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HYDRAULIC CHARACTERIZATION OF OLD WATER PIPELINES

The increase in the hydraulic resistance of pipes (particularly in those made of steel or cast iron) should be attributed to the encrustation of their walls by precipitation from water or by the products of pipe corrosion. Encrustation is responsible for the decrease and deformation of the pipe cross-section, thus increasing surface roughness in the course of service. The process has been reported by many investigators referred to in this paper. The authors of the present study have investigated the increase of resistance in water supply pipes for many years. They made use of empirical formulae incorporating the relationships between internal diameter, wall roughness, service time, water stability index, and diameter of the pipes.

The study has led to the following findings: 1. The thickness of encrustation is proportional to service time, i.e., it increases with the increasing pipe diameter and decreases with the increasing water corrosivity. 2. The absolute roughness is also proportional to service time, but increases with water corrosivity and decreases with pipe diameter. 3. The thickness of encrustation and wall roughness depend not only on service time, but also on water stability index and water properties, location of the pipes in the network, etc. These factors, however, have not been incorporated in the formulae proposed.

NOTATIONS

a, a_1 – annual increment in encrustation thickness, mm/a,
a_k – annual increment in absolute roughness of pipeline, mm/a,
d – internal pipe diameter, mm,
d_0, d_t – internal diameters of new and t years' old pipe, mm,
Δh – measured head loss, m,
k – absolute pipe roughness,
k_0, k_t – absolute roughnesses of new and t years' old pipes, mm,
k_{ot} – apparent pipe roughness after the service time t determined at the assumption that $d_t = d_0$, mm,
l – length of measured section, m,
t – service time, years,
v – average flow velocity, m/s,

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I_{st} – Strohecker's stability index,
Q – flow rate, m^3/s,
Q_0, Q_t – flow rates in new and t years' old pipes, m^3/s,
Re – Reynolds number,
S_t – thickness of encrustation, mm,
α – significance level,
λ – friction factor,
λ_0, λ_t – friction factors of new and t years' old pipes.

1. INTRODUCTION

Many years' experience in water networks has shown that the hydraulic resistance of the pipes (particularly those made of steel or cast iron) increases with service time as a result of wall encrustation produced by settleable solids or by corrosion.

Our research group has concentrated on the rise in the hydraulic resistance of the water mains since 1968. Some of the results obtained have been presented at a number of national and international conferences (PEŁKA [7], [8], PEŁKA and MIELCARZEWICZ [9]). Under the project sponsored by the State Committee for Scientific Research, we have carried out *in situ* investigations and have analyzed the state-of-the-art. As a result, we have modified some of the formulae which describe the friction factor λ of old water mains (MIELCARZEWICZ et al. [4]).

The value of λ can either be determined using the Darcy–Weissbach formula

$$\lambda = 2gd\Delta h(lv^2)^{-1}, \tag{1}$$

or may be calculated from some other well-known relations, such as that of the Colebrook–White equation:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{k}{3.71d}\right]. \tag{2}$$

In order to calculate the values of λ for the pipes with an increased wall roughness, we can use the Prandtl–Karman equation

$$\lambda = [2\log(3.71\,d/k)]^{-2}. \tag{3}$$

The encrustation of the pipes (especially those made of cast iron or steel) reduces their effective surface and deforms their cross-sections, thus accounting for the decrease of the internal diameter from d_0 to d_1 and for the rise in wall roughness from k_0 to k_t. The result is that the friction factor increases from λ_0 to λ_t. According to literature reports, the roughness of new cast iron pipes approaches 0.6 ± 0.2 mm (PEŁKA [6]), whereas that of new steel pipes ranges approximately from 0.10 to 0.15 mm.

Relations (1)–(3) are also valid for water pipes which have been in service for t years, provided that all the time-variable parameters will be denoted by the subscript t (λ_t, d_t, k_t). The rate, at which the hydraulic resistance of the mains undergoes changes, is affected by a variety of factors, some of them being time-variable. These contributing factors can be itemized as follows:

the material of which the pipe has been made and the lining of the pipe interior;

pipe diameter;

physicochemical and bacteriological composition of the water transported.

Some investigators were interested only in the problem of how the duration of service affected the apparent roughness k_{ot} of the pipe interior (pipe wall) (KORTE and BODARWE [2] and SCHIWING [10]); others extended the range of their studies by including the effect of the water stability index (LAMONT [3], PEŁKA [6]). MOSTKOV [5] showed how the internal diamter of a new pipe d_0 contributed to the k_{ot}-value by determining the annual increment in apparent roughness for the diameter ranges of 150–300 mm and 400–600 mm.

The effect of the service time t on the thickness of encrustation S_t and, consequently, on the internal diameter of the pipeline d_t was investigated by MIELCARZEWICZ et al. [4] and PEŁKA [6].

2. METHODS OF HYDRAULIC INVESTIGATIONS

Our investigations reported in this paper covered the time span from 1980 to 1992. We investigated 85 mains for drinking water supply (78 being made of cast iron and the remaining 8 of steel) in 13 municipalities in the south-west of Poland (MIELCARZEWICZ et al. [4]). Some of the water mains had been studied earlier, i.e. over the period of 1968–1976 (PEŁKA [6]). The results for the city of Świdnica are gathered in table 1. *In situ* investigations were carried out to calculate the λ_t-value using the Darcy–Weissbach equation (1). For this purpose the following parameters were measured: the internal diameter d_t of the pipeline, the length l of the section studied, the head loss Δh along the length l, and the flow velocity v in the pipes.

The d_t-value was calculated as follows:

$$d_t = (d_v d_h)^{0.5}, \tag{4}$$

or

$$d_t = 1.128\, F_e^{\,0.5} \tag{5}$$

where d_v and d_h denote the respective vertical and horizontal diameters of the effective pipe cross-section measured with appropriate probes (PEŁKA [6]), and F_e is the surface of the effective pipe cross-section determined from the measured value of the pipe interior profile (ultrasonic method) (MIELCARZEWICZ et al. [4]).

Table 1

Hydraulic parameters of the water mains of Świdnica

No.	Measuring site	Year	d_0 [mm]	t [a]	d_t [mm]	S_t [mm]	k_t [mm]	Material
1	1	1972	350	95	304.0	23.0	3.93	cast iron
2	2	1972	300	17	283.0	8.5	1.78	cast iron
3	2	1976	300	21	280.0	10.0	2.25	cast iron
4	2	1981	300	26	277.0	11.5	4.18	cast iron
5	2	1989	300	34	275.5	12.3	4.62	cast iron
6	3	1972	300	95	278.0	11.0	3.93	cast iron
7	3	1976	300	99	277.0	11.5	6.95	cast iron
8	3	1981	300	104	273.0	13.5	9.51	cast iron
9	4	1972	200	80	182.0	9.0	6.23	cast iron
10	4	1976	200	84	181.0	9.5	8.14	cast iron
11	4	1981	200	89	180.0	10.0	13.90	cast iron
12	4	1989	200	97	175.0	12.3	16.70	cast iron
13	5	1972	200	32	183.0	8.5	3.90	cast iron
14	5	1976	200	36	182.0	9.00	4.40	cast iron
15	5	1981	200	41	181.0	9.50	6.51	cast iron
16	5	1989	200	49	180.0	9.90	8.81	cast iron
17	6	1972	200	37	191.0	4.50	5.69	cast iron
18	6	1976	200	41	191.0	4.50	6.32	cast iron
19	6	1989	200	54	188.0	6.00	8.03	cast iron
20	7	1972	175	34	173.0	1.00	6.15	cast iron
21	7	1976	175	38	173.0	1.00	6.31	cast iron
22	8	1972	150	81	145.0	2.50	7.69	cast iron
23	8	1976	150	85	145.0	2.50	9.38	cast iron
24	9	1972	150	5	145.0	2.50	0.50	cast iron
25	10	1972	150	43	140.0	5.00	2.94	cast iron
26	10	1976	150	47	140.0	5.00	4.23	cast iron
27	10	1981	150	52	138.0	6.00	5.16	cast iron
28	10	1989	150	60	135.0	7.50	8.10	cast iron
29	11	1989	150	78	128.5	10.80	13.30	cast iron
30	13	1981	125	55	109.0	8.00	8.61	cast iron
31	13	1989	125	63	106.0	9.35	10.40	cast iron
32	13	1989	100	85	78.0	11.00	11.90	cast iron
33	14	1992	400	14	395.4	2.30	0.46	cast iron
34	15	1992	300	19	277.2	11.40	1.59	cast iron
35	16	1992	200	27	182.5	8.75	2.27	cast iron
36	17	1992	100	10	93.1	3.45	7.21	cast iron

To calculate the average thickness of encrustation S_t, we made use of the relation

$$S_t = (d_0 - d_t)/2. \tag{6}$$

The head loss Δh was measured by means of a differential liquid column gauge.

Making use of the maximum flow velocity $v_{\max}$ measured in the pipe axis (using a cylindrical probe described in [6]), the average flow velocity in the pipe section investigated was calculated in terms of (1), as well as using the formula

$$v = v_{\max}(1 + 1.04\,\lambda_t^{0.4})^{-1} \tag{7}$$

derived by Pełka on the basis of 31 measurements of the flow velocity distribution and friction factor in the water mains (PEŁKA [6]).

Maximum flow velocity was calculated as follows:

$$v_{\max} = [2gH(K)^{-1}(\rho_m - \rho_{wm})(\rho_w)^{-1}]^{0.5} \tag{8}$$

where H denotes head difference measured by the swelling probe of the differential manometer; K is coefficient of swelling probe strengthening; ρ_m indicates fluid density in differential manometer at ambient temperature T_a; ρ_{wm} is water density in differential manometer at T_a; and ρ_w is water density in water mains at the temperature T_w.

The values of Δh and H were measured 7–21 times at varying flow velocities. In further computations, use was made of measured average flow velocity values greater than, or equal to, 0.4 m/s. For each measurement the values of λ_t and k_t were calculated using relation (1) and relation (2), respectively. The final k_t-value for each investigated section was the arithmetic mean of all the k_t-values calculated during individual measurements (table 1).

Our investigations involved both steel and cast iron pipes carrying treated ground water or infiltration water. Taking into account the water quality data obtained from many years' investigations of the municipalities of interest, we established the water stability index in terms of the Strohecker relation (9) (table 2):

$$I_{st} = \mathrm{pH} - 11.39 + 2\log A \tag{9}$$

where A is total alkalinity (g of CO_2/m^3).

Table 2

Average stability indices I_{st} of the water treated

Municipality	I_{st}	Municipality	I_{st}
Brzeg	− 0.80	Racibórz	− 0.33
Kłodzko	− 0.76	Strzelce Opolskie	+0.06
Lewin Brzeski	− 1.51	Strzelin	+0.25
Milicz	+0.08	Świdnica	− 0.31
Oleśnica	− 0.18	Zawadzkie	− 0.16

Making use of the results from *in situ* investigations, the contributions of the service time t, the pipe diameter d_0 and the water stability index I_{st} to the thickness of encrustation S_t on the pipe walls (and, consequently, to the values of d_t and k_t) were investigated.

3. GROWTH OF ENCRUSTATION S_t

It has been assumed that S_t is a function of time according to the relation

$$S_t = S_0 + At^b \tag{10}$$

where A may be function of the diameter d_0 and the stability index I_{st}. Since encrustation is absent in new pipes ($t = 0$), the term S_0 in the equation of the regression line equals zero ($S_0 = 0$).

Two forms of relation (10), i.e. linear and exponential, were considered:

$$S_t = (A_1 + A_2 d_0 + A_3 I_{st})t \tag{11}$$

and

$$S_t = At^{C1} d_0^{C2} (I_{st} + u)^{C3} \tag{12}$$

where u is a numerical value greater than $/I_{st\,\min}/$, because I_{st} can take values smaller than zero.

For municipalities with water supply from more than one source of varying water quality (and also for purpose of generalizing the results obtained for the urban areas investigated), we can define the effect of the I_{st}-value on the S_t-value in terms of (11) and (12). But when the municipality draws drinking water from a single source, the stability index undergoes only insignificant changes and relations (11) and (12) take the folowing forms:

$$S_t = (A_1 + A_2 d_0)t \tag{13}$$

and

$$S_t = At^{C1} d_0^{C2}, \tag{14}$$

respectively, because the contribution of I_{st} to S_t cannot be determined.

The numerical parameters A_1 and A_2 for relation (13) were determined *via* the same route as for a multiple linear correlation, whereas the parameters A, C_1 and C_2 for relation (14) were established in the same manner as for a curvilinear correlation or for a linear multiple correlation after its logarithmization. Hence:

$$\ln S_t = \ln A + C_1 \ln t + C_2 \ln d_0. \tag{15}$$

When the effect of d_0 on S_t according to (13), (14) and (15) was not significant on the level $\alpha = 0.05$, the contribution of the service time t alone was analyzed, using the relation

$$S_t = a_1 t^m, \tag{16}$$

or

$$S_t = at. \tag{17}$$

For those municipalities, in which the number of mains investigated was smaller than 6, relation (17) included the arithmetic mean of the parameter a.

Making use of (13) and (14), particular formulae were derived to describe the water networks of several municipalities in which investigations were underway. One of these was the city of Świdnica with 17 investigated cast iron mains of diameters ranging between 100 and 400 mm. Some of those mains were investigated several times within several years' intervals (PEŁKA [6], MIELCARZEWICZ et al. [4]), yielding 35 sets of the data measured. Analysis of correlation in terms of (13) and (14) showed that relation (14) provided more reliable results. The numerical parameters A, C_1 and C_2 in (14) were established in the same way as for correlation (15). Thus we have

$$S_t = 0.0169\, t^{0.439} d_0^{0.841} \tag{18}$$

where d_0 and t are expressed in mm and years, respectively. The real standard error is $SE(t, d_0) = 3.42$ mm, the correlation coefficient and significance level being $R = 0.666$ and $\alpha = 0.0093$, respectively.

Figure 1 compares the measured thickness of encrustation S_t with those calculated in terms of (18).

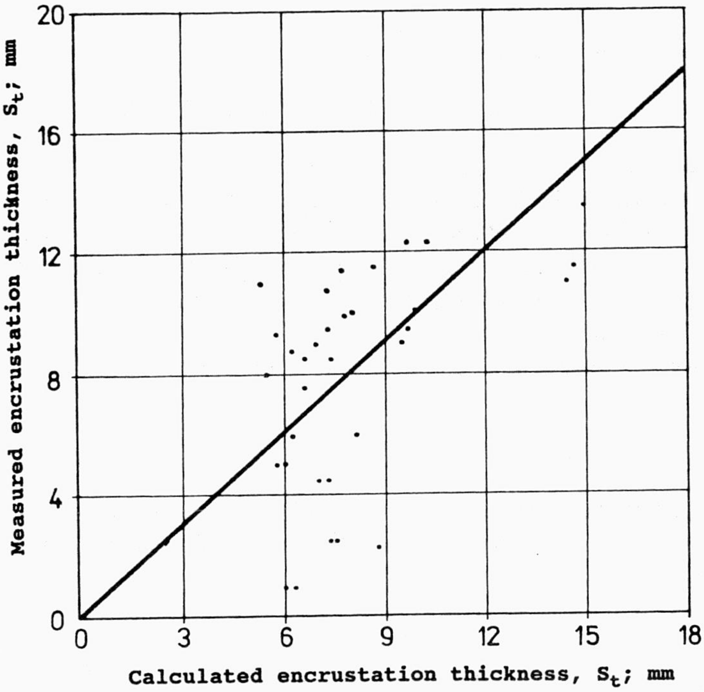

Fig. 1. Measured and calculated (in terms of (18)) thicknesses of encrustation (S_t) in the water mains of Świdnica

Neglecting the effect of pipe diameter on encrustation thickness and adopting the model (16), we obtain

$$S_t = 1.71\, t^{0.362} \tag{19}$$

at a standard estimation error $SE(t)$ of 4.0 mm.

Adopting a linear regression according to (17), we have

$$S_t = 0.133\, t \tag{20}$$

and an estimation error $SE(t) = 4.51$ mm.

Thus the effect of pipe diameter d_0 on the thickness of pipe encrustation rising with the increasing service time was found to be significant, so it is no longer negligible. The time of service still remains an important contributing factor.

Attempts were also made to determine some universal relations between the variables incorporated in (11) and (17). For this purpose, use was made of 81 results obtained while investigating the water of 10 municipalities. The resources of water supply and the treatment methods applied did not change significantly during service. The number of investigated mains varied from one municipality to another, ranging from 1 to 17. Determination of correlation according to (11) revealed the following significance levels: $\alpha = 0.0003$ for service time t; $\alpha = 0.0015$ for the variable td_0 and $\alpha = 0.0055$ for the variable tI_{st}. After substitution of numerical values for the parameters A_1, A_2 and A_3 we obtained

$$S_t = (0.088 + 0.00031\, d_0 + 0.0084\, I_{st})t \tag{21}$$

with a standard error $SE(t, d_0, I_{st}) = 3.66$ mm.

Figure 2 provides calculated (in terms of (21)) and measured values of S_t. The correlation established by relation (12) yielded a low significance level for the stability index I_{st}, which amounted to only $\alpha = 0.44$. Neglecting I_{st} in relation (12) gives relation (14). The correlation determined by virtue of (14) showed a significance level $\alpha = 0.052$ for the diameter d_0.

If we neglect the effect of d_0 and I_{st} on S_t in relation (11), we obtain a particular form of relation (16):

$$S_t = 0.105\, t^{1.04}. \tag{22}$$

The correlation between the variables in (21) has a significance level of 0.0001 and a standard error $SE(t) = 3.56$ mm. Assuming a linear relationship between S_t and t (by virtue of (17)) gives

$$S_t = 0.118\, t \tag{23}$$

with a correlation on a significance level $\alpha = 0.0001$ and a standard error $SE(t) = 4.0$ mm.

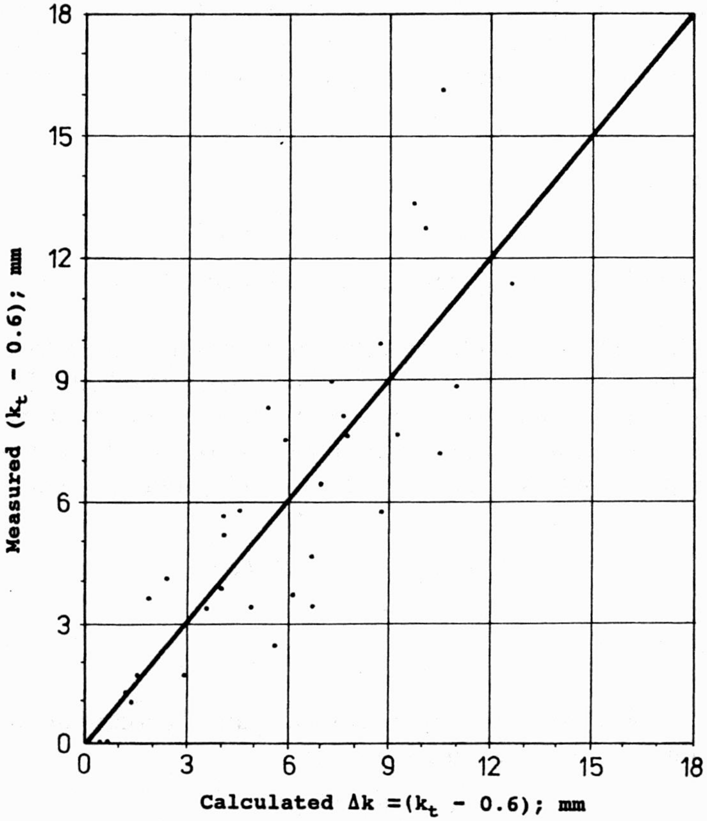

Fig. 2. Measured and calculated (in terms of (21)) thicknesses of encrustation (S_t) in the water mines of the municipalities under study

Relations (21), (22) and (23) are of utility in the approximate estimation of S_t when hydraulic investigations are lacking. The formulae have been derived by making use of the measured results for cast iron mains of diameters ranging between 100 and 400 mm. The mains carry treated water of a stability index I_{st} varying from (–)1.51 (corrosive water) to (+) 0.25 (non-corrosive water).

4. INCREASE OF WALL ROUGHNESS k_t

It has been assumed that the absolute pipe wall roughness is a function of the service time t and the initial roughness k_0 by virtue of

$$k_t = k_0 + Bt^m. \tag{24}$$

For the purpose of analysis it has been anticipated that $k_0 = \text{const} = 0.6$ mm (PEŁKA [6]). The term B in relation (24) may be a function of the diameter d_0 and the stability index I_{st}. Two forms of (24) were considered, i.e. the linear one

$$k_t = k_0 + (B_1 + B_2 I_{st})t \tag{25}$$

and the exponential one

$$k_t = k_0 + Bt^{a1} d_0^{a2} (I_{st} + u)^{a3} \tag{26}$$

where u is a numerical value greater than $I_{st\,\min}$ because I_{st} can take values smaller than zero.

Relations (25) and (26) may be of utility in determining the effect of I_{st} on the increment of k_t only if the pipeline is fed by more than one source of varying water quality, or if use is made of a generalization of results coming from more than one municipality. If the mains are fed by a single source and I_{st} does not undergo significant variations with service time, relations (25) and (26) will reduce to the form

$$k_t = k_0 + (B_1 + B_2 d_0)t \tag{27}$$

and

$$k_1 = k_0 + Bt^{a1} d_0^{a2}, \tag{28}$$

respectively. Thus, when the correlation between k_t and d_0 according to (27) and (28) was insignificant ($\alpha = 0.05$), we made use of

$$k_t = k_0 + a_0 t^m, \tag{29}$$

or

$$k_t = k_0 + a_k t. \tag{30}$$

When the number of mains investigated in the municipality was smaler than 6, we calculated the arithmetic mean of the term a_k incorporated in (30), assuming that $k_0 = 0.6$ mm. Thus, for a number of municipalities (in which the water mains were studied), we derived particular formulae by making use of relations (28)–(31). Again, for the purpose of illustration, we consider the city of Świdnica for which 35 measured data sets were obtained on water mains with diameters d_0 ranging between 100 and 400 mm. Assuming that $k_0 = 0.6$ mm, and after calculating the values of B_1 and B_2, relation (28) takes a particular form:

$$k_t = 0.6 + (0.187 + 0.00039\, d_0)t. \tag{31}$$

The values of the parameters B_1 and B_2 were defined on the significance level of 0.0001. By virtue of (30) the correlation between the variables is also significant on the level of 0.0001, the standard estimation error being $SE(t, d_0) = 2.10$ mm.

The fitting of the regression equation is shown in figure 3. The correlation established in terms of (28) showed that the effect of the variable d_0 was not significant on the level $\alpha = 0.05$ ($\alpha = 0.066$), so we made use of (29) and (30) to determine the effect of service time t on the k_t-value alone. After having determined a_0 and m, relation (29) became

$$k_t = 0.6 + 0.00102\, t^{2.12}. \tag{32}$$

The values of the parameters a_0 and m were determined on the significance level of 0.00001, correlation (31) was significant on the level $\alpha = 0.00001$, and the standard estimation error was $SE(t) = 3.49$ mm.

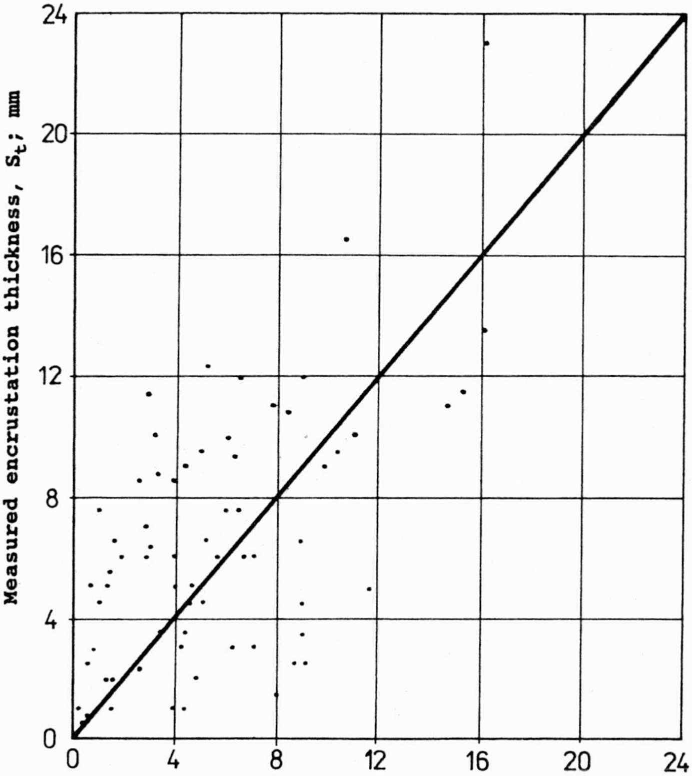

Fig. 3. Measured and calculated (in terms of (31)) absolute roughness ($\Delta k = k_t - 0.6$) in the water mains of Świdnica

After substitution of a numerical value for the parameter a_k, relation (30) takes the form

$$k_t = 0.6 + 0.104\, t. \tag{33}$$

The parameter a_k was calculated on the significance level of 0.0001. The significance level for relation (33) is $\alpha = 0.0001$, the standard estimation error being $SE(t) = 2.72$ mm.

By virtue of (25) and (26) and making use of 81 results from investigations of water mains in 10 municipalities, we aimed at deriving universal formulae, such that would relate the roughness k_t of the pipeline not only to the service time t and the pipe diameter d_0, but to the water stability index I_{st} as well. Thus, determining the correlation according to (25) and assuming that $k_0 = 0.6$ mm, we arrived at the following regression equation:

$$k_t = 0.6 + (0.119 - 0.000203\, d_0 - 0.121\, I_{st})\, t \tag{34}$$

with a significance level $\alpha = 0.0001$ and a standard estimation error $SE(d_0, I_{st}, t) = 2.70$. The significance levels for the variables td_0 and tI_{st} amount to 0.006 and 0.0001, respectively. It should be noted that relation (34) is only valid for $t < 100$ years, $d_0 = 100–400$ mm, and $I_{st} = (-)1.51$ to $(+)0.25$.

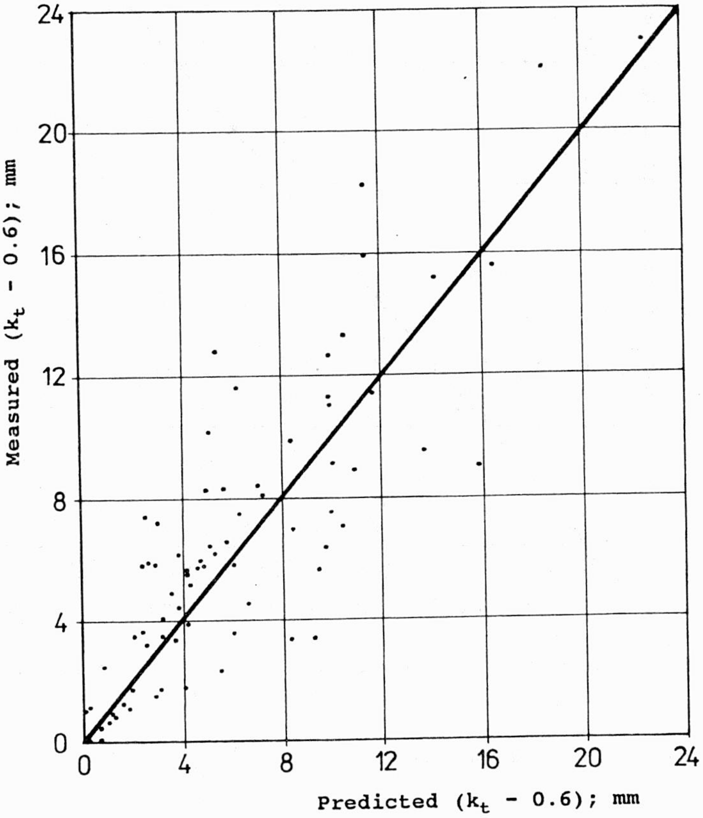

Fig. 4. Measured and calculated (in terms of (34)) absolute roughness ($\Delta k = k_t - 0.6$) in the water mains of the municipalities under study

Figure 4 provides the calculated (by virtue of (34)) and measured absolute values of the roughness k_t for the pipelines in all municipalities investigated.

5. SUMMARIZING COMMENTS

Statistical processing of the results measured showed that the parameters characterizing the hydraulic behaviour of cast iron pipes are influenced by the

age of the pipeline,
internal diameter of the pipes,
stability index of the water carried by the pipes.

The results obtained were presented in the form of empirical formulae which enable approximate estimation of the hydraulic resistances for old iron mains of water networks, as well as predictions for the purpose of further service.

In order to achieve further generalization of the formulae proposed, intensive *in situ* studies are needed, which allows us to increase the available data base.

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CHARAKTERYSTYKA HYDRAULICZNA EKSPLOATOWANYCH PRZEWODÓW WODOCIĄGOWYCH

Powodem wzrostu oporności hydraulicznej rurociągów (szczególnie stalowych i żeliwnych) jest inkrustacja wewnętrznej ich powierzchni osadami wytrącającymi się z wody bądź produktami korozji.

Narastająca, w miarę upływu czasu, inkrustacja powoduje zmniejszenie i deformację przekroju poprzecznego rurociągu, a także wzrost chropowatości wewnętrznej jego powierzchni. Proces ten był przedmiotem szeregu prac badawczych przytoczonych w niniejszym artykule.

Autorzy prezentowanej pracy od wielu lat zajmują się procesem wzrostu oporności przewodów wodociągowych i opracowali formuły empiryczne uwzględniające zależności występujące między średnicą wewnętrzną, chropowatością ścian, czasem trwania eksploatacji, indeksem stabilności wody a średnicą rur nowych.

Osiągnięte wyniki badań umożliwiły sformułowanie wniosków:

1. Grubość warstwy inkrustacji rośnie proporcjonalnie do czasu eksploatacji i zwiększa się wraz ze wzrostem średnicy rurociągu, maleje zaś w miarę wzrostu korozyjności wody.

2. Bezwzględna chropowatość ścian rurociągów rośnie wraz z czasem trwania eksploatacji rur i ze wzrostem korozyjności, a maleje wraz ze wzrostem średnicy rurociągu.

Grubość warstwy osadów i chropowatość ścian rurociągów zależy nie tylko od czasu trwania eksploatacji, indeksu stabilności wody i średnicy rurociągu, ale także od takich czynników jak np. prędkość przepływu wody, inne właściwości wody, umiejscowienie przewodu w sieci wodociągowej itp. Czynniki te nie zostały uwzględnione w zaproponowanych formułach empirycznych.