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Comparative study on shotcrete repair solutions of buried steel pipelines

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Abstract. The research aims to optimize the rehabilitation works of steel buried pipes after their lifespan is reached. It is based on objective real situations met in the Romanian agricultural irrigation system. The study proposes an analytical approach to predict the behavior of the rehabilitated pipelines initially subjected to various corrosion rates, from low to high agressivity of the environment. Besides traditional lining with reinforced concrete, a new trend given by the relative modern structural repair mortars is considered. The time behavior of the shotcrete lining is estimated based on information given by the appropriate European norm. The results question the design philosophy, still not clarified in the field, and emphasize the superior performance of modern cementitious materials, both in terms of technical performance and economical efficiency. Future research perspectives are also underlined with regard to the new materials meeting sprayed concrete technology requirements, and design philosophy.

1 Background

1.1 General considerations

Steel pipelines are traditionally used to transport liquids or gases over long distances, during time proving reliability and cost efficiency. Such pipelines operate at high pressures and sometimes elevated temperatures. During service, pipelines endure damage due to built-in metallurgical defects, welding imperfections and interaction with internal and external surroundings.

Most pipeline systems were designed for a lifespan of 30 years but are still in service after more than 40 years. External corrosion is the most frequent cause for buried pipeline failures. It reduces strength capacity, affects structural integrity and results in shorter service life and increased vulnerability. Besides service disruption, deterioration could end in leakage and bursts that may provoke significant financial losses and serious environmental damage.

When dealing with corrosion, repair techniques must comply with the demands to prevent future corrosion, leakage sealing and restore strength performance. When affected by extended damage, pipelines repair presume full-encirclement sleeves. Spraying thin layers of concrete/mortar inside pipes is a traditional technique, which improves hydraulic properties and ensures corrosion protection. However, to control strength and cracking, steel mesh is needed: leading to thick layers and steel consumption. Thus, the technique becomes expensive, time consuming and hard to implement on long segments.

Nowadays, the new generation of discrete reinforced cementitious materials (e.g., fiber reinforced concrete, engineered cementitious materials, structural repair mortars etc.) deliver versatile alternatives. Even if they require full flow diversion, pipe cleaning and primer coating, their use ensures fulfillment of all demands and provides durability of the repaired systems as well.

1.2 The Romanian irrigation system

The water supply for Romanian agriculture is ensured by an irrigation system built mainly between 1971 and 1989 (Figure 1), which covers an area of about 29,920 km^2. The River Danube provides 85 % of the water transported through 26,700 km of buried pipelines and 10,670 km of channels.

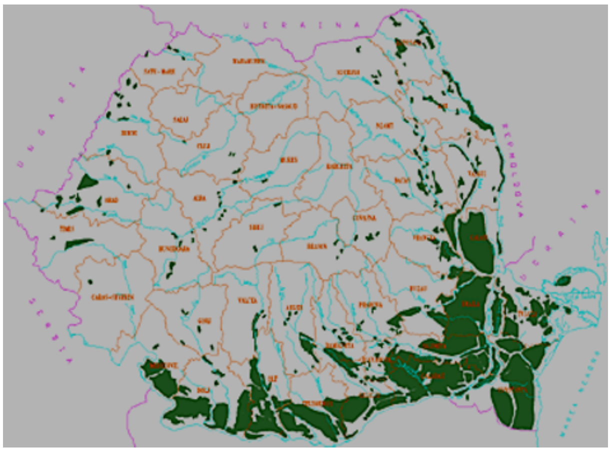

Fig. 1. Areas operated by the Romanian irrigation system.

Given the extended service and poor technical state of the system (e.g., about 75 % of the capacity was inoperable at the beginning of the decade), in 2016 a

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governmental effort was launched to rehabilitate the public system and guarantee access to the all end users from the served zones.

2 Research significance

The study aimed to optimize the interventions made at the steel buried pipes from the Covurlui plain (Galați county, as shown in Figure 2). These were in service since 1985-1989 and are under a comprehensive rehabilitation program.

Fig. 2. Irrigation system emplacement.

In previous work, Mircea et al. [1] presented a successful rehabilitation project made by shotcrete reinforced with steel welded meshes. This research refers to the rehabilitation by sprayed concrete, through a comparative analysis. Besides the traditional reinforced concrete solution, a structural repair mortar class R4 is considered. After detailed but limited technical inspections and tests on materials, an analytical model was proposed and the solutions are objectively compared.

Various pipe diameters and functions (e.g., siphon, adduction or suction) were considered. Table 1 presents data for three characteristic pipes, analyzed forward within the paper.

Table 1. Pipe characteristics.

Characteristic \ Pipe symbol	P1	P2	P3
Exterior diameter D_e [mm]	3500	3100	1800
Pipe thickness t_{ps} [mm]	10	10	10
Steel pipe yielding strength f_{spy} [MPa]	240	240	240
Modulus of elasticity E_{sp} [GPa]	200	200	200
Working pressure p_w [MPa]	0.62	0.95	0.80
Hydraulic shock pressure p_{hs} [MPa]	1.00	1.30	2.00

3 Analysis and modeling

3.1 Inspections and preliminary remarks

Besides local damage (e.g., rusted grilles and flanges, silting etc.), general electrochemical corrosion was noticed on several pipes during technical inspections. The measurements performed with ultrasonic thickness gauges revealed steel section reductions on average up to 41.7 % (i.e., 4.17 mm). However, a few zones fully corroded were also found.

According to EN ISO 12944-2:2018 [2], pipes are framed in the corrosion class IM 3.

Considering corrosion rates from low (i.e., 20 µm/year for soil without aggressivity) up to high (i.e., 250 µm/year for soil with high aggressivity), Table 2 presents an estimation of the possible pipe thicknesses after 30 years of service and processing for rehabilitation.

Table 2. Estimated pipe thickness.

Corrosion rate [µm/year]	Remaining thickness [mm]	
	gross	effective
20	9.40	9
50	8.50	8
100	7.00	6
150	5.50	5
200	4.00	3
250	2.50	2

Table 3 presents the framing of the pipe lining in exposure classes on the ground given by EN 1992-1-1 [3].

Given a design lifespan of 30 years for the rehabilitated pipes, a concrete class C 30/37 and a pre-dosed repair mortar class R4 were considered.

Table 3. Framing of shotcrete lining in exposure classes.

Risk	Exposure class
Corrosion induced by carbonation	XC 4 - cyclic wet and dry environment
Chemical attack	XA 3 - highly aggressive chemical environment

3.2 Materials properties

The results of the mechanical tests (Figure 3) made on the concrete C 30/37 and repair mortar R4 mixes at the age of 28 days are summarized in Table 4.

Table 4. Mean experimental strengths.

Mix	f_{cm} [MPa]	f_{ctm} [MPa]	τ_{bm} [MPa]
Concrete C 30/37	39.2	3.1	0.6
Structural repair mortar R4	58.4	10.3	2.3

Characteristic strengths and secant Young's modulus were determined using standard relations given by EN 1992-1-1 [3]. The results are shown in Table 5.

Fig. 3. Specimens and tests.

Table 5. Characteristic strengths and Young's modulus.

Mix	f_{ck} [MPa]	f_{ctk} [MPa]	E_{cm} [MPa]
Concrete C 30/37	31.2	2.1	33144
Structural repair mortar R4	50.4	7.2	37345

For the case of reinforced concrete, a steel mesh with characteristic yielding strength of f_{yk}=460 MPa and Young's modulus E_s=200 GPa was considered to ensure both cracking control and resistance capacity.

3.3 Basics of the analytical model

The proposed analytical model considers a perfect bonding assumption (Figure 4) between the steel pipeline and the shotcrete lining. This statement may be considered valid even for the case of concrete with much lower bonding strength (see Table 4) because the steel reinforcing meshes require numerous fixing points, that result also in improved intimate contact.

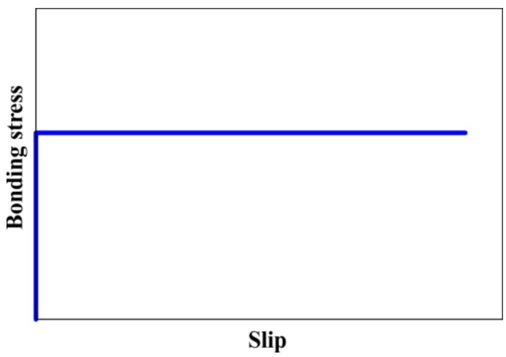


Fig. 4. Perfect bond followed by free slip assumptions.

The axial restraint degree between the initial steel pipe and the shotcrete lining is introduced [4, 5] to consider shrinkage in analysis

$$R = \frac{\text{free slip - restrained slip}}{\text{free slip}} \tag{1}$$

resulting in

$$R = \frac{1}{1 + \dfrac{A_c E_{c,eff}}{A_{sp} E_{sp}}} \tag{2}$$

where A_c and $E_{c,eff}$ are the shotcrete normal area and the effective Young's modulus of shotcrete, and A_{sp} and E_{sp} are the steel pipe normal area and modulus of elasticity. The areas depend by the direction considered in analysis, the transversal ring cross-sectional areas for the longitudinal direction, and the area of the unit strips on the radial direction.

The corresponding tensile stress in the shotcrete due to restrained shrinkage becomes

$$\sigma_{cs} = R \varepsilon_{cs} E_{c,eff} \tag{3}$$

with ε_{cs} the free shrinkage strain (i.e., autogenous and drying shrinkage are considered) and $E_{c,eff}$ calculated according to the European norm [3]. Integrated on the entire surface of shotcrete lining, the axial force results as

$$N_{cs} = R \varepsilon_{cs} E_{c,eff} A_c \tag{4}$$

The internal pressure p (i.e., p_w or p_{hs}) in the pipe of internal diameter D_i generates the axial tensile forces as follows:

- in the radial direction

$$N_r = p \frac{D_i}{2} \tag{5}$$

- in the longitudinal direction

$$N_l = p \frac{D_i}{4} \tag{6}$$

Finally, the axial forces are distributed to the steel pipe and shotcrete proportional with their axial stiffness. The total axial forces are:

- In the old steel pipe

$$N_{r(l),sp} = N_{r(l)} \frac{A_{sp} E_{sp}}{A_{sp} E_{sp} + A_c E_{c,eff}} \tag{7}$$

- In the new shotcrete lining

$$N_{r(l),c} = N_{r(l)} \frac{A_c E_{c,eff}}{A_{sp} E_{sp} + A_c E_{c,eff}} + N_{cs} \tag{8}$$

In the case of ordinary reinforced concrete lining, the influence of reinforcement increases the effective area. Therefore, the idealized cross-sectional area A_{ci} should be introduced

$$A_{ci} = \iint_{A_c} \frac{E(x,y)}{E_{c,eff}} dxdy = A_c + \left(\frac{E_s}{E_{c,eff}} - 1 \right) A_s \qquad (9)$$

where A_s is the reinforcement area.

All above relations are time dependent due to the influence of creep. Finally, standard relations [3] are applied to control the crack width and ensure water tightness of the rehabilitated ensemble. The resistance capacity must provide an allowable tensile stress higher than the hydraulic shock pressure both in the steel pipe and the shotcrete lining. If ordinary reinforced concrete is implemented, only the reinforcement may be considered, and the tension stiffening neglected.

To meet the above performance at the reinforced concrete solution, c=20 mm concrete cover was adopted, and the layer of concrete taken with a thickness t_c=50 mm. Just the quantity of reinforcement was varied. In the second solution, shotcrete with structural repair mortar class R4, the lining thickness was varied t_c.

4 SYNTHETIC RESULTS

4.1 Reinforced concrete solution

Table 6 presents the time dependent evolution of the free shrinkage strain (i.e., autogenous shrinkage cumulated with the drying shrinkage) and the creep coefficient for a relative humidity of 90 % on radial and longitudinal direction of the pipes.

Table 6. Free shrinkage strain and creep coefficient (P1/P2/P3).

Shotcrete age [years]	Free shrinkage strain ε_{cs} [mm/m]	Creep coefficient φ
Radial direction		
1	0.169 / 0.179 / 0.175	1.35 / 1.33 / 1.31
5	0.185 / 0.195 / 0.190	1.79 / 1.77 / 1.74
10	0.187 / 0.197 / 0.192	1.91 / 1.89 / 1.86
15	0.188 / 0.198 / 0.193	1.96 / 1.93 / 1.90
20	0.188 / 0.198 / 0.193	1.99 / 1.96 / 1.93
25	0.188 / 0.198 / 0.194	2.00 / 1.98 / 1.95
30	0.188 / 0.198 / 0.194	2.01 / 1.99 / 1.96
Longitudinal direction		
1	0.190 / 0.192 / 0.193	1.52 / 1.58 / 1.19
5	0.197 / 0.198 / 0.194	1.90 / 1.96 / 1.64
10	0.198 / 0.198 / 0.195	1.99 / 2.04 / 1.78
15	0.198 / 0.199 / 0.195	2.02 / 2.07 / 1.83
20	0.199 / 0.199 / 0.195	2.04 / 2.09 / 1.86
25	0.199 / 0.199 / 0.195	2.05 / 2.10 / 1.88
30	0.199 / 0.199 / 0.195	2.06 / 2.10 / 1.90

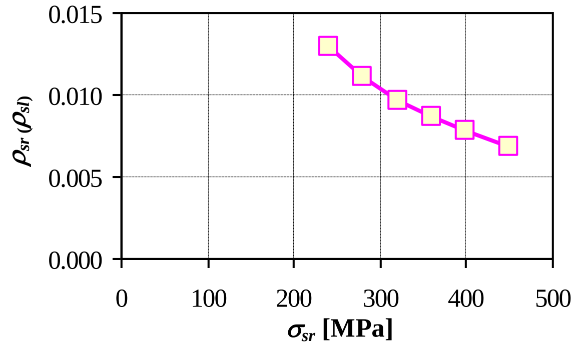


Fig. 5. Minimum reinforcing coefficient for cracking control.

Figure 5 shows the reinforcement coefficients corresponding to the radial ρ_{sr} and longitudinal ρ_{sl} directions, resulting from the control of cracking corresponding to maximum crack width of 0.1 mm and various stress values after cracking σ_s, and resistance capacity respectively. Figure 6 presents the same coefficients derived to ensure the resistance capacity.

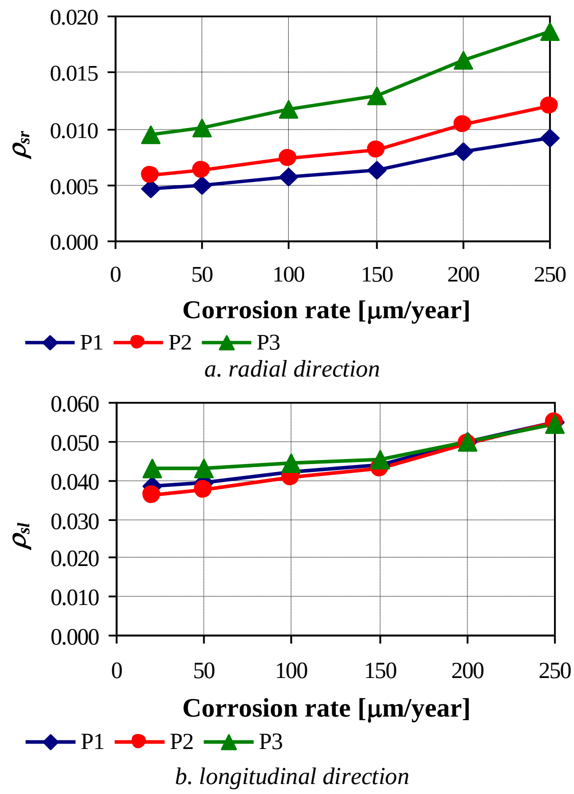


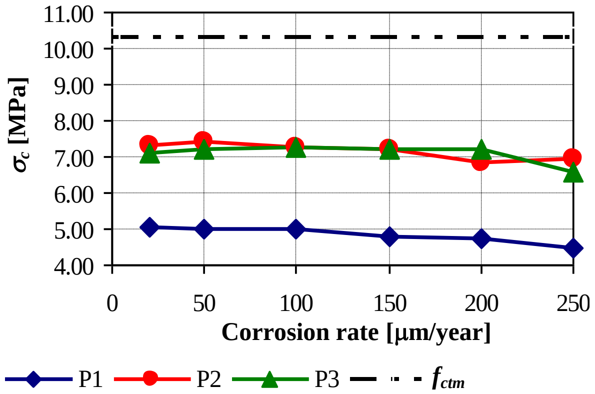
Fig. 6. Minimum reinforcing coefficient for resistance capacity.

4.2 Structural repair mortar R4 solution

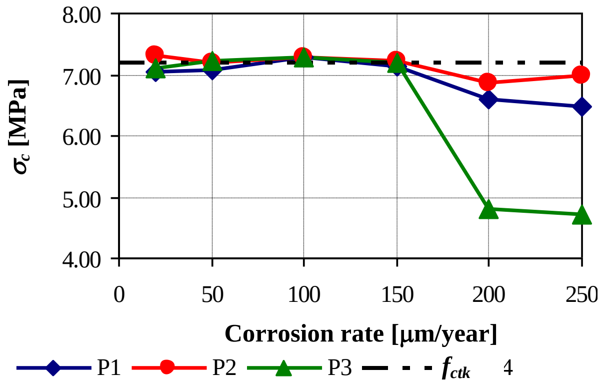
Table 7 presents the time dependent evolution of the free shrinkage strain and the creep coefficient for a relative humidity of 90 %.

Table 7. Free shrinkage strain and creep coefficient (P1/P2/P3).

Shotcrete age [years]	Free shrinkage strain ε_{cs} [mm/m]	Creep coefficient φ
Radial direction		
1	0.175 / 0.183 /	1.28 / 1.27 / 1.25
5	0.190 / 0.188 /	1.50 / 1.41 / 1.38
10	0.192 / 0.191 /	1.54 / 1.45 / 1.40
15	0.193 / 0.191 /	1.56 / 1.47 / 1.41
20	0.193 / 0.191 /	1.56 / 1.48 / 1.41
25	0.194 / 0.191 /	1.57 / 1.48 / 1.42
30	0.194 / 0.191 /	1.57 / 1.48 / 1.42
Longitudinal direction		
1	0.196 / 0.192 /	1.40 / 1.29 / 1.21
5	0.199 / 0.194 /	1.64 / 1.43 / 1.26
10	0.199 / 0.197 /	1.69 / 1.47 / 1.29
15	0.199 / 0.198 /	1.70 / 1.50 / 1.31
20	0.199 / 0.198 /	1.71 / 1.50 / 1.32
25	0.199 / 0.198 /	1.72 / 1.50 / 1.32
30	0.199 / 0.198 /	1.72 /1.50 / 1.32

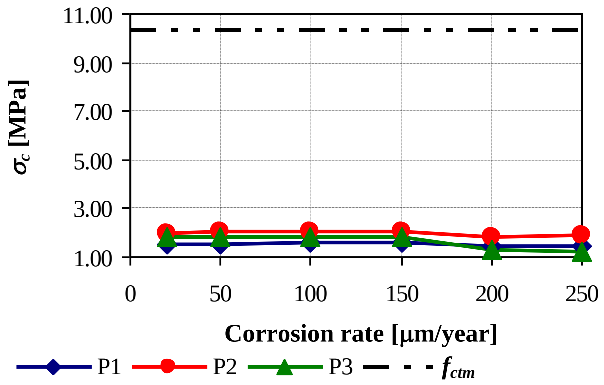


a. under working stress

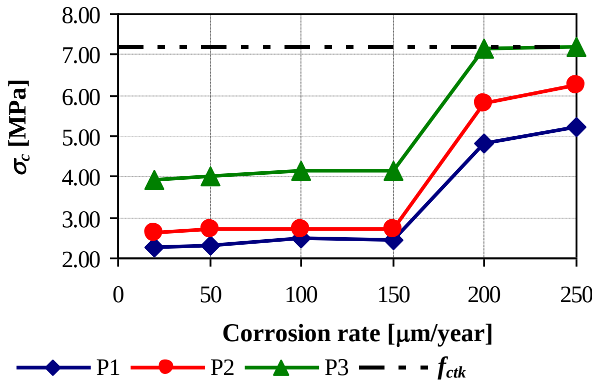


b. under hydraulic shock

Fig. 7. Shotcrete radial tensile stress with corrosion rate.



a. under working stress



b. under hydraulic shock

Fig. 8. Shotcrete longitudinal tensile stress with corrosion rate.

Figures 7 and 8 emphasize the tensile stresses related to the shotcrete lining depths shown in Table 8. With two exceptions, the depths resulted from the longitudinal resistance criterion, the other being related to the same criterion on the radial direction.

Table 8. Shotcrete depths for rehabilitated pipes.

Corrosion rate [µm/year]	P1	P2	P3
	t_c [mm]		
20	55	70	80
50	60	80	85
100	70	95	100
150	80	105	110
200	35	40	60
250	40	45	70

4 Final Remarks

It is evident the reinforced concrete shotcrete lining requires high work costs and low material costs, and vice versa is valid for the repair mortar R4 lining. After a global analysis, the authors are inclined to recommend the second alternative, which seems to be more reasonable from economical motivations, but not entirely.

At the present, there is not much research done on the topic. Therefore, more reliability analyses may accept lower values for the allowable stresses under a hydraulic shock (i.e., water hammer), phenomenon that is also subjected to technical equipment control. Moreover, given the relative reduced social and economical impact of such an event, a mean tensile strength is recommended to be considered as allowable stress under such an accidental situation. Thus, the acceptable shotcrete depths reach reasonable values of 20-50 mm - very competitive from both the technical and economical perspective.

More research is needed in order to quantify more accurately the long-term behavior of the rehabilitation shotcrete lining, both for ordinary/traditional reinforced concrete and structural repair mortars. Other cementitious materials should also be considered, as soon as their fresh state properties become compatible with the sprayed concrete technology.

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