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Research paper

The influence of the properties of water pipes made of PE on their durability and reliability

Andrzej Studzinski[1], Vlasta Ondrejka Harbulakova[2], Izabela Skrzypczak[3]

Abstract: This article engages in detailed discussion of the material properties of water pipes made of polyethylene (PE). It describes the influence of properties of the material (including its geometric dimensions) on the level of reliability of pipelines made from PE 100. Values for the index of reliability obtained from analyses carried out using probabilistic methods were compared with those recommended for the index in regard to a reference period of 50 years and different Reliability Classes (RCs). The fully probabilistic (3rd level) method – Monte Carlo simulation method was used to analyze the reliability. The probabilistic calculations were carried out with account taken of different values for the coefficient of variation describing material parameters, adopted as random variables; as well as the correlations between them. The work detailed here reports an influence of material geometry on the reliability index reported for the analysed pipeline made from PE. Where the analysed PE pipe was associated with a coefficient of variation for wall thickness at or over 0.07, this denoted non-compliance with standard PN-EN 1990:2002 as regards the minimum level of reliability recommended for a reference period of 50 years and Reliability Class RC2.

Keywords: coefficient of variation, material properties, polyethylene pipes, reliability

[1]PhD., Eng., Rzeszow University of Technology, Faculty of Civil and Environmental Engineering and Architecture, ul. Poznańska 2, 35-084 Rzeszów, Poland, e-mail: astud@prz.edu.pl, ORCID: 0000-0002-6551-9490
[2]PhD., Eng., Technical University of Kosice, Faculty of Civil Engineering, Vysokoskolská 4, 042 00 Košice, Slovak Republic, e-mail: vlasta.harbulakova@gmail.com, ORCID: 0000-0003-3001-3059
[3]PhD., Eng., Rzeszow University of Technology, Faculty of Civil and Environmental Engineering and Architecture, ul. Poznańska 2, 35-084 Rzeszów, e-mail: izas@prz.edu.pl, ORCID: 0000-0003-0978-3040

1. Introduction

The durability and reliability of systems of water pipes offer a measure of ongoing functionality in defined operational conditions. Specifically, analyses of the anticipated reliability of pipes made from thermoplastics need to take account of:

- the physical and mechanical properties of the material involved,
- the resistance of that material to environmental factors of a mechanical, chemical, physical and biological nature,
- stability of mechanical properties,
- the type of ground in which a pipeline is laid,
- the quality of manufacture and installation,
- adherence to operational parameters,
- monitoring of the network in the course of its operation.

The growing demand for plastic pipes and the trend for these to take the place of water pipes made from steel or grey cast iron is first and foremost a reflection of durability, ease of installation and desirable operational features. The durability of the pipes and the networks developed from them also reflects the quality of manufacture and installation, as well as the quality of monitoring of the system as it is in operation. The current forecast is that world demand for plastic pipes will reach some 37 million tonnes in 2021. And it should be stressed that, in the case of systems of pipes, reliability and durability represent measures, not only of ongoing operability and functionality, but also – above all – of possibilities for continued safe operation.

In line with the EN 1990 standard [1], reliability is the ability of a structure or structural member to fulfil specified requirements as regards safety, capacity, serviceability and durability during the anticipated service life (period in use), as usually expressed probabilistically. The ISO 2394 standard [2] also distinguishes "reliability of a structural member" (i.e. an individual construction element), as well as of a system comprising more than one structural member.

In general, in line with provisions set out in the standards, the key requirements as regards capacity, serviceability and durability should be met through:

- selection of appropriate materials,
- proper design and calculations in respect of construction and developed details,
- the determination of procedures by which to monitoring and audit design, production, manufacturing and operation – as appropriate in respect of a given design.

The complexity of issues of durability, reliability and safety of both buildings and installations in the circumstances in which they are required to operate demands the use of probabilistic calculations methods, hence the focus here on the impact material properties and geometric dimensions are able to exert on levels of reliability of water pipes made of PE. The further goal was to compare the values obtained with those recommended for the reliability index in relation to a reference period of 50 years, as well as various Reliability Classes (RCs). The probabilistic calculations that were carried out took account of different values for coefficients of variation when it came to material parameters adopted as random variables, as well as the correlations pertaining between them.

2. Properties of water pipes made of PE

The base materials for producing PE-type piping are medium- and high-density polyethylene (MDPE and HDPE). However, additions as polyethylene is being manufactured include stabilisers, pigments and antioxidants all brought together in a homogeneous mix. As can be noted, polyethylene is often classified in terms of its density [3]; hence the distinction drawn between [4]:

- very low density polyethylene (VLDPE), at < 910 kg/m^3,
- low-density polyethylene (LDPE) – in the range 910–930 kg/m^3,
- medium-density polyethylene (MDPE) – in the range 930–945 kg/m^3,
- high-density polyethylene (HDPE) – in the range 945–965 kg/m^3,
- ultra-high molecular-weight polyethylene (UHMWPE), at > 965 kg/m^3.

The ethylene polymers used in the production of pipes also gain classification in line with their strength. Pipes are subject to internal hydrostatic pressure and a temperature of 20°C, for a service life of at least 50 years. Minimum Required Strength (MRS) expressed in bars is used to denote the different types of PE, e.g. with PE80 (MRS = 8.0 MPa) and PE100 (MRS = 10.0 MPa). The utilisation of pipes of high strength requires that a polymer of higher density and crystallinity be used, with this at the same time denoting a worse situation where susceptibility to processing is concerned. Nevertheless, improved methods of polymerisation do allow for the obtainment of MDPE of slightly increase molecular weight that display lower melt viscosity and enhanced long-term durability. Examples of polymers of high molecular weight and low values for the Melt Flow Rate (MFR) index are PE 100-type bimodal polyethylenes. Density (as linked with crystallinity), the flow rate index (dependent on the polymer's molecular weight) and the distribution of molecular weights are all parameters determining the strength-related properties of a polyethylene, and hence also the durability of pipes made of it. As a given type of PE is selected to produce pipes, it is important for account to be taken of the influence of quality parameters on physical and mechanical properties of the product.

It is now common for the polyethylenes PE80 and PE100 to be used as pipes designed for the transmission of water under pressure are being manufactured. This reflects a good balance achieved between the three main properties (Fig. 1) [4]:

- resistance to creep and long-term strength,
- resistance to stress corrosion cracking (SCC) – as a critical property when it comes to resisting the process whereby cracking induced by scratching or point loading is initiated and propagated, resistance to the rapid propagation of cracks.

A leading parameter in the case of polyethylene piping is its stability – as expressed in terms of the oxidation induction time (OIT), and thus dependent on the type and amount of antioxidant added to the polymer. In this context, degradation of pipes made from PE is found to ensue when the supply of the substance safeguarding the polymer is exhausted, and there is then a decline in strength-related properties, influencing durability in a drastic way. Hydrostatic strength is a fundamental parameter relating to the durability, as well as the reliability, of thermoplastic pipes used under defined operating conditions (and it is capable of being determined for all suitable materials on the basis of extrapolation) [5].

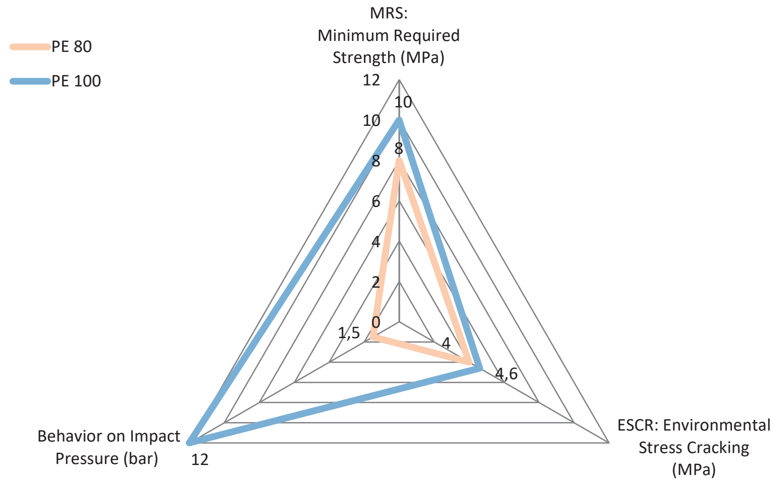

Fig. 1. Graphical overview of the properties of PE80 and PE100 – own elaboration on [4]

The suitability of a plastic is defined in line with the behaviour of the material when placed under a burden (as hoop stress, and with account taken of defined operating conditions, not least temperature). Hoop stress is induced by hydrostatic pressure, with the assumption being that a pipe of a given material will withstand operating conditions over a period of 50 years where the temperature in the surroundings is of 20°C [6–8]. Water is the internal medium researched. Where extrapolation coefficients are used, the limit time may be extended to 100 years. Methods applied in determining hoop stress allow for the determination, not only of service life or exploitation time, but also of:

- the maximal stress (or pressure) a given system of pipes can withstand at a given temperature over a given period of time,
- the working life of a pipeline under a given amount of stress (or pressure) at a given temperature,
- the lower limit values for stress (within 97.5% confidence limits) that a pipe made of a material under study can withstand over 50 years, at a temperature in the surroundings equal to 20°C (with either water of air used as the research media),
- the expected lower limit value for stress (within 97.5% confidence limits), or for different periods of durability, also at a variety of temperatures.

Thus, for each polymer material, it is necessary to determine long-term hydrostatic strength, so that durability under given operating conditions can be foreseen.

By reference to the research detailed in [9], it was possible to determine the influence of manufacturing on the quality and durability of pipes. This reflects the way in which processing not done properly or adequately may have a considerable influence on the durability of thermoplastics. Inclusions, a lack of uniformity of material and agglomerates of fillers or dyes in walls can all signal places in which cracking can be initiated, exerting the obviously major possible influence on durability.

Pipe networks made of PE and applied in the transmission of media under pressure are characterised by the key durability parameter that vulnerability to brittle fractures represents. Given the possibility of pipes being impaired by, for example, mechanical damage at the surface or sudden jumps in pressure, individual normalised tests are run to determine resistance to factors of this kind (and at the same time therefore durability). Requirements regarding the resistance of polyethylene pipes to the rapid propagation of cracks are as laid down in the PN-EN 12007-2 and ISO 13477 standards [10].

Further key parameters characterising the materials used to manufacture pipes relate to chemical resistance and that involving abrasive wear. It is generally true that the polymer materials used in this context are resistant to most of the typical corrosive environments. Therefore the degradation of the polymers concerned is mainly induced by substances capable of acting as oxidants, as well as by UV, thermal loading and cyclical mechanical loading. To enhanced the resistance displayed to agents capable of causing these kinds of degradation it is necessary to enhance stability through the addition of an antioxidant, soot and heat stabilisers.

A key sphere of use of PE pipes is the transport of drinking water, hence the importance of using appropriate means of disinfection that do nothing to impair the durability of pipes.

Research into this has been done in Italy [11] and – where pipes made from PE100 were concerned – the impact on properties of pipes was found to be greater where chlorine dioxide (ClO_2) was used, as opposed to sodium hypochlorite (NaClO). However, in the cases of samples in contact with both substances it was possible to note impairment as regards elongation at break, as well as reduced oxidation induction time (OIT) (Fig. 2) [4].

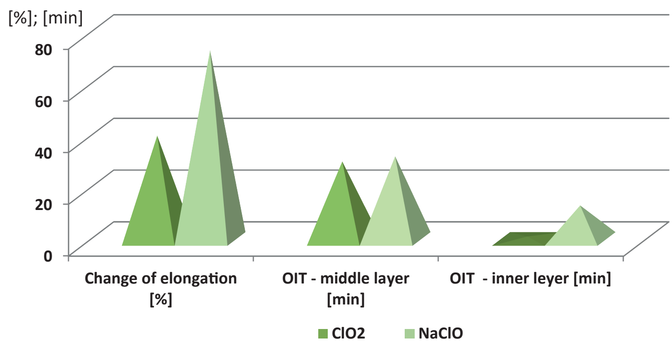

Fig. 2. The impact on properties of pipes PE100 after 360 hours contact with water containing chlorine dioxide and sodium hypochlorite – own elaboration on [4]

However, where the disinfectant was ClO_2, these effects were more rapid and larger. A major decline in OIT noted for a sample exposed for several weeks to water treated with ClO_2 attests to a clear deactivation of antioxidants present in the polymer – in particular in the surface layers making direct contact with the treated water. However, the work revealed no significant influence of the chemicals studied on the ultimate tensile strength or hydrostatic strength of the pipes researched [4].

In water-supply systems that are under pressure it is possible for short-lived increases in internal pressure to arise – to a degree that exceeds the nominal value for working pressure. This is the so-called "water hammer" effect, and it arises in water-supply systems where pumps begin or cease operating, there are sudden opening or closing of armatures, fracturing of pipes and so on, with the result that continuity of flow is interrupted by sudden changes in flow conditions. Where there is short-term loading of the pressure-wave type, the stresses that a designed pipe should be in a position to withstand over 50 years may be exceeded greatly, as long as the waves remain within reasonable limits. Testing done in Gothenburg, Sweden, involved the impact of the water hammer on 110 mm-diameter PE100 pipes. This found that the pipes could withstand 106 pulses of changed pressure without showing any signs of damage (where the temperature was 23°C, pressure deviations were of ±50% around the 10-bar nominal pressure and the frequency of change was at 5 impulses each 10 seconds) [9]. It was also confirmed that the influence of the water-hammer effect on the durability of pipes where depths of notches on the surface were of up to 5% of the thickness of the wall did not exert an influence on fatigue limit.

Pipes laid in the ground are subject to burdening by both the soil itself and by circular motion. Where pipes characterised by elasticity are laid, their capacity to tolerate loading also depends on the circumferential rigidity of the pipes themselves, and the rigidity of the surrounding ground [12, 13]. Thermoplastic pipes – displaying elasticity – bear external loading along with the ground surrounding them. A feature inseparable from pipes with elastic properties is that external loading causes them to bend. The size of the distortion involved is in the main dependent on the burdening of the land surrounding the pipe. Research shows that 80% of deflection noted is a reflection of (the quality of) the work done at the time of installation, while 15% is depth-related. That leaves just around 3.5% attributable to circumferential rigidity and some 1.5% to the material used [14].

Clearly then, it is not really the technical parameters of the piping used that makes a difference here, but rather the quality of the work done at the time of installation – proving to be of key importance in determining how much deflection of the courses followed by piping will take place subsequently. Equally, where some limit value for the loading of pipes laid in the ground is exceeded, this will then induce excessive radial deflection, buckling or compression, or else the mechanical destruction of walls [15].

Experiments to date plus the study of samples of PE piping from operational water-supply systems allow us to anticipate that these will retain their operability for at least 100 years, provided that external and internal loading do not give rise to hoop stress of more than 12.5 MPa; and further assuming that the walls of the pipes are free of microfractures and mechanical damage, that the system will run with low water pressures and limited fluctuations in pressure, and that new connections are not made. Equally, this anticipated level of operational durability of existing plastic pipeline systems is capable of being curbed – especially where there is qualitatively "worse" situation – as a consequence of additional burdening, the presence of microfractures, or land subsidence [4, 9].

There are many cases in which what serves as a measure of the durability of water pipes made of different materials is simply their failure rates. UKWIR (UK Water Industry Research) runs a database of pipeline failure developed in cooperation with all the country's water companies. It runs to some half a million entries relating to failures and breakdowns along some 350,000 km of water mains. Analysis of what has been registered there in the years since 1995 shows that PE is the material among all possible candidates used in the manufacture of pipes that is least prone to failure. Furthermore, where failures do relate to PE as the material, it is mostly first-generation examples that are involved [15].

Likewise, work carried out in Denmark – which has considerable experience with the operation of plastic pipelines (given that 50% of the network is of PVC and 23% of PE) – confirms that installations made of this material manifest the lowest rates of failure. When relevant research in the USA is concerned, PE pipes are again shown to fail less than networks made of traditional materials. Furthermore, a figure in excess of 100 years is again given for the duration of possible exploitation of the material in water-supply networks. It is further important to note that the main causes of failure are considered to be design flaws, as well as poor practice at the installation stage [16]. Polish studies have furnished similar results [4, 17].

An advantage of plastic pipes that determines their durability in many cases relates to their capacity to carry weight in cooperation with the ground around them. This fact gains confirmation in the case of sewer systems located in Germany, The Netherlands and Sweden [18].

3. Reliability

The properties and quality of materials have an impact on the assessment of built infrastructure, hence efforts to determine the influence of both the geometry of materials and operating pressure on the failures rates noted for water pipes made from PE 100. In the case of designs in line with the standards EN 12201-1 [19] and ISO 13761 [20], it has been possible to ascribe a failure index. The present study has limited its considerations to what is recommended in the EN 1990 [1] and ISO 2394 [2] standards, when it comes the First-Order Reliability Method relating to the β probability of failure/reliability index. It is assumed there that random variables are defined with the aid of two parameters of a normal or normal equivalent distribution, i.e. the mean and the standard deviation.

The reliability index β in the case of two independent primary variables can be entered as (3.1):

$$\beta = \frac{\bar{Z}}{\sigma_Z} = \frac{R - E}{\sigma_Z} \tag{3.1}$$

where: $\bar{Z}$ – mean value for the limit-state condition, σ_Z – standard deviation for the limit-state condition, R – mean effect of capacity, E – mean effect of impacts.

On the other hand, the measure of reliability β is linked with the probability of an element or construction being destroyed, by way of relationship (3.2), i.e.:

$$P_f = \Phi(-\beta) \tag{3.2}$$

where: P_f is a probability of failure, $\Phi(\ldots)$ is the Laplace function.

A construction may be regarded as reliable where the value for the index calculated in line with formulae (3.1) and (3.2) is not lower than the target value (3.3):

$$\beta \geq \beta_{\lim} \tag{3.3}$$

where: $\beta_{\lim}$ is a recommended minimum value.

Annex B of standard PN-EN 1990 [1] supplies recommended minimum (target) values for the index ($\beta_{\lim}$) in respect of limit-states function for capacity of constructions assigned to different Reliability Classes and for different reference periods, i.e. $T_0 = 1$ year and 50 years (Table 1).

Table 1. Recommended minimum (target) values for the index ($\beta_{\lim}$) [1]

Reliability Class	$\beta_{\lim}/P_{f\,d}$ for $T_0 = 1$ year	$\beta_{\lim}/P_{f\,d}$ for $T_0 = 50$ years
RC3	5.2 / 9.96E–08	4.3 / 8.54E–06
RC2	4.7 / 1.30E–06	3.8 / 7.23E–05
RC1	4.2 / 1.33E–05	3.3 / 4.83E–04

The fully probabilistic (3rd level) method – Monte Carlo simulation method was used to analyze the reliability. The procedure algorithm is presented in Table 2.

Table 2. Algorithm for determining the probability of failure using the probabilistic method

No.	Step
1	Generate randomly the values of the variables for the R effect according to the assumed probability distributions
2	Generate randomly the values of the variables for the E effect according to the assumed probability distributions
3	Calculate $Z(x_i) = R - E$
4	Keep the calculated value of the variable $Z(x_i)$
5	Repeat steps 1-4 until the number of generated values of the variable $Z(x_i)$ is 106
6	Adjust the density function to the generated values
7	Read probability value (area under the density function) for values $Z \leq 0$

Algorithms and calculation details for MCS methods can be found, among others in publications [21–23].

Raw materials used in the manufacture of pipes of appropriate external diameters and wall thicknesses applied to rated pressures ensure a minimal safety factor adopted for water pipes that is equal to 1.25 under EN ISO 12162 [24]. To determine the service life of polyethylene pipes and their creep under external pressure, the producers of the raw materials from which pipes are made give so-called “regression curves” for them. Pressure applied is converted into the tension reduced in the wall, in line with the equation:

$$\delta = P \cdot \frac{\mathrm{SDR} - 1}{2} = \mathrm{PN} \cdot \frac{d_n - e_n}{2e_n} \tag{3.4}$$

where: P – internal pressure, PN – nominal pressure, d_n – outside diameter of the pipe, e_n – thickness of the pipe wall, *SDR* – standard dimension ratio – ratio between external diameter d_n and pipe wall thickness e_n.

To analyse reliability, it is essential that a statistical model of internal pressure be determined, and this was adopted by reference to the models proposed in [21, 25]. The description of the probability distribution for internal pressure was log-normal, while the coefficients of variation for pressure that were adopted lay in the range 0.05 to 0.2, in line with [21].

A normal distribution after [21,25] was used in describing the probability distribution for geometric dimensions. In line with [6,19], values for the coefficient of variation in these cases were in the range 0.05 to 0.1 (Fig. 3).

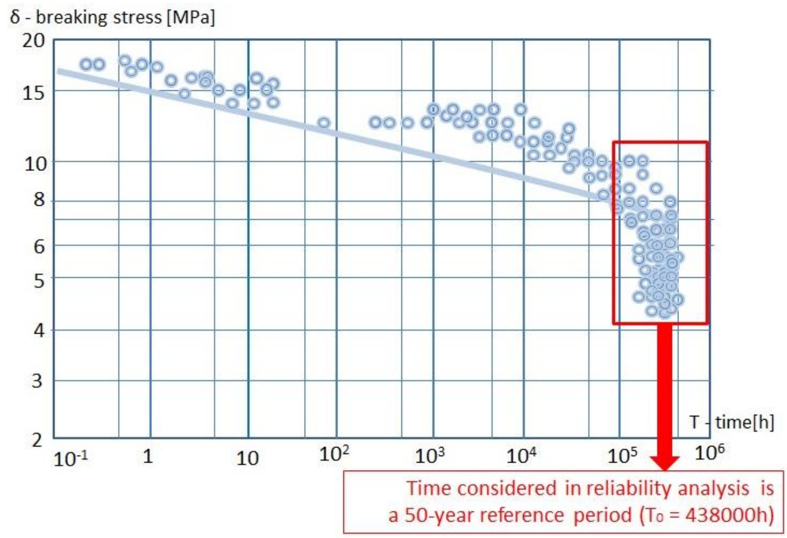

Fig. 3. Time dependence on damage (stress) of PE pipes for the 20°C test temperature – own elaboration on [9]

The influence of variation in geometric parameters of the pipe on the level of reliability was defined for the pipes used widely in Poland which are made of PE 100 and have a mean external diameter of 110 mm, as well as a nominal pressure rating PN equal to 10. Values obtained were compared with those recommended for the reliability index in respect of a reference period equal to 50 years, as well as the Reliability Classes recommended in [1].

4. Case study of calculation

In determining the influence of material geometry on values of the reliability index for PE100 water piping, the assumption was of a pipe of outside diameter $d_n = 110$ mm and a wall thickness equal to 6.6 mm.

The limit-state condition was then defined as (4.1):

$$Z = R - E = \frac{20 \cdot \mathrm{MRS}}{\dfrac{d_n}{e_n} - 1} - \mathrm{PN} \tag{4.1}$$

where: MRS – minimum required strength.

Table 3 and Table 4 sets out the density function and distribution parameters for the primary variables used in probabilistic-method calculations. Coefficients of variation for different variables are as adopted from relevant publications [21].

Table 3. Basic variables dependent on the quality of production, their density functions and distribution parameters

Dependent variable	Density function	Mean	Coefficient of variation	Unit
MRS	lognormal	12.4	0.2	MPa
d_n	normal	110	0.05	mm
e_n	normal	6.6	0.05	mm

Table 4. Basic variables independent of production quality, their density functions and distribution parameters

Independent variable	Density function	Mean	Coefficient of variation	Unit
PN	determined	10	–	MPa

The probabilistic calculations referred to were carried out with account taken of different coefficients of variation for parameters of the piping and pressure, as well as in the face of lack of correlations between primary variables. Particular random variables were treated as stochastically independent (Tables 3 and 4). The probability of limit states for capacity being exceeded were calculated, together with the corresponding reliability indices (Fig. 4).

Reliability is inter alia achieved through the incorporation of materials of appropriate quality. In the same way, the quality of materials implies the achievement by installed infrastructure of the anticipated level of safety and reliability. The analyses conducted revealed a noticeable influence of quality of materials on values obtained for the reliability of piping. A higher coefficient of variation is associated with significantly lower values for the reliability index.

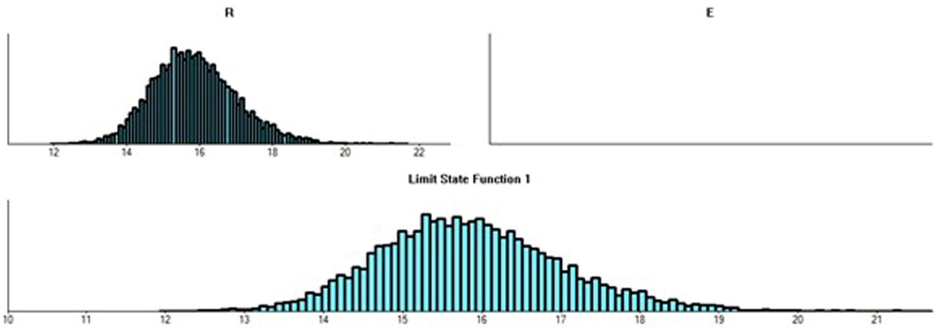

Fig. 4. The limit state function for uncorrelated random variables

In the case of the PE100 piping analyzed, and in line with an assumption that its geometry and pressure are stochastically independent variables, it proved possible to note non-compliance with requirements for Reliability Class RC2 in relation to a 50-year reference period.

A further assessment concerned the sensitivity of the reliability index to each of the independent random variables, in relation to a defined limit-state condition (3.1) – the values of the latter being obtained via Monte Carlo simulations. Sensitivity coefficients were designated in the face of a lack of correlation between primary variables, as well as where a correlation was present between variables for geometry, and where pressures were of 0.5. Analyses further assumed coefficients of variation for geometry and pressure of $v = 0.15$ and $v = 0.05$ respectively. In the case considered, values obtained for the index were of 2.22 and 4.73 respectively.

The bar graph in Fig. 5 presents the sensitivity of the response variable (i.e. the reliability index) to each random variable. Correlation coefficients are normalised by reference to the correlation coefficient of the model error. It may be assumed that the Pearson correlation coefficient corresponds with sensitivity coefficients determined for primary variables.

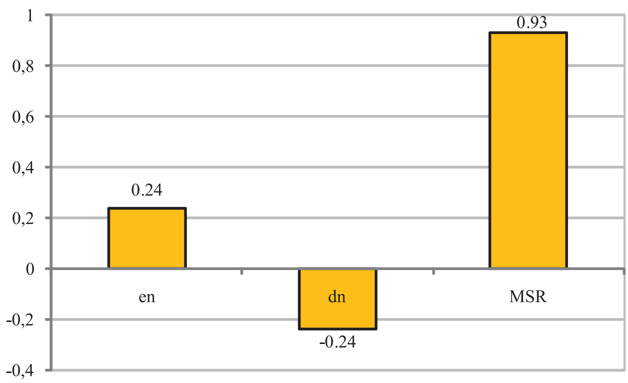

Fig. 5. Sensitivity of the reliability index to random variables of the limit stare function without taking correlation coefficient into account

Figure 6 presents sensitivity of the reliability index to random variables of the limit stare function taking into account the wall thickness and the pressure correlation coefficient at 0.5, Fig. 7 shows correlation between MRS and the effect of capacity, taking into account the correlation coefficient of wall thickness and pressure at 0.5.

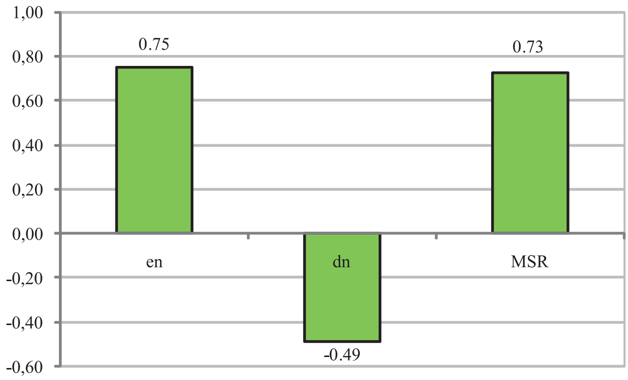

Fig. 6. Sensitivity of the reliability index to random variables of the limit stare function taking into account the wall thickness and the pressure correlation coefficient at 0.5

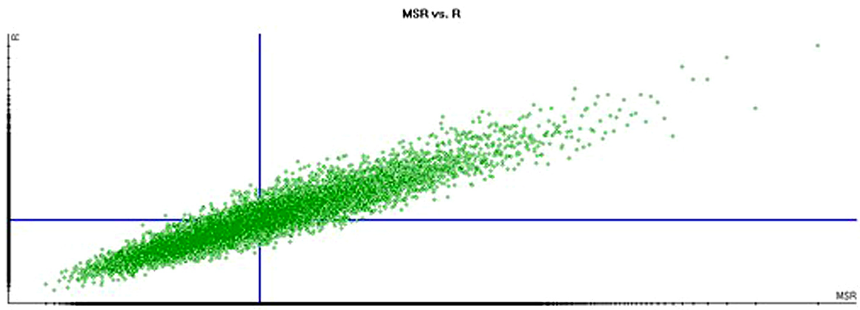

Fig. 7. Correlation between MRS and the effect of capacity, taking into account the correlation coefficient of wall thickness and pressure at 0.5

As will be clear, aspects of key importance when it comes to the operation of pipelines are:

– the course taken by the curve for destructive hoop stress in the wall over time and with a given temperature of operation,
– limit values for service life(durability) under defined conditions (e.g. of pressure and temperature).

The analysis detailed here confirms that the most crucial material variables influencing a change of response (in the reliability index) is pipe-wall thickness. The diameter of water piping has a negative influence on values of this index, while wall thickness and pressure have positive influences. Even as wall thickness is the subject of only limited variation, uncertainty regarding this variable still has a significant influence on reliability values.

Analysis of the results obtained for the sensitivity coefficients shows that, where account is taken of the correlations between primary variables, there is an influence on the result obtained for the index of reliability.

5. Conclusions

Research carried out to date on the polyethylene piping used in pressurised or unpressurised water-supply installations is reinforced by long-term experience with the operation of systems featuring the material, in implying ongoing reliability for a period of at least 100 years [17, 26]. However, a condition for such durability and operability is proper (supervision of) installation work, as well as monitoring over the time the system is in use.

The work detailed here reports an influence of material geometry on the reliability index reported for the analysed system of piping made from PE. The probabilistic analyses carried out on the reliability of PE100 pipes confirmed that higher coefficients of variation for materials are associated with significantly lower values for the reliability index.

Where the analysed PE piping was associated with a coefficient of variation for wall thickness at or over 0.07, this denoted non-compliance with standard PN-EN 1990:2002 as regards the minimum level of reliability recommended for a reference period of 50 years and Reliability Class RC2. In the cases of the other Classes, the condition of reliability continues to be met.

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Wpływ właściwości rur wodociągowych wykonanych z PE na ich trwałość i niezawodność

Słowa kluczowe: niezawodność, rury z PE, właściwości materiałowe, współczynniki zmienności

Streszczenie:

W artykule szczegółowo omówiono właściwości materiałowe rur wykonanych z polietylenu PE. Określono wpływ właściwości materiału, w tym wymiarów geometrycznych na poziom niezawodności przewodów wodociągowych wykonanych z PE100. Otrzymane wartości wskaźnika niezawodności z analiz wykonanych metodami probabilistycznymi porównano z zalecanymi wartościami wskaźnika niezawodności dla okresu odniesienia 50 lat i różnych klas niezawodności (RC). Obliczenia probabilistyczne przeprowadzono uwzględniając różne wartości współczynników zmienności parametrów materiałowych przyjętych jako zmienne losowe oraz korelacji pomiędzy nimi.

W celu określenia wpływu geometrii materiału na wartość wskaźnika niezawodności przewodów wodociągowych wykonanych z PE 100 przyjęto rurę o średnicy zewnętrznej $d_n = 110$ mm oraz grubość ścianki $e_n = 6{,}6$ mm.

Na podstawie przeprowadzonych analiz stwierdzono wpływ geometrii materiału na wartość wskaźnika niezawodności dla analizowanego przewodu wodociągowego wykonanego z PE. Przeprowadzone analizy probabilistyczne dotyczące niezawodności rury PE100 potwierdziły, że wzrost współczynników zmienności materiałów powoduje istotny spadek wskaźnika niezawodności.

W przypadku analizowanego przewodu wodociągowego wykonanego z PE i współczynnika zmienności dla grubości ścianki większego od 0,07 nie są spełnione wymagania normy PN-EN 1990:2002 odnośnie minimalnego poziomu niezawodności zalecanego dla okresu odniesienia 50 lat i klasy niezawodności RC2. Dla pozostałych klas warunek niezawodności jest spełniony.

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