directives and standards. Rigidity testing of flexible and rigid pipes analysed in this paper can also be carried out via analytical methods (according to the Scandinavian- and German methods, respectively), while semi-rigid pipes are tested experimentally according to DIN 53769.

Experimental tests are mainly aimed at determining the strength of the structures produced by experimental testing of pipe ring stiffness and ring deformations. Tests of the manufactured pipe samples were carried out on the basis of DIN 53769 standard, according to the diagram shown in Fig. 5.

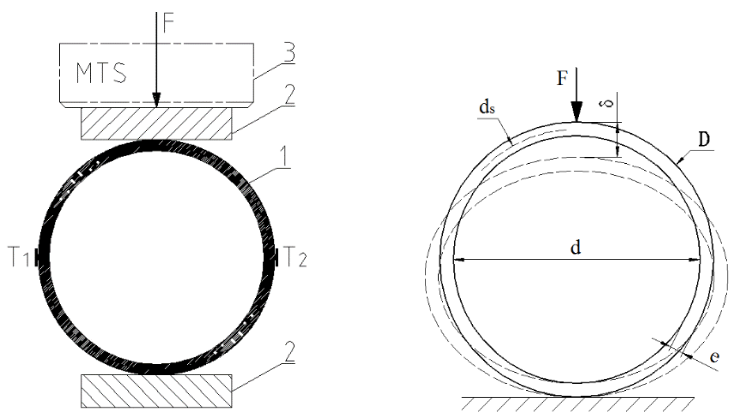

Fig. 5. Diagram of the rig for testing ring stiffness (left) and diagram of sample deformation after loading (right); 1 – tested sample, 2 –- support elements, 3 – universal testing machine crosshead, T1 and T2 – strain gauges

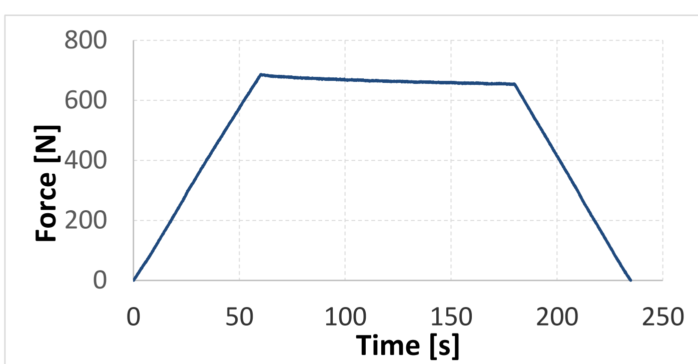

Fig. 6. An example of how to test a ring sample according to DIN 53769 standard

The test consists in selecting annular samples from a batch and subjecting them to such a linear load which, within one minute, would cause pipe deformation equal to 3% of its diameter (δ/D = 3%). After 2 minutes, during which a deformation is being maintained, the bending force and the deflection value are measured. The procedure is repeated twice. An example of the testing process is shown in Fig. 6.

Experimental determination of pipe ring stiffness. Test samples were made in the form of rings with an internal diameter of 113 mm and thicknesses given in Table 6, where average thicknesses were read from five samples from each material. Based on the known outside diameter, the required ring deflection was calculated during the tests.

Table 6. Geometric parameters of test samples

No.	Type of sample material (composite)	Average wall thickness e [mm]	Ugięcie próbki δ=0,03D [mm]
1.	ES	3.91	3.62
2.	EB	3.90	3.62
3.	EW	4.46	3.66

During the experiment, rings were placed successively between the universal testing machine supports and appropriate crosshead movement was directed. Fig. 7. presents a photograph from the EB composite ring compression test.

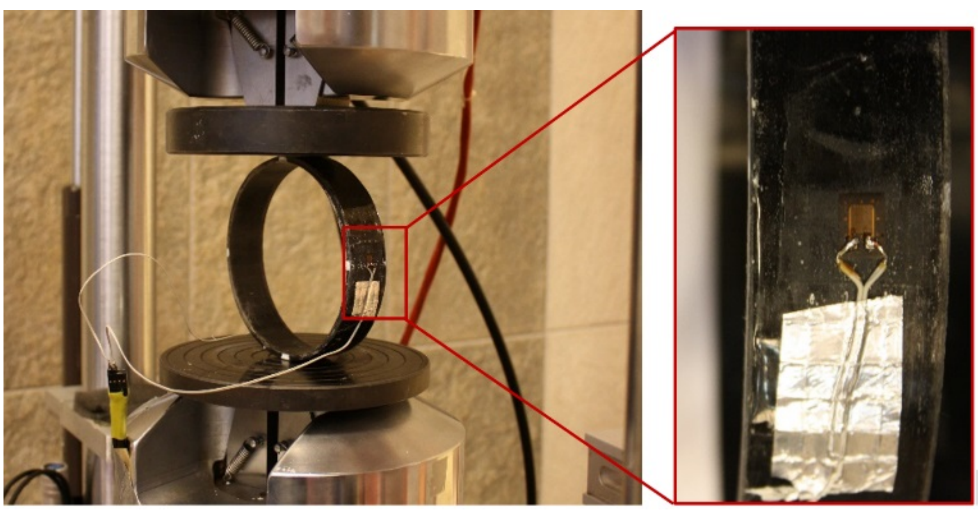

Fig. 7. An example of how to EB composite sample test is tested. Strain gauge is visible

The movement of the universal testing machine crosshead caused compression of the rings, while due to the rigidity of the rings which prevented its deformation of the support elements a reaction was set off, which was measured at each load test. Two measurements were made for each sample. Table 7 presents the test results for all the materials.

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Table 7. Results from ring stiffness tests for ES, EB and EW samples

	Measurement No.	ES composite	EB composite	EW composite
Reaction value F [N]	1	754.7	580.4	2049.8
	1.1	703.4	592.1	2081.3
	2	756.6	577.8	1772.0
	2.1	792.6	604.2	1588.8
	3	555.9	569.4	1791.4
	3.1	583.2	593.4	1821.7
	4	703.4	633.9	1557.2
	4.1	731.8	625.1	1414.9
	5	735.2	680.5	1747.9
	5.1	754.2	686.0	1760.4
	Average	**707.1**	**614.3**	**1758.5**
	Standard deviation	**77.4**	**41.6**	**206.0**
	Standard deviation [%]	**10.9**	**6.8**	**11.7**

Ring stiffness is defined as its resistance to peripheral deflection as a result of dividing the force acting on the sample by the length of the tested sample and the deflection [7].

$$S = \frac{F \cdot f}{l \cdot \delta} \tag{5.1}$$

where:
F – force [N],
l – sample length [m];
f – deflection coefficient of the pipe deformed as the result of its ovalization, as determined from the following formula:

$$f = 10^{-5}\left(1860 + 2500\frac{\delta}{d_s}\right) \tag{5.2}$$

From the data obtained and summarized in Table 5.2, and on the basis of dependence 5.1, ring stiffness of the manufactured pipes was determined and summarized in Table 8.

Table 8. Experimentally determined ring stiffness of manufactured samples

No.	Pipe material	Reaction force **F** [N]	External diam. of the pipe **D** [m]	Pipe length **l** [m]	Ring stiffness **S** [N/m^2]
1.	ES	707.1	120.82	0.025	6 194
2.	EB	614.3	120.80	0.025	5 381
3.	EW	1758.5	121.92	0.025	15 329

The analysis of the obtained results reveals that for samples manufactured of differing materials but with similar ring wall thickness, different reaction values were obtained, which is obviously related to the strength properties of the materials from which the samples were fabricated.

Experimental determination of pipe ring stiffness. During the ring stiffness test, deformation measurements were also taken for each ring at two points on opposite sides of the ring (Fig. 6). The graph (Fig. 8) shows an example distribution of strain values for a sample from ES composite at a full load cycle.

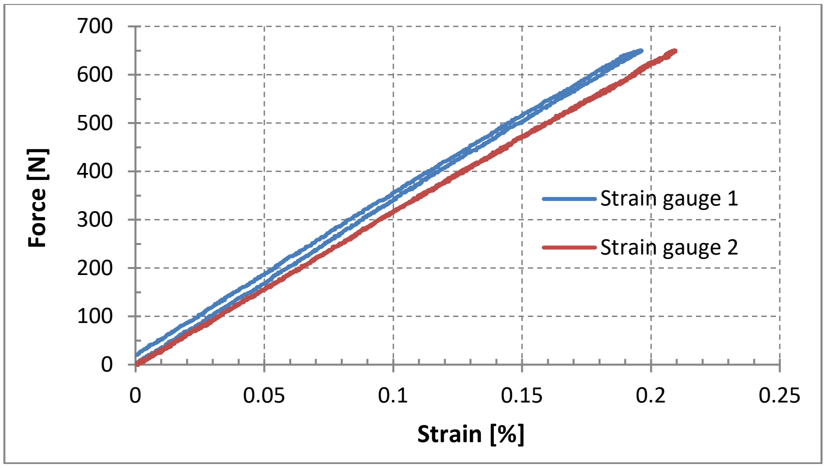

Fig. 8. Distribution of ring deformation values for a ring made out of ES composite

The measured maximum values of ring deformations from the measurements taken are summarized in Table 9. The mean value and standard deviation were also determined, which provides the opportunity to compare the results obtained for different materials quickly.

Table 9. Ring deformation results for a rings made out of ES, EB and EW composites

	Measurement No.	**Composite ES**		**Composite EB**		**Composite EW**	
		T1	**T2**	**T1**	**T2**	**T1**	**T2**
Deformation ε [‰]	1.0	1.82	1.61	1.93	1.97	2.27	2.64
	1.1	1.88	1.68	1.98	2.01	2.31	2.68
	2.0	2.12	1.63	1.86	1.89	2.04	2.10
	2.1	2.25	1.75	1.98	2.01	1.96	1.99
	3.0	1.74	1.51	1.92	1.99	2.06	2.26
	3.1	1.85	1.61	2.01	2.08	2.10	2.30
	4.0	1.96	2.09	1.96	2.14	1.84	1.63
	4.1	2.07	2.22	1.97	2.13	1.89	1.56
	5.0	2.18	2.12	2.08	2,23	2,04	1,75
	5.1	2.22	2.16	2.09	2,25	2,07	1,78
	Average	**1.92**		**2.02**		**2.06**	
	Standard deviation	**0.24 (12.7%)**		**0.11 (5.2%)**		**0.29 (14.2%)**	

Comparing the results of the tests carried out with the assumptions regarding the design of this type of objects, which determine the maximum peripheral deformation to be at the level of 0.5% (5 ‰), the results presented in Table 5.4 indicate values almost 2.5 times smaller. The analysis of the obtained values points to the fact that the smallest dispersion of the results is characteristic of basalt fibres. It can be noted that composites made from carbon fibres, which exceed the

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strength properties of both the glass- and basalt fibres by almost three times, exhibited a similar level of ring deformation.

Application of the test results

The pipe embedded in the ground works under conditions of internal load, due to gas pressure (e.g. CNG), and external load, resulting from soil pressure and road traffic. An extremely unfavourable situation occurs when the pipe is temporarily exposed to only one of the loads listed (e.g. when testing the pressure of the pipe on the surface or when laying the pipeline without introducing operating pressure or during maintenance works). For some comparison, Table 10 presents maximum allowable loads relative to the weight and price for 1 m of pipe from materials analysed in the paper.

Table 10. Calculation results for manufactured pipes

	Composite ES	Composite EB	Composite EW
Internal diameter d [mm]	113	113	113
Wall thickness e [mm]	3.91	3.90	4.46
Tensile strength R_m [MPa]*	2244	1879	2990
Safety factor n [–]**	3.65	3.65	2.35
Allowable stress R_m/n [MPa]	615	514	1272
Young modulus E_1 and E_2[GPa]	48.8 12.1	55.4 11.8	149.7 12.3
Density [kg/m3]	1944	2016	1407
Maximum internal pressure p_0 [bar]***	440	368	910
Traffic load per axis [kN]	~150	~130	~370
Min. embedment depth [m]	0.5	0.5	0.5
Mass/1m [kg]	2.85	2.95	2.36
Price/1m [zł]	~40	~50	~134

*determined basing on mixture theory;
**item [1];
***calculated basing on Lamé's equation

Summary

1. For all composites, the packing of fibres in the matrix is at a high level; the values of 66% for ES, 64% for EB and 62% for ES are almost limit values (e.g. the highest tensile strength for ES oscillates at about 72% fibre content in the composite).
2. Due to the high fibre content in the composites and their unidirectional arrangement in the matrix, high strength parameters of the structures produced were obtained.
3. Tests of the ring stiffness of the obtained structures prove that circumferential winding positively the said value positively. Typical composite pipes exhibit ring stiffness of 5 ÷ 10 kN /m^2. The results within the range of of 5.4 ÷ 15.3 kN/m^2 were obtained.
4. Comparing the results of the strength tests carried out with the assumptions regarding the design of semi-rigid pipes, which determine the maximum ring deformation at the level of 0.5%, the values were almost 2.5 times smaller.

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