Problems related to storage of acid substances in reinforced concrete tanks

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Abstract. In an industrial plant with continuous production, there were two breakdowns in the company's sewage treatment plant for liquids with a high sulfuric acid content. Despite securing the underground walls of reinforced concrete tanks with protective coatings resistant to the impact of highly concentrated solutions with sulfuric acid as well as liquids with high alkaline concentration, there was sulphate corrosion destroying the insulation and structural reinforcement. The reasons for the failure were simultaneously improperly selected protective coatings and the technology of applying these coatings to the walls of tanks. In addition, the appearance of cracks in concrete and in polypropylene slabs is influenced by the rheology of construction materials, which is permanently ignored in the construction of multi-layer walls.

1. Introduction
The acid corrosion resistance is a crucial issue in the case of various range of concrete structures. Interaction between loading, corrosion, and serviceability of reinforced concrete was described in work [1]. Numerous examples of sulphuric acid impact on concrete are given in references, starting from underground utilities [2], through concrete beams exposed to acid rains [3] up to general impact of chemical hazards in construction industry [4]. The importance of corrosion is emphasized in terms of adhesion between reinforcement and concrete [5] and bearing resistance of concrete elements [6].

2. Description of underground tanks construction
In one of the industrial plants, there is a monolithic, rectangular, underground reinforced concrete tank built in 2005 (figure 1) for liquids with high concentration of sulfuric acid and liquids with a strong alkaline reaction. The tank is part of the technological line of the factory sewage treatment plant. Its height is 4.850 m, the length of the longer side is 11.3 m and the shorter one is 8.9 m. The tank is internally divided into 7 separate chambers, each having the capacity of about 30 m³. The thickness of the bottom plate is 0.4 m, the thickness of the side and partition walls is 0.3 m. The thickness of the bottom slab without offsets placed on the B10 concrete is 10 cm. The ground water level is below the tank foundation level.

The walls, the bottom and cover plate as well as the beams for steel truss plates of the tank were designed using C25/30 concrete, waterproof (W8) concrete and AIII reinforcing steel. The upper slab, partially covering the tank, located in the middle part of the tank along the vertical internal wall, is
0.25 m thick. On both sides of the plate, there are reinforced concrete beams with dimensions of
0.34×0.30 [m×m], on which the bridging steel mesh HNS boards were placed.

The lower slab reinforcement is symmetrical, and placed in two perpendicular directions and
consists of the φ16 bars arranged in a mesh of 30 cm. The symmetrical reinforcement of the external,
internal and middle vertical walls consists of φ16 rods arranged in a 30 cm mesh, in two perpendicular
directions. The two tanks inside a clutched tank were allocated for the waste of a substance containing
about 20% sulfuric acid solution, which in a chemically aggressive manner affected the reinforced
concrete walls of tanks.

Vertical insulations were made on the external walls of the tank and horizontal ones under the tanks
as a geomembrane Gamrat FolGam 0Z 1.5 GEO. Internal anti-chemical insulations on the surface of
walls and the bottom of tanks and sewage inlets were designed from polyester GFK.

Figure 1. Underground reinforced
concrete tank for acid sewage

Figure 2. Peeling off polyester coating

Figure 3. Damaged protective coating, defects in coating material zyan

3. Tank's failure description
After ten years of exploitation due to the impact of chemically aggressive sewage, the protective
coating on the interior walls and the bottom of the tank commenced peeling off. After ten years of
exploitation due to the impact of chemically aggressive sewage, the protective coating on the interior
walls and the bottom of the tank commenced peeling off [7].

The GFK polyester coating was damaged (figures 2, 3). Numerous defects of concrete cover and
corrosion of the reinforcement appeared in the place of the damaged coating. In January 2016,
renovation of the damaged protective coating and concrete cover was carried out. It was decided to
repair the walls by:
- removing the damaged protective coating,
- removing the lagging, which was subject to degradation to the depth of the detected sulphate
corrosion,
- cleaning of the surface exposed after removal by sandblasting,
- preparing the surface for the location of a new casing made from a set of PCC II type weber mortar (i.e. a protective layer of reinforcing steel against corrosion, a fastening layer, a layer designed to fill voids in disposable layers up to 5 cm thick, a layer for levelling and smoothing of concrete surfaces). The total thickness of the new repair layer was 2 to 4 cm thick or more, depending on the losses, the layers were applied with a putty knife,
- layers placed in such a manner were fixed with PP polypropylene plates in sheets 1 m x 2 m and 10 mm thick by using steel anchors, the boards on joints were welded and a sealing layer was applied to the anchors.

The repair layers are shown in figure 4, where a concrete sample taken from the borehole in the tank wall is shown.

![Concrete sample taken from a tank wall](image)

**Figure 4.** Concrete sample taken from a tank wall

- approx. 1.5 cm thick levelling layer applied to the reinforcement surface,
- approx. 4 cm thick repair layer applied to the levelling layer,
- the next layer, which was sulphated and fell apart in the form of a loose "smear,"
- grey rust stain under reinforcement testifies to the presence of rust and corrosion of concrete near the reinforcement line.

After less than two years of exploitation, noticeable bulges in the vertical walls of the cover made of polypropylene plates were noticed. Some anchors have been moved along with the detachment of the panel from the wall (figure 4, 5, 6). In several places the plates cracked. Cracks appeared along the welding seams and in the areas of the largest bulges (figure 6, 7). The verticality of the walls of the tank immersed in the ground and wall displacements were measured using the laser scanning technique described in [8] After the completion of opencasts and several drillings, the presence of a pulp of soft-plastic consistency was found which was the result of sulphate corrosion of the applied repair layer as well as concrete.

Sulphate corrosion is one of the most dangerous corrosions occurring during the life cycle of a concrete structure and occurs most often in structures exposed to a chemically aggressive external environment in which sulphate ions are accompanied by large amounts of chloride, sodium and magnesium ions, which creates favourable conditions for corrosion processes in concrete. In direct contact with sulfuric acid, these phenomena multiply many times.

There are two types of sulphate corrosion: internal and external [9]. The inner one occurs in the concrete in which cement with a high gypsum content was used (the regulator of the setting time), and therefore an excessive amount of sulphate ions was introduced. Internal corrosion may occur in the case of concretes subjected to thermal treatment at a temperature higher than 60° C. External corrosion occurs when concrete is treated with sulphate solutions. The sulphate ions from the environment react with the cement matrix to form gypsum and/ or ettringite.

During the formation of both compounds, the volume is increased, in the case of ettringite even by over 150%. The physical effects of sulphate aggression include expansion, cracking, flaking or loss of strength, and in the case of strong corrosion, even the complete destruction of concrete in the structure can occur.
Figure 5. Tank – visible bulges of PP plates

Figure 6. Cracked PP board with visible ettringite

Figure 7. Cracked welding seam and a broken anchor

Figure 8. Section through welding seam, plate is 10 mm thick, the weld is between 3 mm and 5 mm thick

Figure 9. Section through the welding seam, the crack in the seam resulted from the expansion of the mortar subjected to sulphate corrosion
4. Reasons for the penetration of the sulfuric acid solution under PP boards

The reason for the "bulging" of PP panels is the progressive sulphate corrosion of the reprofiling mortar (figures 5, 6). Sulfuric acid from the liquid stored in the tank, got through the leaks into the space between the PP slab and weber mortar and reacted with the mortar causing its degradation and then expansion by increasing the volume and pressure [10]. Increasing the volume of the mortar almost twofold during the sulphate corrosion process, which the mortar undergoes, causes the appearance of large stresses related to volume expansion. Increasing the volume under the PP slab anchored in the wall causes the appearance of large bending moments and the accompanying cutting forces (and high tensile forces).

There is also a significant difference in the factors of thermal expansion of concrete and polypropylene. The factor for polypropylene is several times larger than for concrete. A reinforced concrete wall located below the ground level is not very sensitive to daily or weekly temperature change, while PP panels, characterized by a 15 times higher thermal expansion factor compared with concrete, hold the temperature of the substance being stored. Fixing a PP board to the wall surface without the possibility of mutual displacement results in additional stresses caused by the change of temperature value in the panel.

These stresses increase repeatedly in the welding seams due to the change of the stiffness of the panel in the seam (reduction) and the asymmetrical position of the seam in relation to the mid plane and the smaller thickness of the seam compared to the thickness of the plate. Additional stresses at such plate and seam geometry result from the so-called notch impact (stress concentration at internal acute angles). In addition, when the welded seam is made asymmetrically in relation to the centre plane of the plate, an additional bending moment and edge stress are created, which results in cracks between the joined plates (figures 7, 8, 9).

The expected stresses in the welding seam were calculated for the average values of the strength parameters of the PP plates and the applied geometry.

\[ g = N_D T_N D T_s k o t w a k o t w a h M_D T M_D T \]

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**Figure 10. Bending the welding connection of polypropylene plates**

In a polypropylene plate with a modulus of elasticity \( E_{pp} = 2.5 \) GPa, a thermal coefficient \( \alpha_{pp} = 1.5 \cdot 10^{-4} \); thickness \( g = 0.01 \) m, for the width of the weld seam \( s = 0.002 \) m, the tensile force \( N_{\Delta T} \) caused by the periodic change in temperature \( \Delta T = 15^\circ \) causes an additional bending moment \( M_{\Delta T} \). It arises as a result of eccentric action of this force in the place of asymmetrical connection of the seam (figure 10). For \( \Delta T = 15^\circ \); \( E_{pp} = 2.5 \) GPa; \( \alpha_{pp} = 1.5 \cdot 10^{-4} \); \( h = 0.01 \) m and \( s = 0.002 \) m:

\[ N_{\Delta T} = \Delta T \cdot \alpha_{pp} \cdot E_{pp} \cdot h = 56.25 \text{ kN/m} \]  

\[ M_{\Delta T} = N_{\Delta T} \cdot (h/2 - s/2) = 0.225 \text{ kNm} \]

\[ W = 1 \cdot s^2/6 = 7 \cdot 10^{-7} \text{ m}^3 \]
Stresses in polypropylene $\sigma_{pp}$ exceed polypropylene tensile strength $f_{ppd}$ by many times, causing cracking of the weld seam:

$$\sigma_{pp} = M_D T / W + N_D T / s \Delta T = 365.50 \text{ MPa} \gg f_{ppd} = 20 \div 38 \text{ MPa} \quad (4)$$

The levelling mortar, which underwent corrosion, lost its tightness properties and facilitated the penetration of sulfuric acid into subsequent wall areas under the polypropylene lining. Accelerated corrosion of the carrying reinforcement occurred. Tanks filled with acidic liquid went off-line.

5. Conclusions, a proposition for tank wall repair technology

PP panels should not be rigidly fixed to the walls and the bottom of a reinforced concrete tank due to different values of the thermal coefficient of polypropylene and concrete. A dilatation should be formed to allow the panel to move relative to the wall. The thickness of the PP board is sufficient, provided that the right polypropylene is selected, resistant to long-term environmental impact with a low pH reagent; however, it does not function properly after leakage and resulting damage.

Similar further damage can be expected in those places where too thin welds were made or the construction was exposed to severe vibrations [10,11]. The failure could not have occurred if the PP plates were free to deform and the welding seam were to be located on the entire width of the joined panels. Another solution would be the use of protective coatings applied by spraying or laying putty, for example, using the appropriate polyuria-resistant or polyurethane coatings of Ucrete type floors [12].

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