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Damage to plastic pipelines and its consequences

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Abstract. The paper will present the issue of damage to plastic pipelines - especially thermoplastic ones, while also considering the aspect of testing their technical condition using standard diagnostic tools. The results of the strength analysis for the effects of local overheating of the sewage pipe wall - as an effect of inflow of sewage with a high temperature, will also be presented.

1 Introduction

Studies carried out in Poland show that the technical condition of sewage networks is unsatisfactory and information on this subject is still incomplete ([1], [2]). A similar situation also occurs simultaneously in other European countries, even where tests of the technical condition of ducts are carried out systematically and where there is a longstanding awareness of the need to conduct their technical rehabilitation, a large part of the network is still in a state requiring short or medium-term intervention (see the results contained in [3]). It is emphasized in [1] that the results of the research on the sewage network failure rate to date refer mainly to the sewers made of traditional materials such as vitrified clay, concrete and reinforced concrete and, to a lesser extent, to plastic pipes. This is probably due to mundane reasons - practical tests carried out in Poland on those sections of the network which already show signs of damage, are at an advanced age or are ducts of greater importance in the system - these are usually collectors with larger diameters, built in the past from these traditional materials.

The testing of sewers during their operation is carried out as a standard using CCTV inspections, possibly supplemented by measurements of observed changes (e.g. measurement of deformations and slopes of the sewer) and (although rarely in Polish conditions) by pressure leakage tests. The range of acceptance tests is similar, but leakage tests are usually not omitted. Only special tests carried out in order to plan in detail a specific technical rehabilitation method for a sewer already selected can have a wider scope and thus their level of detail is much higher. Undoubtedly, the dominating test is CCTV inspection, which results from the lack of availability of ducts and their length, which objectively limits the possibility of using alternative solutions to CCTV inspection.

Due to the nature of the CCTV inspection (visual observation), the recorded image is an observable (noticeable) set of changes related to the cause of its creation. These include, for

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example, longitudinal cracks, infiltrations, losses of material in the sewer walls, exposed reinforcement, etc. The analysis of the technical condition of plastic sewage pipelines is particularly difficult, as the effects of excessive forces are not expressed in the form of changes (damages) that can be easily noticed and interpreted with CCTV inspection. While there are catalogues and fairly detailed interpretations for rigid pipe failures, there is particularly little information for susceptible pipes. In addition, routine TV checks often lead to the conclusion that the plastic sewer is free from damage, in extreme cases also because, even if a camera inspector had noticed a change, they may have ignored it, interpreting it as insignificant.

The opinion on the technical condition of a sewer section (e.g. between wells) covers the phenomenon of its destruction in a comprehensive manner, which results from a detailed analysis carried out by an expert. The data provided by the inspection are not sufficient here, as all the conditions and operating history of the sewer (in general) are relevant. This is clearly visible in the case of changes in the material structure over time, caused by natural ageing and corrosion processes. This is particularly true for plastic pipelines, for which, for example, the long and short-term material parameters can vary considerably. At the same time, there is cooperation between the structure and the ground medium (susceptible pipelines), while at the same time, taking into account rheological phenomena occurring both in the pipe material and in the ground environment, the assessment of the situation becomes generally complicated. To sum up, it is more difficult to give a reliable opinion on the condition of a plastic pipe in operation for many years than in the case of pipelines made of traditional materials, and the lack of noticeable changes during inspection by CCTV may increase doubts (in traditional materials, the picture of the interior of the pipe usually provides premises for stating a weakening of the structure of the material as a result of corrosive processes, particularly characteristic in this respect is concrete or reinforced concrete).

2 Damage to plastic pipelines

As mentioned above, there are only a few literature reports on the results of the testing of used plastic sewage pipes. Valuable information on this subject is provided by the monograph [2], which presents the results of multi-year research on sewers carried out by the Świętokrzyskie University of Technology in cooperation with companies which manage sewage networks in selected cities in Poland. Among the analysed sewers there were also PVC sewers, which made it possible to compare the damage occurring in them with the damage in concrete and vitrified clay ducts. These and other CCTV tests of the ducts in operation (e.g. [4], [5]) confirm a limited set of defects occurring in plastic ducts and the lower frequency of their occurrence. At the same time, damage typical for plastic pipes (susceptible pipes), not observed in rigid pipes, can be listed. These are:
- lateral deflection (ovalisation) of the pipe,
- loss of stability of the wall (buckling),
- local deformations (e.g. dents caused by point load from e.g. stones),
- scratching the external surface of the pipe,
- bending of the pipe in a longitudinal direction, in the vertical and horizontal plane.

Treating the scratch of the external surface as a damage characteristic of plastics assumes that the scratch concerns the structural layer of the material - as opposed to the damage of protective layers (insulation) of steel and cast iron pipelines at similar external forces. Alternatively, the scratch inside can be treated as specific, mainly due to non-linear pressures, with specificity resulting from the phenomenon of slow crack growth. Damage to the external surface of the pipe is primarily related to the construction of pipelines using trenchless methods, where the greatest potential risk occurs in the implementation of HDD technology and in technical rehabilitation using cracking technology (burst lining). Lack of access makes it impossible to record these damage from the inside of the sewer - the possibility to assess the actual scope of damage and their propagation is very limited.

The observed lack of continuity of a straight line of the sewer is regarded as a bend of a pipe in the vertical and horizontal plane, which, unlike rigid sewers, also occur outside the area of pipe connections. This does not have to be due to damage to the wall structure (which, accordingly, results in cracks in the rigid pipes). The longitudinal deflection of the pipe is associated with its ovalisation, which is then locally increased. Distinction of this type of damage is necessary because it causes secondary effects, which are characteristic of the formation of local counterslopes in which sediments accumulate over time. The lack of a straight line is due to inadequate workmanship of the pipes, in particular due to errors in compacting the backfilling, and, as secondary damage, due to loosening of the soil in the vicinity of the sewer (e.g. as a result of infiltration). The distinction proposed here between local loss of stability (buckling) and sharp-edge non-linear local deformation, caused by stone pressure in the backfilling zone and potentially resulting in cracks over time (at least theoretically), may seem debatable. At the same time, it need not be equivalent to a change in the section corresponding to an exceeding of the deformation limit.

Cases of damage to plastic pipes resulting from illegal discharges of wastewater of higher temperatures or chemically aggressive towards plastics, e.g. petroleum-based compounds against polyethylene, can be considered as difficult to record in routine inspections. Potentially, they may result in the local deterioration of material parameters and further deformation (high temperature) or the loss of wall thickness, the loss of elasticity and tendency to crack (chemical compounds impact). Damage of this type can also be considered as specific for plastics. Examples of damage to plastic pipelines are shown in Fig. 1.

As mentioned above, the results of the study [2] into the frequency of various defects in PVC sewers are interesting (these studies did not take into account the lack of straightness of the sewer and incorrect slopes). The study presents the results of the classification of the considered damage due to their hazard, taking into account three standard evaluation criteria: hydraulic and operational, structural safety and environmental criteria. Classes I to IV were assigned to damage, where Class I meant immediate renovation, while Class IV meant long-term renovation. The most common defects were: (as linear damage) movable and fixed sediment, deflection of the sewer top; (as non-linear damage): longitudinal displacements at the connections, local dents made by stones, observed infiltration, and incorrect household connection resulting in leakage. The above mentioned types of damage, both primary and secondary, are primarily the result of incorrect construction works and "economical" operation allowing for the retention of large amounts of movable sediment in the inspected sewer (unless a design error is assumed for taking over the unclassified soil in the backfilling zone, which is unlikely). At the same time, the movable sediment deposited in the sewer is usually soil deposited inside the sewer together with infiltrating water, which indicates the scale and importance of infiltration and the high probability of an incorrect pipe profile (the zones where sediments are deposited are usually in places where counterslopes occur).

The results of the damage classification presented in [2] showed in very few cases the need to carry out immediate rehabilitation: for movable sediment deposits - 0.04% of the detected cases, for the longitudinal displacement of connections - 0.3% of the cases, for the losses of fragments of the pipe wall - 43% of the cases. The latter damage - resulting from the installation of defective pipes or their subsequent mechanical damage, although rare (0.06 cases/100 m), are by definition very dangerous and require decisive intervention. The classification of all defects of the tested PVC pipes turned out to be more advantageous in comparison with the appropriate classification of defects found in a non-susceptible sewer - concrete and vitrified clay pipes. Definitely less damage to PVC pipes was classified as Class I, II and III, which, according to the authors of this publication, well reflects the trend in the observed level of risk posed by the poor technical condition of plastic pipes in operation (in comparison with non-susceptible pipes). However, this conclusion applies in particular to the damage characteristic of plastic pipes installed in an open trench. This does not necessarily apply to trenchless ducts, where damage to the external surface of the pipe may be significant and not recorded during CCTV inspection.

It is also worth recalling the comment contained in monograph [6], that observations from practice indicated numerous cases of brittle fracture of pressure PVC pipes, which were caused by manufacturing defects in the pipe wall. For this reason, a fracture toughness test, introduced into British Standard BS 3505, was developed.

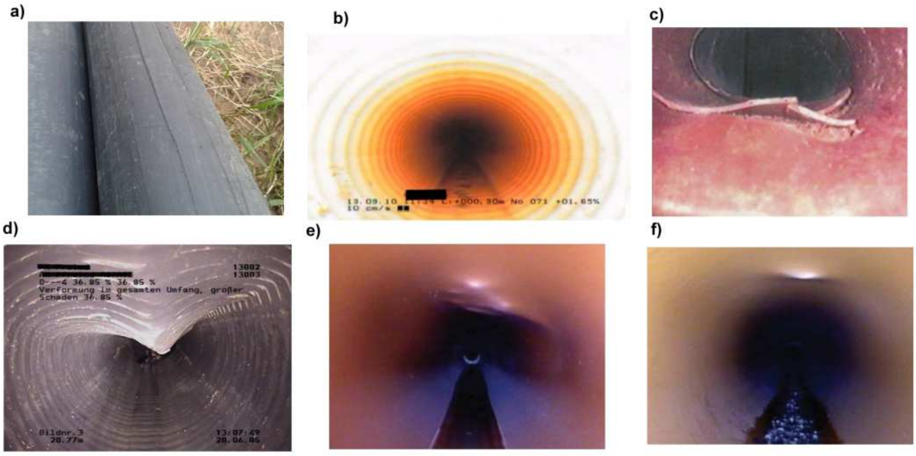

Fig. 1. Examples of typical damage of plastic pipes: scratching in the external surface (a), ovalisation (b), brittle cracks in PVC(c), loss of stability (d), local deformation (e and f) (own images and Internet sources).

3 Possibility to assess the technical condition in practice

The limitations of visual inspections in the analysis of the technical condition of the sewers are known. The branch literature has long drawn attention to this, pointing to the need for additional research, which is more important than the previous visual analysis. In practice, however, designers often decide to undertake technical rehabilitation and even carry out technology-specific calculations based entirely on CCTV inspection materials. It seems that this should be approached with great caution, especially in the case of plastic pipes.

In the course of expert tests, in situations ambiguous for the sewer evaluation, e.g. in the case of a lack of cracks and in the case of deformations not exceeding the limit value, the sewer resistance is estimated. Such calculations may be required, for example, by the need to check the loads that the pipeline can carry (now and in the future). It is checked whether the pipeline has been correctly selected by the designer (e.g. whether long-term material parameters have been taken into account). The question arises how to perform such calculations in order to make the results as reliable as possible. The most common solution is FEM modelling, but the designer faces the problem of developing a model that represents as faithfully as possible the behaviour of the considered object in the ground. The problem is the selection of appropriate characteristics of the pipe material and the surrounding soil - in fact, it is necessary to take samples and carry out laboratory tests. The question arises as to when this is realistic and financially viable (as an alternative to the zero-one statements like "we leave it unchanged as everything is still all right" or "we replace everything just in case").

The authors of the study decided to carry out calculations for the assumed situation in which a PVC pipe does not show any visible damage, but it is known that it operates under conditions of temporary inflow of sewage at higher temperatures (e.g. at the point of discharge from a heating pipe). For this purpose, two numerical models were built, simulating the operation of a PVC cable. Model A reflected the operation of the structure in laboratory conditions, while model B in conditions close to real life, i.e. in the ground environment. Numerical simulations using the Finite Element Method (FEM) require detailed data to allow the use of constitutive material models that are adequately matched to the design task and the expected range of results.

While the parameters of polyvinyl chloride pipes operating at typical temperatures of up to approx. 40°C are easily accessible, the problem arises of obtaining short-term data for higher temperatures. Designers are familiar with the procedure for accepting increased wall thicknesses for pressure pipes to operate at elevated temperatures, but this does not provide information useful for FEM modelling. For the situation in question, the ineffective short-term modulus of elasticity ER, average coefficient of lateral deformation and coefficient of longitudinal expansion were sought for PVC operating at higher temperatures. Finally, the results of laboratory tests of circumferential stiffness of PVC pipe DN 300, tested at temperatures of 20, 40, 60 and 80C, presented in [7], were used. On this basis, short-term elasticity modules were calculated according to the formula:

$$E_R = \frac{12 \cdot S_o \cdot d_m^3}{s^3} \tag{1}$$

where: S_o - circumferential stiffness, d_m - average diameter of pipe, s - wall thickness of pipe; and relevant long-term elasticity modulus values $E_{RL} = 0,4 \cdot E_R$.
Calculations were made for the PVC-U external sewer pipe: SN 4; SDR 41, d_m = 307.3 mm and s = 7.7 mm, υ = 0,3, γ =14.0 kN/m^3. The results are given in Table 1.

Table 1. Mean circumferential stiffness according to [7] and elasticity modulus calculated on its basis.

Temperature [°C]	**20**	**40**	**60**	**80**
Circumferential stiffness [kPa]	4.2	4.0	3.6	3.0
Short-term E_R elasticity modulus [MPa]	3203.66	3051.10	2745.99	2288.33
Long-term E_{RL} elasticity modulus [MPa]	1281.46	1220.44	1098.40	916.33

The purpose of the simulation was to calculate the deflections and to obtain an image of the deformed pipe cross-section, assuming partial filling with hot sewage and an assumed soil load. The Δd_v deflections calculated in [7] for the determined circumferential stiffness variables S_o and for the assumed load were known, as shown in Fig. 2.

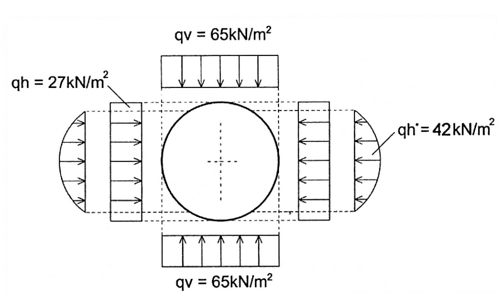

Fig. 2. Load distribution of the pipe adopted in [7].

The simulation was carried out accordingly to the variants of filling the pipe with hot sewage up to the height of 31.5 mm and 157.5 mm above the bottom of the manhole (10% and 50% of the height). Two load diagrams have been adopted. In the first one, the support scheme was applied, as in the case of laboratory testing of circumferential stiffness (Fig. 3), for the concentrated force load F = 600 N, which corresponded to the force used in [7] to determine the circumferential stiffness at 20°C (at a standard deflection of 3%). This made it possible to verify the correct operation of the pipe model adopted in the simulation. In the second diagram, the ground was laid up to the level of the pipe vault together with the surface load q_v = 65 kPa, similar to the situation shown in Fig. 2. The calculations were based on the elastic-perfectly plastic model of PVC material preservation and the elastic-plastic constitutive model of soil with the Coulomb-Mohr strength criterion with the following parameters: volumetric density ρ = 1.8 g/cm^3, primary soil deformation modulus E_o = 36 MPa, lateral expansion coefficient ν = 0.2, internal friction angle φ = 35°, angle of dilatation ψ = 5°. The first support scheme (model A), due to the lack of soil reaction, corresponds to the situation of maximum deformations, so it was supposed to be the basis for comparison for the deformations of the pipe working in the ground space (model B). Model A was also used to verify the correctness of the model and the adopted parameters based on the results of the tests described in [7]. The above-described analyses of the structure's work carried out with the use of both models were conducted in the non-linear range. The results of the simulation are presented in Table 2.

Table 2. Results of the simulation: model A: pipe without ground, load 600 N, model B: pipe in ground, load 65 kPa.

No.	Model	Sewage filling [%]	Temperature	E_R/E_{RL}	Deflection [mm]	Deflection [%]
1	A	0	20	E_R	9,53	3,1 [%]
2	A	0	20	E_{RL}	23,92	7,8 [%]
3	A	50	40	E_R	9,21	3,0 [%]
4	A	50	60	E_R	9,79	3,2 [%]
5	A	50	80	E_R	10,92	3,6 [%]
6	A	50	40	E_{RL}	24,70	8,0 [%]
7	A	50	60	E_{RL}	26,14	8,5 [%]
8	A	50	80	E_{RL}	29,50	9,6 [%]
9	B	0	20	E_{RL}	3,23	1,1 [%]
10	B	50	80	E_{RL}	3,29	1,1 [%]

The values of deformations (deflections) obtained for filling the pipe with hot sewage up to the level of 10% of its height were only slightly different from the deflection of the pipe for temperatures of 20°C and 40°C. The obtained millimetre differences, even for 80°C, did not give grounds to conclude on any significance of temperature increase. The temperature increase became noticeable only for the variant of sewage filling up to half the height of the pipe (50%), however, the deflections determined here differed only slightly in relation to the initial temperature of 40°C. The relative vertical deformation for long-term parameters increased only from 8.0% for 40°C to 8.5% for 60°C and 9.6% for 80°C. For model B - a pipe in the ground, the vertical deflection percentage has not changed (by an absolute value of 1 mm).

The results obtained were different from those expected. The first proposed justification indicates that the model adopted is inadequate for analysing this situation. At the same time, the authors did not find in the literature available to them the results of research (measurements), which would allow verifying such correctness. At the same time, the adopted model was used in the engineering analyses of typical cases and gave correct results. Finally, a question remains open about the behaviour of the pipeline leading the periodically heated waste water - especially for small diameters - and about the need for more accurate simulations. However, it would have to be supported by laboratory tests in conditions similar to those presented by the model. At the same time, it can be stated that simple calculation methods used in the work of an engineer do not allow for certain conclusions in ambiguous situations - when diagnostic techniques do not provide information about the material parameters of a cable.

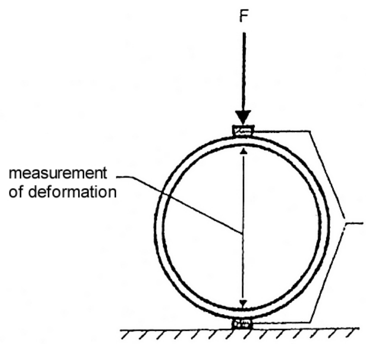

Fig. 3. Diagram of support and load with force F for normal testing of circumferential stiffness according to PN EN 1228: 1999.

4 Summary

The sewage network, especially the one which conducts the sewage by gravity, is characterized by the possibility of long-term functioning in the condition of partial damage. The hydraulic capacity of the individual sewers may be impaired, their design may be substantially impaired and this condition may not be detected at least for the period between inspections, which are relatively rare (on average once every 5 or 10 years). This situation poses a certain risk. While the theory of damage for non-susceptible sewers is well described in the literature, relatively little information can be found on the behaviour and damage of susceptible plastic sewers. This is due to their shorter usage in practice and most often for smaller diameters, which has so far caused fewer problems and perhaps no need for further knowledge on this subject. Less recorded damage to plastic pipes does not necessarily indicate their superiority over rigid pipes, which still play an important role in the construction of new sewage networks. Plastic pipes are resistant to short-term overloads, however, rheological processes and deteriorating material properties of plastics extrapolated over a period of 50 years under certain conditions must be taken into account.

It seems that the most common practical problems of plastic pipes are related to the effects of their leakage. Indirectly related to this effect was all damage classified as urgent for renovation according to the tests described in Chapter 2.

Cases of leakage in connection with exfiltration and/or infiltration phenomena causes the loosening of soil around the sewer, which is assumed to pose a threat, as the load-bearing capacity of the susceptible sewer, considered in cooperation with the ground medium.

The direct leakage of plastic pipes is a result of:

- excessive lateral deformation (ovalisation) in the connection zone,
- connection displacement,

- damage to the gaskets, incorrect assembly of the gaskets in the connections (protruding gaskets) or (less frequently) their chemical destruction during operation,
- lack of proper welding of elements connected with the use of electrofusion sockets or by butt welding,
- discontinuities of pipe walls (cracks of various nature, losses and chipping - especially in PVC and composite pipes).

The leakage is also encountered as a result of the impact of hydraulic and secondary contamination of the gasket during the time of vacuum formation. Even if the permissible deformation in the pipe connection area is not exceeded (e.g. 9% for the long-term value), there is no guarantee of tightness - the decisive factor in this respect are the connections.

Leakage problems of sewage pipes are solved with the use of technical rehabilitation methods, which have been applied on the market for many years. However, it should be noted that some of the recognised methods are not applicable in the renovation of plastic sewers (or their application is significantly hampered). These are mainly local repair methods that involve the bonding (gluing) of a sealing element (packer, cap liner, etc.) to the wall of a plastic pipe or using a centrifugally applied sealant.

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