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Comparative tests of the wall thickness effect of a glass-reinforced thermosetting plastic coating with a non-circular cross section in a soil-coating object for economic aspect

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ABSTRACT

Culvert structures made of plastics are employed extensively in the construction of new facilities as well as the renovation of existing ones. Due to the high costs of materials required for the manufacturing of these goods, the objective of this research is focused to lessen the thickness of the walls, which may, on the other hand, result in a reduction in the stiffness of the system. In the course of the testing, the structure was subjected to both vertical and horizontal displacements, and wall deformations were measured in both the central portion of the section and at the junction. The results of the tests were assessed to determine whether or not the reduction in wall thickness had an effect on the amount of deformation that occurred in the structure's internal cross-section as well as the wall stresses. GRP pipes with reduced (optimized) wall thickness can withstand comparable loads to the ones with thicker walls, which opens up consideration about possible application of such products for sustainable development of circular economy.

Keywords: Glass reinforcement polyester; Culverts; Flexible structures; Model tests; Road loads

1. Introduction

Plastics are utilized for the building of culverts and animal passages in both the construction of new facilities and the reinforcement of existing structures (made of concrete, bricks or steel sheets). Plastic goods are distinguished by superior chemical resistance, tightness and flexibility of both the components themselves and the connections between the parts, allowing for their usage in mining-damaged areas, among other places. Due to the comparatively low rigidity of plastic components, things made from them are viewed as vulnerable soil-shell structures. Positive soil hardening and the transfer of external loads to the ground near to the plastic covering element are phenomena observed [1,2]. When using glass-reinforced thermosetting plastics (GRP), the structure may exhibit intermediate characteristics between flexible and stiff constructions [3].

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Due to production techniques, the diameter or span of GRP building elements typically does not exceed 4,000 mm. To lower production costs and facilitate and speed up structure assembly, the goal is to reduce the weight of the employed materials as much as feasible. In thermoplastic constructions, structural walls incorporate ribs, notches, or gaps that decrease material consumption while preserving the needed wall rigidity. The production process of GRP components restricts the ability to create geometrical wall cross-section constructions. Nonetheless, it offers a vast array of options for modifying the thickness of the entire wall as well as the thickness and qualities of specific wall layers by, among other things, changing the quantity and structure of glass fibres, resin, fillers, and other components. The thinner wall decreases manufacturing costs, while the more accessible architecture reduces the environmental effect of production, transportation, and assembly. However, the lowering of wall thickness and stiffness generates valid issues regarding the load-bearing capacity and longevity of the structure, as well as the fulfilment of operating criteria, such as the structure's allowable deflections and the maintenance of joint tightness.

The difficulty of lowering wall thickness and stiffness in GRP pipes having a circular cross-section is well understood. The standards [4–6] give test procedures for determining the strength characteristics of items subjected to both short- and long-term loading, extrapolated using calculations up to many decades. Due of the more complicated stress distribution at different cross-sectional positions, non-circular GRP pipes demand a more thorough investigation. The standard [7] on GRP pipes with non-circular cross-section provides methods for determining and checking short-term and long-term bending strength and modulus of elasticity in bending, as well as analysing the behaviour of the structure subjected to variable loads typical of areas exposed to loads from the movement of wheeled vehicles. At the Road and Bridge Research Institute – Wroclaw Branch, full-scale model tests, including the barrier's construction with a culvert and a load-distributing structure according to [8] and strength testing under cyclical variable load, were conducted.

2. Thermoset composite pipes

A composite material is created by combining two or more components at the microscopic level to form a new material with varied characteristics. The resulting substance is homogenous, meaning that its constituents cannot be identified with the naked eye. Composites combine and increase the benefits of the materials used to create them; they may also exhibit new characteristics not seen in the original materials. In the process of creating a composite, the following material properties are improved [9]: resilience; stiffness: corrosion resistance: abrasion resistance; material life; thermal isolation; thermal conductivity; soundproofing. Not all of these properties are continuously enhanced to produce a new composite. Some of these cannot even coexist; for instance, a substance with high thermal conductivity cannot act as an insulator. The initial specifications of the composite are mostly determined by its intended use. Therefore, just a subset of the mentioned properties is necessary for the composite to fulfil the design assumptions for a particular industry sector [9].

Pipes constructed of thermosetting polymers – composite pipes consisting of polyester resins reinforced with glass fibre and thermoplastic – polyvinyl chloride (PVC), polypropylene (PP), polyethylene (PE) – began to acquire prominence on the pipe market in the latter decades of the 20th century. Moreover, thermosetting polymers are distinguished by much greater strength characteristics and greater durability. Thermosetting plastics, sometimes known as thermosets, cannot be reformed, unlike thermoplastics.

Due to the option of applying continuous glass fibre reinforcing in the circumferential direction, the winding method enables the manufacturing of stronger pipes at a reduced cost, which is particularly significant in the case of high-pressure pipes. The axial strength of the glass fibre that has been cut is sufficient. Simultaneously, the addition of quartz sand to the construction of both technologies' pipes increases their stiffness by increasing the wall thickness in the region of the pipe's neutral axis of cross-section. In addition, unique resin spouts are employed in the inner layer of the pipe during the manufacturing process, which gives the pipe great corrosion resistance. Various kinds of polyester, isophthalic, and vinyl ester resins available on the market permit the optimization of the pipe structure, providing the product with chemical resistance in the pH 1–14 range and resistance to high temperatures, depending on the requirements.

Features of composite pipes:

- corrosion resistance,
- low operating costs, without the need for anti-corrosion protection,
- constant hydraulic properties, very smooth interior,
- low weight,
- high abrasion resistance,
- high flexibility for easy installation also in sewer renovation,
- resistance to water hammer.

GRP constituent materials:

- continuous glass fibre, shown in Fig. 1,
- chopped glass fibre, shown in Fig. 2,
- additives (quartz sand, calcium carbonate, etc.), shown in Fig. 3,
- thermoset resins (polyester, vinyl ester).

Characteristic features of winding tubes produced on the mould (Fig. 5):

- rotary-sliding mould, the materials are used externally,
- glass fibre of the continuous type (Fig. 4) is fed in the circumferential direction (axial glass tape),

Fig. 1. Continuous fiberglass [10].

Fig. 2. Chopped fiberglass [10].

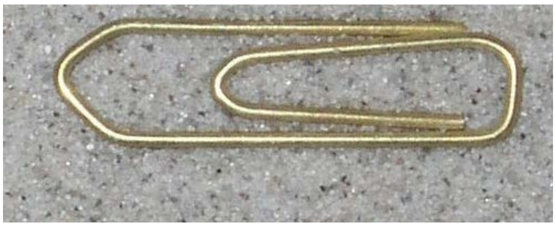

Fig. 3. Additives (quartz sand) [10].

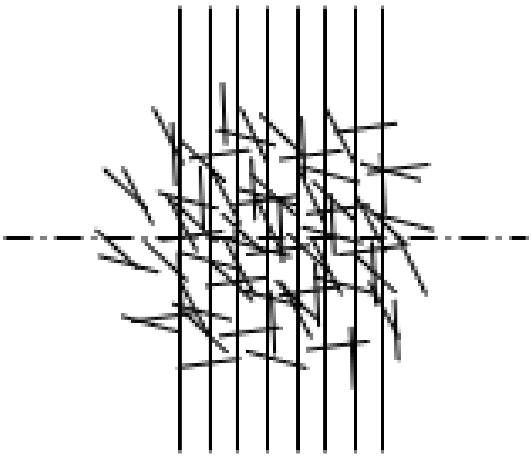

Fig. 4. Arrangement of the glass reinforcement in the tube structure on the mould [10].

- resin, chopped fibreglass and filler (sand) are added.

Advantages:

- production process of tubular profiles of any shape (Fig. 6),
- high mechanical properties,
- available diameters up to 4,000 mm,
- a wide range of performance is possible.

Disadvantages:

- low production efficiency,
- the length of the mould limits piped.

3. Characteristics of GRP pipes with a non-circular cross-section

GRP (glass reinforcement polyester), FRP (fibre reinforced plastic) and in Poland, also known as GRP (glass reinforced plastic), is a composite material whose matrix is

Fig. 5. A typical production system for pipes forming on a mould [10].

Fig. 6. Production technology of non-circular profiles made of GRP material [10].

a polymer matrix reinforced most often with glass, carbon, basalt or aramid fibres [11]. The production is based on the winding technology, where successive layers of a composite composed of glass fibres, quartz sand and polyester resin are placed on the rotating mould (Fig. 7).

The walls of a non-circular profile made of GRP material are designed as sandwich structures with different functions of the individual layers (Fig. 8). The e_5 outer layer ensures high environmental resistance to UV radiation, weather conditions, and mechanical damage (e.g., scratches). Protects the outer layer rich in e_4 glass fibres. The thickness of the outer protective layer is at least 0.5 mm and prevents degradation of the pipe's structural integrity. The outer and inner reinforced layers e_4 and e_2 are designed to withstand the axial and hoop stresses caused by external loads (soil, groundwater, traffic, etc.) after installing the pipeline. These layers are made by winding the fibres and chopping glass fibres. Due to the high strength of glass fibres (~1,500 MPa, that is, about four times the strength of steel), the number and position of glass fibres determine the mechanical strength of the composite. The e_3 core layer consists mainly of quartz sand, glass fibre and thermosetting resin. It contributes to the specific pipe stiffness and high compressive strength, thus forming a typical sandwich composite. The inner protective layer e_1, with a thickness of at least 0.8 mm, consists of a resin resistant to an aggressive environment while creating a smooth, glossy surface with excellent hydraulic properties and chemical resistance. Between the inner protective layer e_1 and the inner high glass fibre e_2, there is a barrier layer consisting of chopped glass fibres with a limited amount of quartz sand for better bonding between the layers.

Fig. 7. Process of applying glass fibre to a non-circular profile [10].

Non-circular pipes made of GRP material can be used both to renovate old culverts and implement new installations in open trenches (Fig. 9). This technology provides excellent hydromechanical properties of the trenches, with practically any dimensions of the cross-section (from 300 to 4,000 mm).

The basic mechanical parameters of GRP pipes with a non-circular profile include [12,13]:

- Modulus of elasticity for short-term loads: 9,500–13,500 MPa,
- Modulus of elasticity for long-term loads: 6,000–8,500 MPa,
- Bending strength for short-term loads: 200–250 MPa,
- Bending strength for long-term loads: 125–160 MPa,
- Abrasion according to the Darmstadt test: less than 0.25 mm after 100,000 cycles,
- Linear expansion coefficient: 30 × 10^{-6} 1/K,
- Poisson's ratio: 0.3.

Long-term research plays a vital role in the design of road culverts.

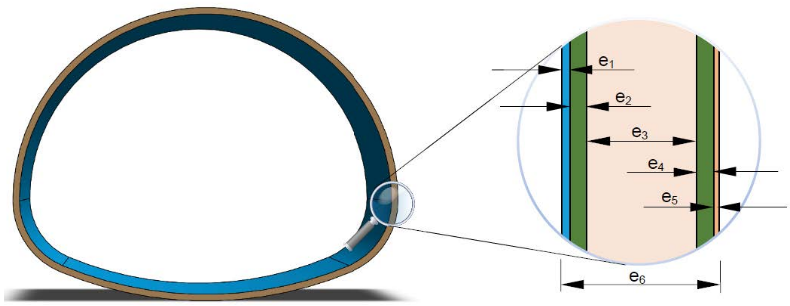

Fig. 8. Structural layers of the wall GRP pipe with a non-circular profile; e_1 – inner layer – liner; e_2 – inner reinforcing layer; e_3 – core; e_4 – outer reinforcing layer; e_5 – outer protective layer; e_6 – total thickness of the wall [10].

Fig. 9. GRP road culvert with a non-circular profile, dimensions 3000/2250 on the S6 road Szemud – Gdynia, Wielki Kack, Poland [10].

4. Long-term research

Long-term tests are designed to determine:

- the most essential standard requirements for products,
- long-term preservation of the pipe parameters,
- product design parameters.

Common to all long-term tests:

- Development of test data in 10,000 h with a minimum of 18 data points,
- Extrapolating the data to 50-y design durability through logarithmic regression analysis using the least-squares method,
- Applying safety factors up to 50-y to establish acceptable design values.

5. Comparative tests of a soil-shell structure made of GRP material with a non-circular profile

Two non-circular ground-shell structures with identical cross-sectional shapes and dimensions but different wall thicknesses: a bell profile of DN3000/2400 with a nominal span of 3,000 mm, height 2,400 mm, and a standard wall thickness of 45 mm GRP composite, and a bell-shaped profile with a reduced wall thickness of 35 mm GRP composite [15]. The tests were carried out at the "STEND" Stand for Dynamic and Fatigue Testing, located at the Research Institute of Roads and Bridges, Wrocław. This stand comprises a reinforced concrete foundation 80.0 m long and 12.0 m wide with a hall and a steel frame constituting a retaining structure for hydraulic load-exerting devices. The stand is equipped with a SCHENCK hydraulic actuator system with measuring systems and a control and power system. The equipment enables carrying out strength tests under variable loads of any waveforms (e.g., in a sinusoidal, trapezoidal cycle, etc.) and recording the behaviour of the tested elements using a system of displacement transducers, force transducers, strain gauges and other sensors.

The tested buildings were constructed on a test stand in accordance with existing legislation and standards for communication construction and construction job execution [14,16]. Under the GRP composite profiles, a 0.50 m thick construction dirt base was utilised. The buried soil was alternatively compacted in layers on both sides, with the desired minimum soil compaction index Is = 0.98 for the foundation, backfill, and bedding layer [16] (Fig. 11).

The loads were transferred using a system of two synchronized hydraulic actuators through the structure according to the scheme "Load Model 1" [8] (Fig. 10). For tests under variable load, the following load values were adopted according to [8]:

- Rolling stock traffic load – per axis Q_{ik} = 300 kN,
- Uniformly distributed load q_{ik} = 9 kN/m^2.

Variable loads were realized using two synchronized hydraulic cylinders of the STEND stand. A sinusoidal shape of the load change cycle with the frequency f = 1 Hz was applied, performing 500,000 load/unload cycles.

To measure the displacement of the GRP profile, three inductive displacement transducers with a measuring range of ±50 mm were used, mounted in one of the two planes of the load action. To record deformations in the load plane, 18 essential electrofusion strain gauges were installed, which allowed the measurement of the circumferential deformation ε. Measurements were carried out at the stage

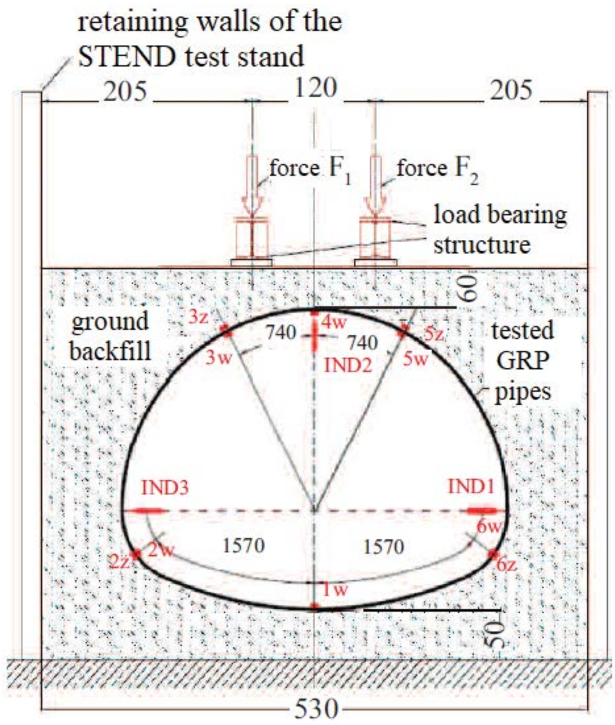

Fig. 10. Diagram of the test stand with built-in structure.

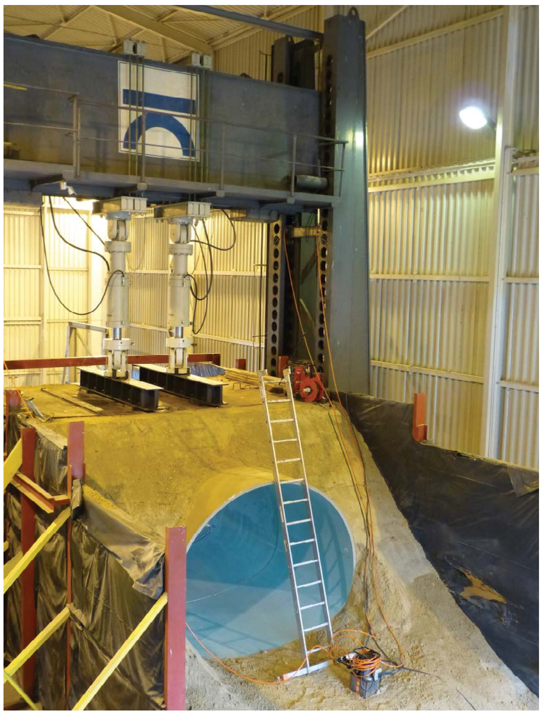

Fig. 11. A built-in model with structure transmitting the load.

of embedding the soil, backfill and bedding, assembly of the load-bearing structure, and testing under variable loads.

6. Impact of wall thickness on the deformation of a composite structure during the phase of model construction

During the phase of model construction, the deformation of the shell structure is greatly influenced by the quality of the earthworks performed, specifically the proper compaction of the soil in the lower grooves and adherence to the recommendations for alternate laying and compaction of the backfill. Errors committed at this step can lead to permanent distortion of the soil-shell structure profile and, in severe situations, exceed the allowable deflection and deformation.

In the comparison experiments, same circumstances of soil placement and compaction, as well as identical soil and construction equipment, were utilised. Fig. 12 depicts the backfill construction phase deflections of the GRP composite structure.

The greatest displacements of a profile built of GRP composite with a wall thickness of 45 mm occur at the last stage of construction, that is, following the assembly of a structure mimicking permanent loads from the road surface. After laying and compacting the soil layers to a height of about 88% of the nominal thickness of the GRP composite covering, the greatest displacements were observed in a profile with a wall thickness of 35 mm. In contrast, as the model building progressed, particularly during the laying of the bedding, the displacements levelled out and eventually achieved lower values than in the case of a profile with a 45 mm wall thickness. However, these phenomena can take several shapes, depending on the structure's shape and size.

During the model construction phase, data from electrofusion strain gauges for both profile wall thicknesses did not indicate that the permitted specified deformation in the GRP composite was exceeded. The deformations of the GRP material during the backfill building phase are often many times lower than those that occur during the loading phase of the model.

7. Effect of wall thickness on displacement and deformation of a model composite structure under load

In both studied constructions, the most substantial increases in deflection and deformation occur after about 10,000 cycles, mostly as a result of compaction of the soil and compensation for local gaps in the structure (e.g., in the area of joints with an elastomeric gasket). With varying weights, the logarithmic deflection diagram approaches a linear one. A structure with a wall thickness of 45 mm has a greater vertical deflection after 500,000 cycles than a building with a wall thickness of 35 mm (difference in vertical deflection by 7.3 mm). However, the tendency of rising displacement is more pronounced in the model with a wall thickness of 35 mm. As anticipated, the greatest deformations of the GRP material of the structure were recorded at the measurement spots placed at the extreme extremities of the structure – at the top and at locations with the greatest profile curve curvature (points 4w, 2w and 6w, respectively, in case (a) and (b) depicted in Fig. 13). Despite the substantial variation in wall thickness between the two tested constructions, the deformation values measured by strain gauges at the proper measurement points are comparable.

In addition, strain gauge measurements were taken in the area of the tongue-and-groove junction sealed with

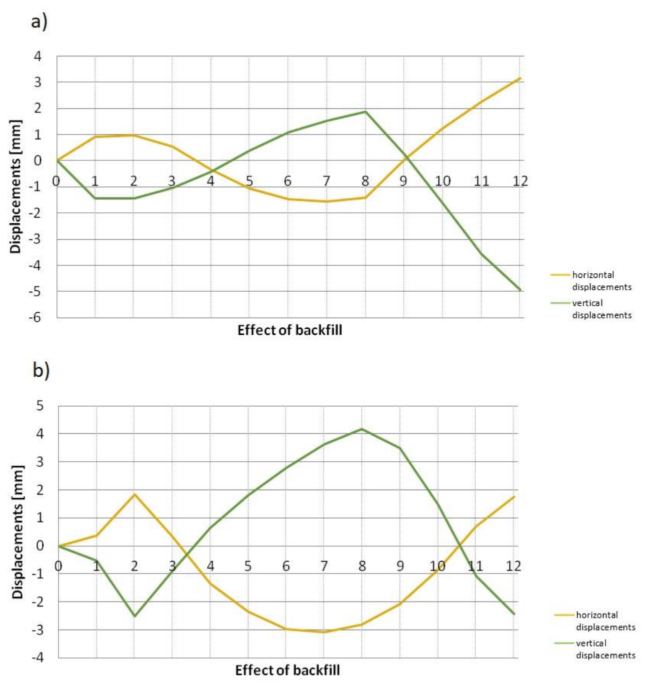

Fig. 12. Displacements of a profile made of GRP composite with a wall thickness of: (a) 45 mm and (b) 35 mm during the incorporation of the backfill.

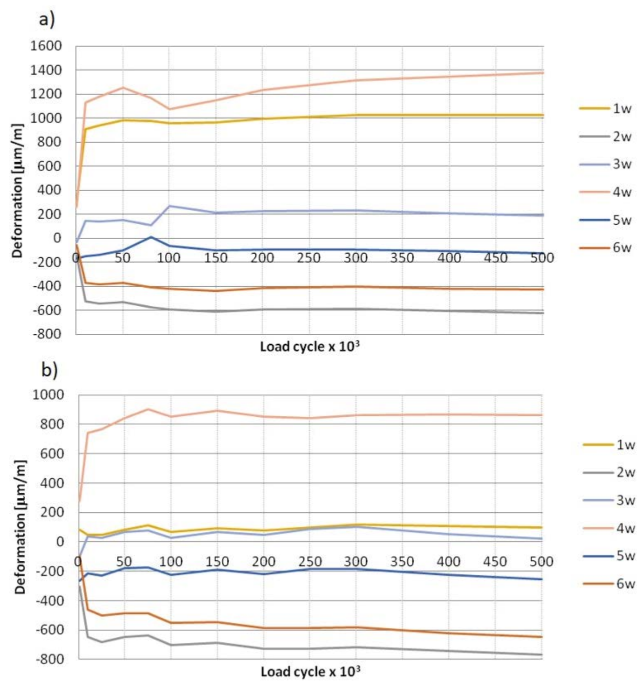

Fig. 13. Deformation of the GRP material (outer layer e_5) of a profile with a wall thickness of: (a) 45 mm and (b) 35 mm during tests under variable load.

a wedge rubber gasket. They are more substantial than the deformations observed in the area of solid wall (in the middle of the structure panel length). At no measurement point was the exceeding of the material's permitted design deformation documented.

8. Possibilities of application of pipes with reduced wall thickness for sustainable development of circular economy

The conducted tests indicate that reduction in wall thickness of pipes doesn't change substantially their mechanical strength parameters. GRP pipes with reduced (optimized) wall thickness can withstand comparable loads to the ones with thicker walls, which opens up consideration about possible application of such products for sustainable development of circular economy.

The main reason would be the reduced weight of every pipe panel as a direct consequence of reduced wall thickness. The reduction in weight would have direct effect not only on the amounts of raw materials used in the production of such pipes but also costs of transportation from a factory to the construction site.

Those advantages exist on top of the fact that GRP pipes in general are very lightweight – more so than pipes made of any other, traditional materials. The other very important factor is their long service life which using methods such as regression analysis can be estimated for at least 50-y – which translates to smaller odds of pipeline failure and in turn smaller overall amounts of raw material used for replacements in case of pipeline system failure, as well as possible of some materials structure part recycling for sustainable development of circular economy.

9. Findings of the results and discussion

One of the main advantages of plastics, such as GRP, is their high chemical resistance. This allows for effective corrosion prevention, which is particularly important in the case of structures intended for use in aggressive environments, for example along roads or highways. Studies show that GRP retains its chemical properties for a long time, which contributes to the long-term durability of the structure.

According to this research the application of a thinner wall thickness of GRP pipes has the potential not only to bring advantages related to gain economic benefits because of lower production costs as well as easier installation and reduced environmental impact. However, it is also important to understand the effect of this reduction on the load capacity, durability, deflections and tightness of joints in the GRP pipes. Further research and numerical analyzes should be performed to evaluate the limiting parameters of the reduced number of raw materials used in the production of pipes with the lower wall thicknesses.

Nowadays pipes made of thermosetting plastics, such as polyester resins (e.g., GRP), are gaining more and more popularity in infrastructure construction. The structure of the pipes shows better strength parameters and durability compared to other materials such as thermoplastics. There are many methods of producing composite pipes, such as winding and centrifugal casting, which offer different benefits depending on the type of system application (waterways, sewage systems etc.). Further research should focus on assessing the mechanical properties of these pipes and optimizing production processes in the development of GRP.

In addition to circular cross-section GRP pipes, it is also possible to produce different type such as non-circular GRP pipes based on advanced production technology, which requires winding layers of a composite of glass fibers, quartz sand and polyester resin. In these circumstances according to the technology, the creation of profiled pipes might be adapted to specific design requirements. However, additional studies should be carried out on the effect of cross-sectional shape on the strength, stability and structural behavior of these specific GRP pipes.

In summary, the scientific discussion on the use of plastics in the construction of culverts and animal crossings made of GRP pipes focuses on important aspects such as chemical resistance, wall thickness reduction, composite pipes and pipes with a non-circular cross-section. Further research, laboratory tests and numerical analyzes are necessary to fully understand and optimally use these materials in economical aspect and engineering practice.

10. Conclusions

In this article, comparative testing of culverts manufactured of GRP were shown. These culverts were constructed in natural settings and tested with a system of forces that simulated traffic loads using the "Load Model 1". Analyses were performed on two constructions, both of which had bell profiles with DN3000/2400, but the standard wall thickness was 45 mm and the reduced wall thickness was 35 mm. The analysis of the test results indicates that it is permissible to reduce the thickness of the walls of the soil-shell structures without a significant impact on the structure's stability and durability, provided that a thorough calculation and design analysis has been performed beforehand, taking into account, among other factors, the desired size and shape of the structure resulting from the conditions to be met by the installation, the amount of soil load, the type of traffic, and the location of the structure. After identifying the shape and dimensions of a non-circular profile and possessing the aforementioned factors, we can begin calculating the necessary wall thickness. To achieve the high precision of computations, the finite element approach should produce the most accurate results. The computations are made while taking both short-term and long-term demands into consideration. In the case of optimum ground-shell constructions built of GRP material with a non-circular profile, it is crucial to perform earthworks correctly, focusing on compaction of the soil in vulnerable areas, and to prevent excessive deformation of the structure during soil inclusion.

The production is based on the winding technology, where successive layers of a composite composed of glass fibres, quartz sand and polyester resin are placed on the rotating mould, so less wall thickness of GRP pipe which was reduced 10 mm in comparison to standard product give a lot of economical savings not only in materials aspects but also in energy demand during production and transportation to building site as weight is less. GRP pipes with reduced (optimized) wall thickness can withstand comparable loads to the ones with thicker walls, which opens up consideration about possible application of such products for sustainable development of circular economy, as many of energy and materials using in production process might be saved, as well as composition is mostly natural and could also be reuse again in future not as a particular waste but full-fledged product for recycling.

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