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Modern concrete pipes: a review of reinforcement and new technologies

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Abstract: The paper discusses existing reinforcement, future reinforcement and new technologies for concrete pipes used in the sewage systems. Concrete pipes currently in use and under investigation are reviewed. Structural fibres, as the main reinforcement of concrete pipes, are known as an attractive alternative to the traditional steel bars. Steel, synthetic and basalt fibres have been considered. The latest research and mechanical properties of individual fibres are presented. Advances in fibre-reinforced concrete provide a new basis for the design of more efficient concrete pipes, especially those resistant to biological corrosion and with a longer service life. In the article, future non-corrosive reinforcement due to the reduction of steel reinforcement and corrosion protection linings has been proposed.

Keywords: concrete pipe; underground structures; fibre; reinforcement.

1 Introduction

Sewer lines are constructed from a variety of materials. The earliest sewer lines were constructed of brick, natural stone and stoneware. New underground constructions are unlikely to be built of brick and natural stone anymore, but many of the most important brick sewer constructions are still in place in towns and cities. Modern sewage systems were developed in the late 19th century. The sewers created then are still durable today.

Contemporary construction materials used for the construction of underground urban network infrastructure are very different (Madryas 2007b). Concrete is the dominant material for producing pipes used in storm sewer systems and other applications, especially for sewer pipes with large cross sections. Concrete pipes with a plastic liner are also commercially available. Polymer concrete is also used for sewer pipelines. Polymer concrete consists of sand, gravel and a binder which is usually a polyester resin.

Conducting research on new products, in which construction parameters are modified and various types of fibres are used, is aimed at increasing the resistance of concrete pipes to biological corrosion and increasing their durability.

2 Characteristics of concrete pipes

The selection of material for the construction of sewerage networks should take into account local ground conditions, the impact of sewage and the properties of the material in order to achieve the durability of the sewerage networks (Table 1) Durability is a measure of how well a pipeline remains functional under specified operating conditions. A threat to the durability of sewer lines from the external side is the corrosive action of groundwater and soil and the impact of soil contaminants. There are more significant threats on the inside: corrosive effects of wastewater, abrasion and cavitation. Domestic sewage poses no threat to concrete. Before designing sewers, the composition of the wastewater and other processes that may occur in the sewer should be analysed. Too low a sewer slope causes sediment to form at the bottom of the sewer line and prevents the sewer from self-cleaning because the flow velocity is too low. Organic sediments are carried on the wastewater mirror and bind permanently to the walls of the pipe (Figure 1).

The accumulated sludge ferments, resulting in the release of large amounts of hydrogen sulphide, which settles on the upper surface of the canal and, as a result of the life processes of *Thiobacillus* bacteria, is transformed into sulphuric acid, which causes corrosion of cement-based materials. This type of corrosion is referred to as biological corrosion.

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$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \bullet 2H_2O \quad (1)$$

In the above reaction, sulphuric acid reacts with calcium hydroxide, which is a component of concrete. Reaction (1) produces gypsum, which increases in volume. Gypsum fills the pores in concrete because concrete is a porous material. This is followed by concrete bursting.

The greatest damage to concrete sewers, therefore, occurs at the top of the pipe section, where there is no contact with the sewage. The cement used in the manufacture of concrete sewer pipes should be resistant to sulphate. The tricalcium aluminate (C_3A) content of the cement is particularly important. It is assumed that cement with a C_3A content of less than 8% has an average resistance to sulphate corrosion and with a content of less than 3% has a high resistance. Concrete on sulphate-resistant cement also has higher tightness. The use of metallurgical cements increases resistance to sulphate corrosion and improves tightness. The use of limestone aggregate also improves the resistance of concrete to sulphate corrosion (Madryas et al. 2002).

Concrete pipes are commonly used in sewerage systems (Figure 2). The threat of biological sulphate corrosion is sporadic, but if there is a risk of this occurring, concrete pipes with a plastic liner can be used.

Usually, pipes are produced in vertical moulds, but some manufacturers use horizontal moulds. A detailed concrete formulation ensures the quality of the concrete pipes. The concrete mixture with the appropriate w/c ratio is delivered to the mould from above. With an adjustable central vibrator, compaction is performed, and then the spigot end is shaped. The finished pipe matures at the appropriate temperature and humidity. Once the concrete has reached the minimum compressive strength (40% of the 28-day strength), the pipes are demoulded.

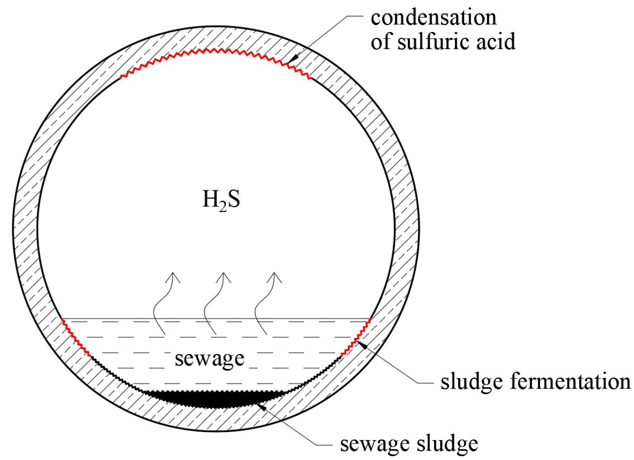

Figure 1: Concrete corrosion mechanism

Table 1: Advantages and disadvantages of concrete pipes.

Concrete pipes	
Advantages	**Disadvantages**
Adaptable to a wide range of loads, design pipes of any load capacity	High pipe weight making installation difficult
The possibility of practically any shaping of the cross-section	Short pipe sections which extend the assembly time
Large range of pipe diameters up to 3600 mm	No resistance to corrosive environments with pH less than 4. 0
	Higher wall roughness than other materials

3 Reinforced concrete pipe

Reinforced concrete pipe (RCP) is the most popular type of structural concrete pipes. RCPs, made of reinforced concrete, are provided with steel bar reinforcement in places where tensile stresses exceed the low strength of concrete for this type of load (Szruba 2017). Nevertheless, design errors, unexpected thrust magnitudes, higher eccentricities, challenging geological conditions and assembly errors, make the pipe prone to cracking. Producing the cage form of the traditional reinforcement bars is time consuming and requires special bending, welding and placement machinery. Reinforced concrete limitations as limited tensile strength of the material cause that the width of cracks can be higher during operation because of the changing loads in time.

The durability of an RCP is equivalent to the durability of the reinforcement. The end of the service life or the need for repair is determined by corrosion of the reinforcement. Due to the loss of concrete cover, the corrosion rate of the reinforcement is very fast.

4 Fibre-reinforced concrete pipes – new designing trends

Fibres improve the physical and rheological parameters of concrete. The use of fibres for concrete reduces the effects of shrinkage caused by the hardening concrete. When fibres are added, the properties of the hardened concrete change. The use of fibres as concrete reinforcement is an alternative to conventional RCPs because it is an effective way for controlling cracks to improve durability and

Figure 2: Concrete pipe on a construction site.

Table 2: Mechanical property of fibers (Sim et al. 2005, Kizilkanat et al. 2015, Karwowska et al. 2011, Deng et al. 2021a).

	Basalt	Polypropylene	Steel
Tensile strength (MPa)	992.4 - 4800	706	550-1100
Elastic moduls (MPa)	95 000 – 115 000	7400	190 000 - 210 000
Corrosion resistance	+	+	-
Adhesion to concrete	Very good	Poor	Very good
Density (kg/m^3)	1700 - 2750	950	7800

serviceability of pipes (Abolmaali et al. 2012). Depending on the fibre content of the concrete, a so-called residual tensile strength appears. The mechanical properties of the fibres vary depending on the material from which they are obtained (Table 2).

Currently, steel is the most common material used to produce fibres for sewer pipe reinforcement. The literature distinguishes between short fibres and long fibres based on their length and work in concrete. There exists considerable experimental and numerical research on fibre-reinforced concrete pipes (FRCPs) and this topic is interesting for scientists as well as for industries. Fibres can be added to the pan-mixer of any concrete plant without any extra process modification. FRCPs can be produced in the moulds similar to the ordinary concrete pipes. Therefore, FRCPs seem to be an economical alternative to the traditional RCPs.

4.1 Steel fibre-reinforced concrete

Steel fibres (SFs) have been accepted in concrete pipes for replacing traditional reinforcing steel bars that are widely used in RCPs. SFs control crack width in concrete and provide the required load-bearing capacity for every pipe strength class. Nonetheless, SFs are prone to suffer from corrosion, which jeopardises the durability of the SF-reinforced concrete pipes (SFRCPs). In addition, SFs reduce the concrete workability. To improve the concrete workability, admixtures like plasticisers must be added, which increases costs.

Haktanir et al. (2007) carried out three-edge bearing and crack size measurement tests using concrete pipes, RCPs and SFRCPs of 500 mm diameter. Tests on SFRCPs including an SF dosage of 40 kg/m^3 revealed that an SF dosage of 25 kg/m^3 seems to be optimum. A 60% rise in the amount of SFs induces only negligible changes. Research has also shown that the longer SFs seem to be more efficient for SFRCPs than the shorter ones. The average three-edge bearing strength and crack size of SFRCPs turned out to be 82% greater and 47% smaller than those of plain concrete pipes, and 6% greater and 15% smaller than those of RCPs, respectively (Haktanir et al. 2007). The authors point out that manufacturing of SFRCPs is less labour intensive and less time consuming than producing RCPs. Results obtained in the work of Haktanir et al. (2007) showed that pipes manufactured by C35 class concrete containing SFs at a dosage of about 25 kg/m^3 have more beneficial mechanical, physical and economical properties over classical RCPs.

In the scientific literature, the lack of a systematic method for the design of SFRCPs slows down the step forward for the use of SFs in this field. Producers have to resort to the crushing test in order to realise an indirect design of the FRCPs through a trial-and-error system. This method is ineffective, given that different types of fibres are present on the market and a significant number of strength classes and geometries are available (De la Fuente et al. 2013). A new comprehensive methodology for the design of FRCPs is presented in the work of De la Fuente et al. (2012, 2013). The Model for the Analysis of Pipes (MAP) simulates satisfactorily the amount of fibres for a fixed internal diameter and required strength class.

Mohamed et al. (2014, 2015) carried out full-scale tests in order to research the mechanical performance of SFRCPs. The researchers investigated an experimental programme on 450- and 600-mm-diameter SFRCPs using the continuous and cyclic three-edge bearing tests. They concluded that SFs significantly increased the ultimate load and post-cracking strength (PCS) and could be successfully applied in manufacturing concrete pipes to replace the typical steel cage reinforcement (RCPs).

At relatively small displacements (2.0–5.0 mm), SFRCPs fabricated with a fibre content of 30 kg/m^3 or more exhibited residual strengths higher than that of RCPs (Mohamed et al. 2015).

Lee et al. (2019) discussed the mechanical responses of steel-and-synthetic-fibre–reinforced pipes. This study concluded that the ideal fibre volume should range between 0.15% and 0.20%. This fibre volume allows reaching the maximum strength capacity. The authors concluded that SFs absorb energy more effectively than synthetic fibres when used as reinforcement. In addition, the SFRCP shows higher ductility than the synthetic fibre-reinforced concrete pipe. SFs are still sensitive to corrosion and, hence, the durability and serviceability can be compromised.

4.2 Synthetic fibre-reinforced concrete

Using synthetic fibres as concrete reinforcement has many advantages: flexibility, slight impact on concrete workability, synthetic fibres being inert to chlorides and aggressive chemicals. Deng et al. stated that polypropylene fibres (PPFs) most effectively prevent concrete pieces from spalling and debonding of the pipe. There are few studies in the literature referring to synthetic fibre-reinforced concrete pipes.

De la Fuente et al. (2013) carried out an experimental campaign in which PPF-reinforced concrete pipes (PFRCPs) with PPF reinforcement at 3, 4.5 and 6 kg/m^3 and internal diameter equal to 1000 mm were produced and tested using crashing tests. The authors proposed design tables, based on the MAP model, in order to remove traditional reinforcement. The scientists suggested more investigation for FRCPs with a pipe diameter larger than 1000 mm.

Pezvandi et al. (2013) undertook complete experimental researches to assess the effectiveness of various synthetic fibres (aramid, AR-glass, carbon and polyvinyl alcohol [PVA]). The researchers indicated that PVA fibres are especially efficient in increasing the mechanical properties of the lean, no slump concrete mixture. The structural performance of concrete pipes was increased by adding PVA fibres. Reduction of steel reinforcement ratio and increasing the thickness of protective concrete over steel were achieved by using PVA fibres at 0.5–1.0 vol.% (about 6.5–9.6 kg/m^3). The load-carrying capacity of concrete pipes was increased by 30%. Direct joint shear tests also demonstrated that PVA fibre reinforcement enhances the joint shear capacity and can potentially eliminate the need for enlargement of joint area, thus facilitating shipment and installation of concrete pipes (Pezvandi et al. 2013).

A new concrete pipe system with synthetic fibres is cheaper, lighter and more flexible than traditional RCPs. Al Rikabi et al. (2019) evaluated the synthetic fibre-reinforced concrete pipes in terms of strength, stiffness and ductility. A three-edge bearing test was carried using three pipe diameters: 600, 1200 and 1500 mm. The authors concluded that using synthetic fibre increased the cracking load (produced 0.3 mm crack width), ultimate load, stiffness and ductility of tested pipes. The scientists found that using synthetic fibre lowered the production cost, as the reduction in the steel cage area ranged from 51% to 100% (Al Rikabi et al. 2019). In the study of Al Rikabi et al. (2018), the authors concluded that the involvement of PPF along with minimal steel area and diminished wall thickness increased the flexibility of PFRCPs. In the research, all tested pipes experienced deflection ratio of 5% of their inside diameter before reaching their ultimate load (Al Rikabi et al. 2018).

4.3 Concrete nanocomposite pipes

Benefits of relatively low-cost graphite nanoplatelets (GPs), used alone or in combination with PVA fibres, were evaluated through industrial-scale production and experimental evaluation of concrete pipes in the work of Peyvandi et al. (2013b). Experimental results demonstrated that surface-treated graphite nanomaterials significantly benefited the structural performance and failure mechanisms of RCPs.

PVA fibres offer the desired chemical stability to concrete when it is exposed to the sanitary sewer environment, resistance to high acid level and the desired bond strength to concrete. Graphite nanomaterials, when compared with fibres, offer distinctly high mechanical and physical attributes as well as enormous surface areas and very close spacing within matrix at relatively low volume fractions (Peyvandi et al. 2013c). Modified GPs at 0.05 vol.%, when used alone or in combination with 0.8 vol.% PVA fibre, produced concrete materials with a highly desired balance of flexural strength, energy absorption capacity, compressive strength, impact and abrasion resistance. RCPs benefited significantly in terms of crack resistance, load-carrying capacity and toughness by introduction of GPs. The gains in pipe structural performance resulting from combined use of PVA fibres and modified GPs enable reduction of conventional steel reinforcement and increasing the concrete cover over reinforcement in pipes. These measures can enhance the service life of RCPs in aggressive (e.g., sanitary sewer) environments (Peyvandi et al. 2013b).

4.4 Basalt fibre-reinforced concrete

In the work of Deng at al. (2021a), basalt fibre-reinforced concrete (BFRC) was examined as a potential structural material to produce sewer pipes, because of basalt's features (Figure 3) The authors carried out an experimental programme that included the production and testing of 1.0-m-internal diameter steel RCPs, considering the combination of basalt fibres (BFs), PPFs and basalt–PPFs (B–PPFs). Pipes were exposed to the three-edge bearing test load configuration and checked to control deflections and crack patterns up failure. The test characterised the bearing capacity under the most unfavourable load and support boundary conditions. For this research, 0.3 mm crack width ($P_{0.3}$) and the maximum load-carrying capacities (P_u) were measured. Normalised pipe load-carrying capacity (DL=P/[L•D_i](kN/m^2)) was used for the analysis. This research concluded that the use of fibres increases the load-bearing capacity and, particularly, reduces the crack width (accepted up to 0.3 mm) for service loads and, with that, increases the pipe durability (Deng et al. 2021a). Based on the results, Deng et al. noted that the density of cracks increases with the addition of fibres. Fibres effectively lead to substantial reduction of the steel cage reinforcement, while meeting the crack width and bearing capacity requirements (Deng et al. 2021b).

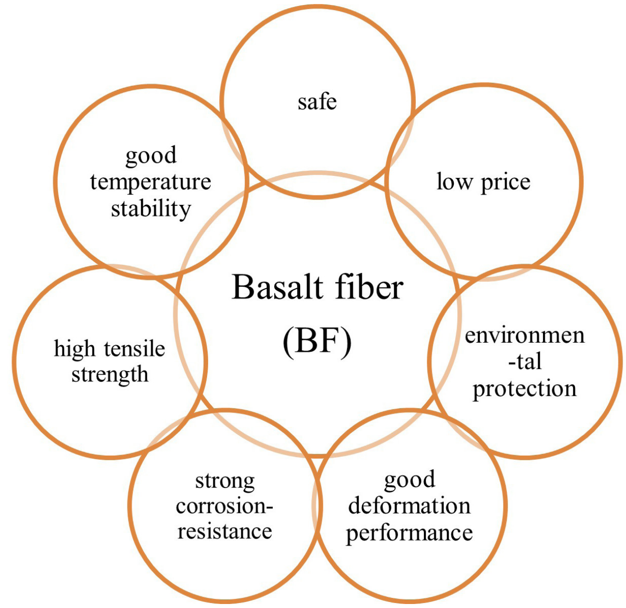

Figure 3: Features of basalt fibre.

4.5 B-PPF-reinforced concrete

An interesting alternative to traditional steel cage RCPs is B-PPF-reinforced concrete (BPFRC) for durable and sustainable pipe production (Deng et al. 2021a). First, testing of the mechanical properties of concrete pipes reinforced with a combination of BFs and PPFs was conducted by Deng et al. Before the study, the researchers predicted that BFs can increase the crack performance in service; in addition, PPFs can enhance ductility and load-bearing capacity of the concrete pipe. The experimental programme showed effective controlling of the crack patterns up to failure loads. In this regard, the service load of DL, when the crack width was 0.3 mm ($\boldsymbol{D}_{0.3}$) of the concrete pipe with 2 and 4 kg/m^3 BFs and B-PPFs, respectively, was found to be 34.1% superior to the $\boldsymbol{D}_{0.3}$ reached by the RCP (Figure 4). A hybridisation of BFs and B–PPFs gave the best result.

The FRCPs presented greater post-cracking energy absorption with respect to that observed for the reference RCP. PCS involves quantification of the energy associated with the post-failure mechanism and other deformational and geometrical variables. It showed a reduced tendency for the pipes with BFs and PPFs, while the pipe with B–PPFs presented an increasing tendency due to the synergetic contribution of both fibres (Deng et al. 2021a).

In the study Deng et al. (2021c), it was found that the optimal mass ratio of BF to PPF was 1:2, with a total content of 6 kg/m^3 (from an economical and technical point of view). The authors concluded that, through the addition of hybrid BF and PPF, the flexural toughness and equivalent flexural strength of the BPFRCPs were increased by 10.2 times and the percentage of equivalent flexural strength was increased by 7.1 times.

5 Corrosion protection linings

Sewage may lead to a high strain on pipelines due to the concentration of chemicals in the wastewater or in the form of biogenic sulphuric acid corrosion. In order to avoid concrete degradation, the fitting of liners can be applied. Manufacturers supply pipes with integrated linings (complete or partially lined) (Figure 6). During the manufacturing process, they are securely fitted on the inside of the pipes. Not only are these pipes highly resistant to aggressive media due to their protective lining, but at the same time, the use of RC ensures that the pipes will withstand high loads. The surface of the corrosion

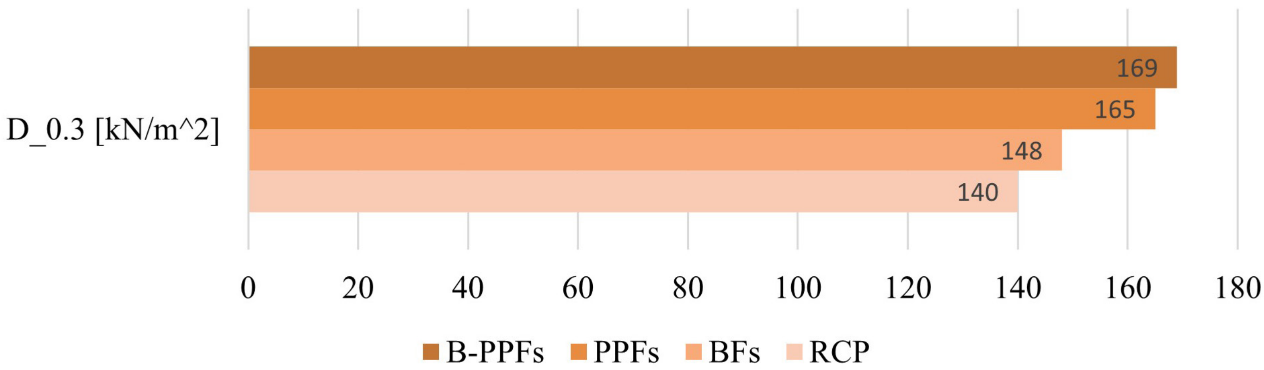

Figure 4: The service load of normalised pipe load-carrying capacity when the crack width is 0.3 mm for different reinforced concrete pipes (Deng et al. 2021a).

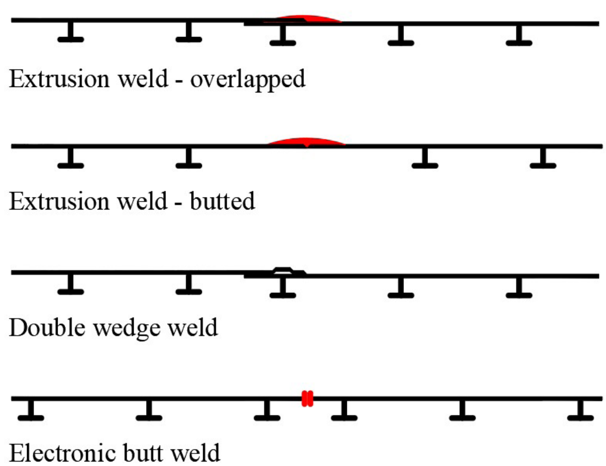

Figure 5: HDPE weld types.

protection liner is continuous and corresponds to the cross profile of the element.

5.1 High-density polyethylene liners

High-density polyethylene (HDPE) can withstand a chemical strain of pH 1–14. The concrete–HDPE composite is reliable all the way through to the pipe joint, thanks to a partially increased number of anchors. Even when the ambient temperature varies during transport and storage, the liner creates a solid connection with the concrete pipe via anchors on the back. The abrasion-resistant lining is designed to have an operational life of more than 100 years.Manufacturers produce concrete pipe with a 2-5mm thick liner, depending on the assumed load capacity. The optimum thickness has been tested in numerous research projects, and therefore ensures necessary corrosion protection [5].

HDPE lining is equally suitable for in situ installations. Sheets can be glued or mechanically fixed to formwork, and the anchors themselves can provide excellent fixing points. Lining the surface area of slabs and retrofitting of walls and complex shapes can be achieved with the use of high-strength grout bedding or injection. A continuous lining system is created through the use of various methods of thermal welding. Overlapped extrusion welds are recommended for site work. As a minimum, all site welds must be spark or vacuum box tested. Extrusion butted, double wedge and electronic butt welds (Figure 5) are used predominately in factory assembly conditions [7].

5.2 Polyvinyl chloride liners

Lining systems are able to bridge any discontinuities in the pipe/structure wall. The chemically inert, plasticised polyvinyl chloride (PVC) material is mechanically fixed to the pipe's internal surface (Figure 7) during the manufacturing process, which gives superior protection against chemical attack inside the pipe, treatment works, industrial waste lines and storage tanks – in fact, any concrete structure where aggressive agents are encountered [7].

5.3 Sole tiles and shape pieces from melted basalt

Products from melted basalt serve not only for construction, but also for reconstruction of sewerage systems. They multiply the lifetime of the works, as compared to other

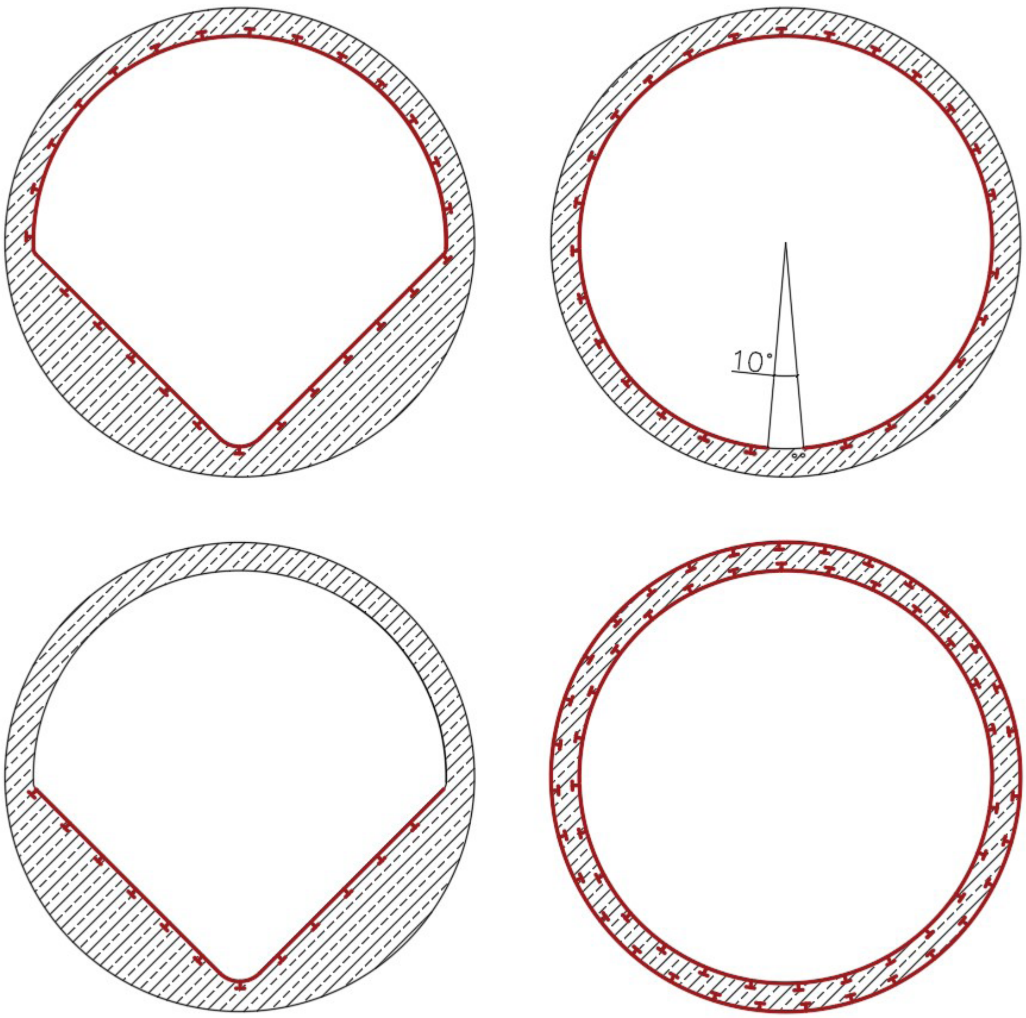

Figure 6: Different installation details of HDPE liners.

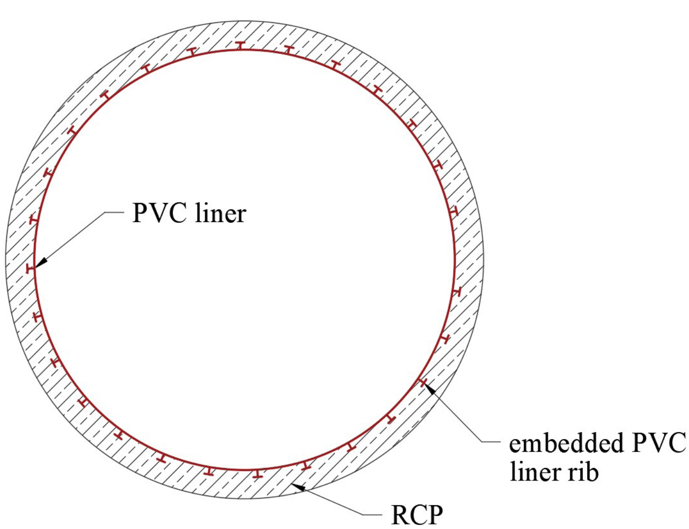

Figure 7: Reinforced concrete pipe with PVC liner

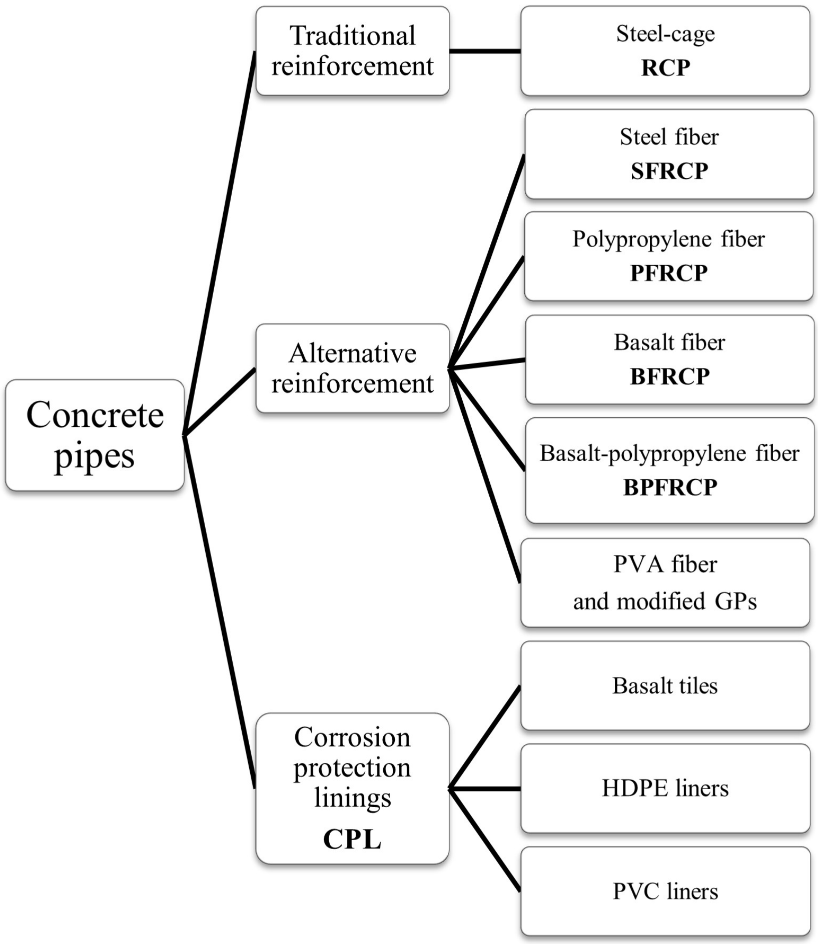

Figure 8: Types of modern concrete pipes.

materials and technologies. Sole tile developed from melted basalt shows high resistance against the abrasive effects of suspended and bottom-moved inorganic materials and is practically passive towards the aggressive impacts of the substances contained in wastewaters. Sole tiles and shape pieces from melted basalt can be used to protect the internal surfaces of new concrete or reinforced concrete sewage pipes against corrosion and abrasion. Concrete pipes with such lining can be used especially in the construction of sewage pipes for transporting very aggressive sewage, sewage flowing at high speed (with large longitudinal slopes) or when it is not possible to ensure effective ventilation of the pipeline, which may cause a high risk of corrosion to the structure.

Depending on the situation, the bottom of the pipeline or the entire section is lined with appropriate fittings. Sole tiles and shape pieces from melted basalt are also used in the production of sewage manholes exposed to corrosion or abrasion by high-speed sewage containing sand grains (Kolonko et al. 2005). The end-use properties of this natural material significantly exceed the lifespan of commonly used materials. Experience from Czech power stations indicates that the lifespan of basalt in the sewage system will be 200 years and more, even under unusual conditions. The fundamental properties include chemical resistance, corrosion resistance, very low hydraulic roughness and resistance to rodents, as well as ecological cleanliness and recyclability [4].

6 Conclusions

It is impossible to unequivocally identify the best material for sewer line construction. Each investment should be considered individually, analyzing the objective criteria that enable an optimal choice. Threats to the durability of the pipeline particularly require careful analysis. The analysis should also include gaskets. In any case, detailed static strength calculations should be a necessary element for the selection of pipes for sewer construction. Currently, the German ATVDVWK- A 127E “Static calculation of drains and sewers” guidelines are the best basis for static strength calculations.

In the construction of new networks, concrete has traditionally played a fundamental role. Concrete pipes can dominate more in the market than ever before, when their resistance to biological and chemical corrosion and durability improve. It is expected that the introduction of new concrete products (Figure 8) in the future will result in an increased use of concrete pipes in material solutions for the construction of underground sewage pipes.

Nomenclature

B–PPF	basalt–polypropylene fibre
BF	basalt fibre
BFRC	basalt fibre-reinforced concrete
BFRCP	basalt fibre-reinforced concrete pipe
BPFRCP	basalt–polypropylene fibre-reinforced concrete pipe
CPL	corrosion protection linings
D_i	internal pipe diameter
$D_{0.3}$	service load of DL when crack width is 0.3 mm
DL	normalised pipe load-carrying capacity
FRCP	fibre-reinforced concrete pipe
GPs	graphite nanoplatelets
HDPE	high-density polyethylene
L	pipe length
P	pipe load
$P_{0.3}$	load-carrying capacity of 0.3 mm crack width
P_u	the maximum load-carrying capacity
PFRCP	polypropylene fibre-reinforced concrete pipe
PPF	polypropylene fibre
PVA	polyvinyl alcohol
PVC	polyvinyl chloride
RC	reinforced concrete
RCP	reinforced concrete pipe
SF	steel fibre
SFRCP	steel fibre-reinforced concrete pipe

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