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MATERIAL-CONSTRUCTION SOLUTIONS APPLIED IN LONG-TERM REPAIRS OF REINFORCED GRANULATION TOWERS IN NITROGEN PLANTS

ROZWIĄZANIA MATERIAŁOWO-KONSTRUKCYJNE STOSOWANE W REMONTACH ŻELBETOWYCH WIEŻ GRANULACYJNYCH W ZAKŁADACH AZOTOWYCH

Abstract

In one of the oldest chemical plants in Poland are two reinforced concrete towers for fertilizer granulation which were built in the nineteen-thirties. These towers have operated continuously in a very hostile environment for about fifty years. The authors of this paper have used ad hoc methods of repair and protection with varying degrees of success for several years. In 2012, the renovation of one of the towers was designed and implemented with a view to its continuous use over a period of twelve years. A new comprehensive method of protecting the tower was applied due to its relatively long-term use. The resulting tower damage, the results of chemical and structural analysis of the concrete and coating stress are presented in this paper. Furthermore, security methods applied by them and their functionality after a few years of use as well as material and construction details relating to works performed to make the tower operational over the next twelve years are presented.

Keywords: *concrete, concrete corrosion, fertilizers, granulation tower, nitrogen plants*

Streszczenie

W jednych z najstarszych polskich zakładów chemicznych w latach trzydziestych poprzedniego stulecia wzniesiono dwie żelbetowe wieże do granulacji nawozów sztucznych. Wieże pracowały nieprzerwanie w agresywnym środowisku przez ponad 50 lat. W celu utrzymania ich w eksploatacji autorzy artykułu w ostatniej dekadzie stosowali z różnym skutkiem doraźne metody napraw i zabezpieczeń. W 2012 roku zaprojektowano i przeprowadzono remont jednej z wież z zamiarem jej dalszej eksploatacji przez okres 12 lat. Ze względu na długi przewidywany okres eksploatacji zastosowano zupełnie odmienny, kompleksowy system zabezpieczenia wieży. W artykule przedstawiono stan techniczny wieży przed naprawą, wyniki badań chemicznych i strukturalnych betonu oraz analizę wytężenia żelbetowej powłoki wieży. Zaprezentowano ponadto stosowane dotychczas doraźne metody napraw wraz z oceną ich skuteczności po kilku latach użytkowania, a także szczegóły materiałowo-konstrukcyjne remontu wykonanego z zamiarem nieprzerwanego użytkowania wieży przez okres 12 lat.

Słowa kluczowe: *beton, korozja betonu, nawozy sztuczne, wieża granulacyjna, zakłady chemiczne*

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1. Introduction

Granulation towers have long been an integral part of the process of granulation of fertilizers. In one of the oldest chemical plants in Poland, two reinforced concrete towers with an inner diameter of 19.6 m and a total height of 36.0 m (Fig. 1) were built in the nineteen-thirties. The upper part of the tower was rebuilt in the post-war years. For over fifty years, the towers operated in the aggressive environment of the chemical plant until the present century. Their poor technical condition and the necessity to keep them operational due to the increasing global demand for fertilizers in agriculture led to their further use in parallel with a modern mechanical fertilizer granulation line. Therefore, since 2002, the towers have been temporarily repaired to prevent their further degradation. In recent years it has been decided to develop the project and repair the towers with the intention of putting them into operation for a further 12 years. The need to ensure safe operation of the structure for such a long time in an aggressive environment forced the authors of this paper to search for materials and repair methods that are much more durable than those used in previous repairs and intended to last for a period of several years.

a) b)

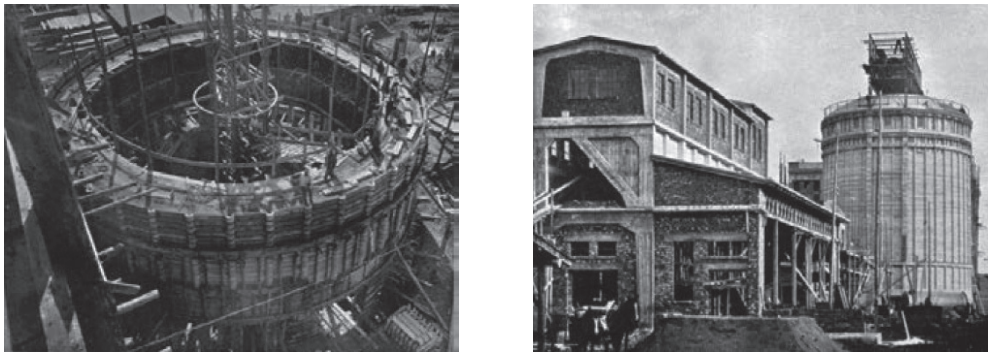


Fig. 1. a) One of the granulation towers during construction; b) A view of one of the towers from the nineteen-thirties

In this work, the experts present the structure of the granulation towers, their technical condition after many years of operation, an analysis of structural stress, the results of chemical analysis and the state of the concrete corrosion. Also, the methodology of emergency repairs and their effectiveness as well as the technology of the repairs are presented considering that they are to be used for the next 12 years.

2. Description of the building in structural terms

The structure of the tower is mixed (Fig. 2). The foundation up to a level of +6.00 m is formed by a reinforced concrete monolithic structure with a height of 3.0 m supported by columns. The main part of the cylindrical shell between the levels of +6.00 and +32.00 m

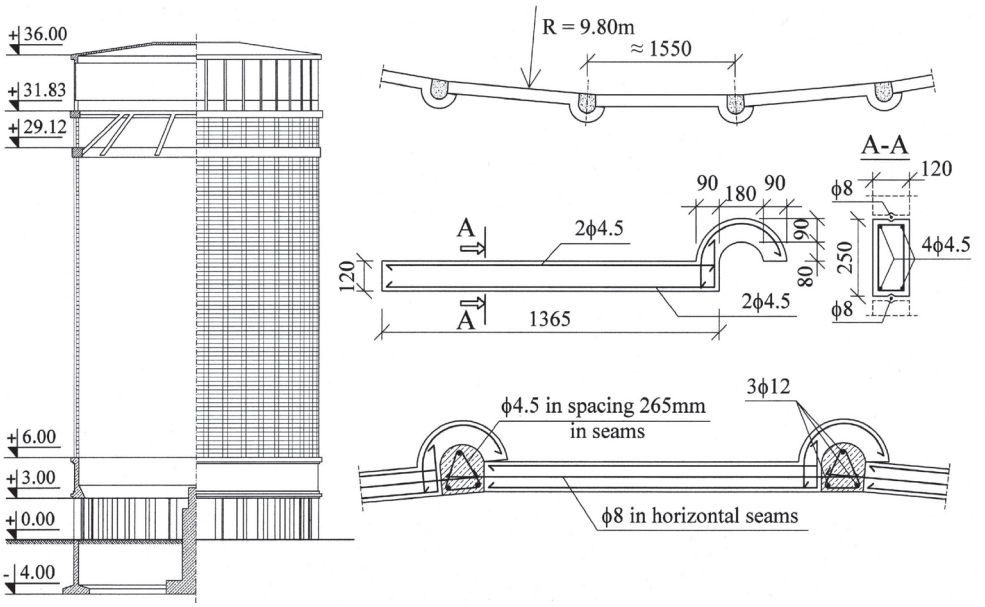


Fig. 2. Geometry and structural details of the granulation towers

is made of reinforced concrete key aggregates using Monnoyer's system. The technology of the erection of polygonal buildings (or circular buildings with a large diameter) using key aggregates was developed by Dumas, the Belgian engineer, mainly for building chimneys. An essential element of the system is a key aggregate with a height of 0.25 m, ending with a head in the form of a hook, the hollow interior of which allows for the insertion of vertical steel bars combined with stirrups. For the analysed towers, key-aggregates with a cross-section of 0.12 × 0.25 m and a modular length of 1.55 m are used. The longitudinal reinforcement of the key aggregate is formed by 4 bars ϕ 4.5 mm. A triangular core composed of three bars ϕ 12 mm and stirrups ϕ 4.5 mm are placed every 265 mm inside the hooks. As a result, a cylindrical coating with a thickness of 0.12 m with 40 vertical ribs on the circumference placed every 1.55 m is created.

Monolithic reinforced concrete tie beams are made at levels of +29.12 and +31.83 m. These beams support a technological ceiling with a strut steel construction. The crowning of the tower is made of a reinforced concrete-masonry structure covered with a reinforced concrete beam-and-slab plate.

3. Description of the damage in 2002 (after 50 years of operation)

In 2002, after fifty years of operation in the aggressive environment of the plant, the towers were subjected to advanced degradation as a result of the ammonium and sulphate corrosion of the concrete. The monolithic foundation of the tower (Fig. 3) as well as the prefabricated

cylindrical shell (Fig. 4) were seriously destroyed. Losses of concrete in the prefabricated wall reached two-thirds of the wall thickness. Additionally, there was considerable local damage to the cross-section of the vertical ribs. In the lower monolithic part of the tower, the concrete cover of the cylindrical walls, columns and tie beams were damaged. Almost completely corroded reinforcing bars were localized.



Fig. 3. Corrosion of monolithic foundation of the tower in 2002



Fig. 4. Corrosion of the prefabricated cylindrical shell (2002)

The samples of concrete taken from the ribs of the cylindrical coating and the columns of the foundation of tower No. 2 were characterised by a very strong absence of alcalisation (pH of the aqueous extract amounted to 8.0–9.0), higher content of chloride ions (about 0.33% of the weight of the binder) and the content of sulphate ions was within the normal range (approximately 2.5% of the weight of the binder).

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4. Ad hoc repairs and strengthening of the towers

In 2002, ad hoc repairs were made and tower number 2 was strengthened with the intention of its further operation for a period of 5 years. It was presented by Dyduch, Płachecki et al. [1]. For the reprofiling of the damaged concrete elements (surface of the prefabricated shell of the tower, tie beams and monolithic foundation elements), class B25 mortar was recommended (or concrete in the case of more extensive damage) to be used on CEM-II/A-D silica Portland cement with the addition of high-quality plastic dispersion – this was based on a styrene-butadiene from a reputable supplier of construction chemicals and designed to improve repair screeds and make a bonding layer. On the basis of that dispersion, it was also recommended to use the bonding layer.

It was recommended to remove the concrete cover from reinforced concrete foundation columns and to protect these columns with a 5–7 cm thick reinforced layer. Additionally, the concreting of the monolithic ring wall from the outside was designed to be at a level of +3.00 to +6.00 m with 15 cm thick concrete reinforced with two meshes ϕ 8 every 150 mm on both surfaces and anchored to the original wall with ϕ 12 mm anchors spaced at 300 × 300 mm.

The reinforcement of the tie beams at a level of +29.12 and +31.83 m were designed in the form of steel casing as well as additional 10 HEA 160 vertical bars extending from a level of +6.0 to +29.12 m and anchored to the prefabricated cylindrical wall (Fig. 5). The role of the designed reinforcement was to safely transfer the loads from the top of the tower (technological ceiling, flat roof and reinforced concrete upward extension) and relieve the prefabricated coating.

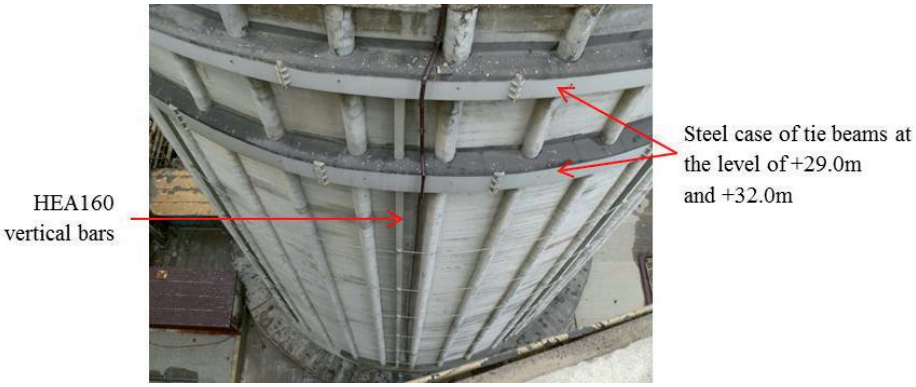


Fig. 5. Steel reinforcement of the granulation tower

The tower had again degraded 4 years after its repair. The precast coating reinforced concrete elements (Fig. 6a) were significantly damaged. The concreting of the pillars of the foundation was seriously cracked and loose. One of the reasons for the damage was certainly the contractor's breach of technological regimes contained in the project and instructions for the use of materials for re-profiling. Undoubtedly, the main reason for the damage was contaminated concrete and the aggressive environment around the towers – this was caused

a) b)



Fig. 6. a) damage of prefabricated shell elements four years after repair; b) exhaust chimney near the tower

by the location of exhaust chimneys in the immediate vicinity (Fig. 6b). Approx. 3 kg/h of ammonium nitrate (NH_4NO_3) is removed from the exhaust air coming from the chimneys. The contamination of concrete and its progress is presented in section 5.

5. The results of chemical testing of concrete

During the technical inspection of the towers, concrete samples were taken to assess the degree of contamination and evaluate the protective properties of the cement material in relation to steel. The condition of the concrete was evaluated on the basis of the pH value of the aqueous extract, the content of sulfate, chloride and nitrate ions, and observations made using a scanning electron microscope.

The measurements of the pH value of the aqueous extract were made with a pH meter microprocessor with an accuracy of ± 0.05 pH. The content of sulphate (SO_4^{2-}), nitrate (NO_3^-) and chloride (Cl^-) ions was determined according to [2]. Sulphates were identified in the acetone environment by titration with a standard $BaCl_2$ solution in relation to Nitrosulfonazo III. Chloride ions were analysed using a MERCK test by bonding them into $HgCl_2$ (the mercurometric method). Nitrates were identified by using an ion-selective electrode (nitrate electrode).

Table 1 summarises the results of chemical analysis of the samples taken from tower No. 1 in 2006 and 2013. When analysing the pH value of an aqueous extract, it may be noted that the value ranged from 8.70 to 11.70 (average value – 10.03) in 2006, while in 2013, it ranged from 8.20 to 8.70 with the average value of 8.43. Such a strong reduction of pH over seven years results from a progressive corrosion of sulfate and ammonium concrete. The elimination of calcium hydroxide from the cement binder causes a strong decrease of pH, which results in the absence of the protective properties of concrete for reinforcing steel. The concentration of Cl^- ion, calculated in relation to the weight of the binder, does not exceed the limit values (0.4%). This indicates that the concrete did not undergo changes associated

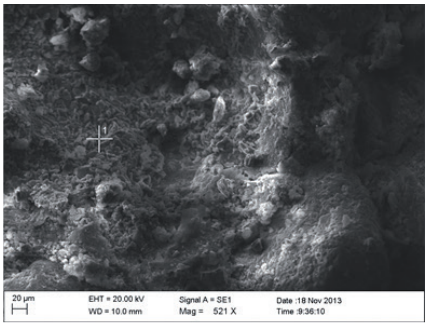
with chloride corrosion. In the considered period of seven years, a significant increase in SO_4^{2-} ions was identified – this proves the progressive corrosion of sulphate. The ion content, as compared to the weight of the binder in 2007, amounted to 2.5% in all three tested samples. Meanwhile, in the samples taken in 2013, that value ranged from 3.5 to 5.0 (with an average value of 4.38). Figure 7 presents the results of observation in the scanning electron microscope for one of the samples taken in 2013. The results present a leaky structure formed by the processes of dissolution and sulfate corrosion (Fig. 7a), as well as its confirmation in EDS analysis (ettringite formation – Fig. 7b).

Table 1

The results of chemical analysis of the concrete samples

Year of test	Sample number	pH	SO_4^{2-}	Cl^-
			% of binder weight	
2006	1	8.7	2.5	0.33
	2	11.7	2.5	0.08
	3	9.7	2.5	0.08
2013	1	8.2	5.0	0.14
	2	8.5	4.5	0.22
	3	8.3	4.5	0.14
	4	8.7	3.5	0.20
Ultimate values		> 11.8	≤ 3.0	< 0.4

a)



b)

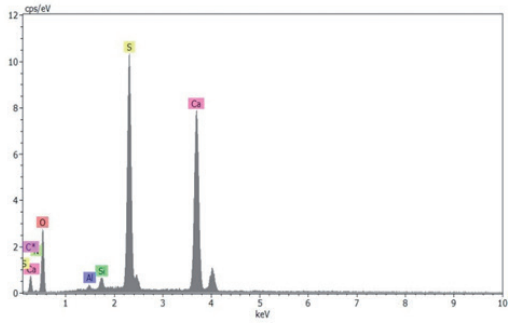


Fig. 7. The results of the observation of the concrete sample in the scanning electron microscope: a) leaky structure formed by the processes of dissolution and sulfate corrosion; b) EDS analysis results (ettringite formation)

6. The material and construction solutions used in the renovation of the towers for the purpose of their use for a further twelve years

6.1. Basic assumtions

In 2011, the decision was taken to repair and secure the two towers, thus providing their trouble-free and uninterrupted use for the following twelve years (until 2024). The repairs of tower No. 2 conducted twice so far have proved that repair techniques will not bring satisfactory results over such a long period. Additionally, the progressive pollution and destruction of the concrete structure reported in the chemical and structural examination have confirmed the need for a much more efficient and more sustainable protection of the reinforced concrete elements.

6.2. The analysis of stress of the tower

In order to estimate the stress of the tower elements, a numerical model in the FEM system was built. The model included all operating fixed and variable loads (the weight of the tower components, technological floor load at a level of +31.83 m, snow and wind).

The analysis considered two options: Option 1 – prefabricated panel thickness reduced to 60 mm (equivalent to seriously damaged panels), Option 2 – the wall with a full thickness of 120 mm. In both options, the interaction of vertical steel pillars in the transferring of loads was taken into consideration.

In Figure 8, the analysis of the results in the form of vertical stresses in the coating (8a) and forces in the steel pillars (8b) for Option 1 are presented. Compression in the concrete

a) b)

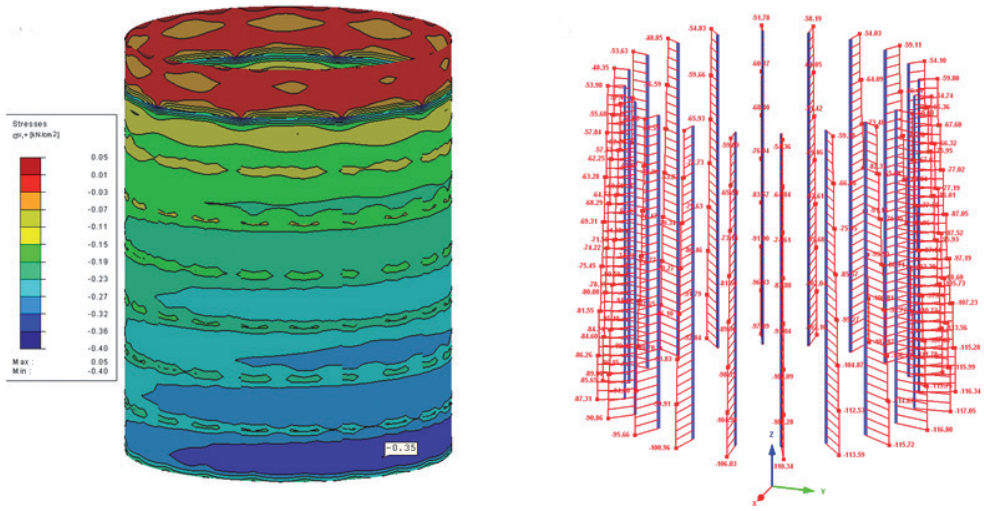


Fig. 8. The results of static analysis of the structure for Option 1: a) concrete shell vertical compression [kg/cm^2]; b) steel pillar forces [kN]

slabs of the coating amounted to 3.5 MPa for Option 1 and 1.9 MPa for Option 2. Forces in the steel pillars amount to 117.1 and 65.0 kN, which generate compression in the steel sections equal to 30.2 and 16.8 MPa.

The conducted analysis of stress indicates a high level of compression in the concrete slabs (3.5 MPa) in Option 1. Given a dramatically low technical condition of the concrete, the loss of even half of thickness of the coating resulting the concrete stress increase can be considered. As a result, the compressive stresses can cause a loss in the stability of the reinforced concrete cylindrical shell and losses of concrete fragments.

6.3. Material and structural solutions for repairs and reinforcements

Because of a high level of concrete stress, a low durability of previously conducted repairs and a long period of the planned operation of towers had to be used a good protection. The effectiveness of repairs to deeply damaged concrete elements depends on the bonding of the applied repair layer with a concrete base. For this reason, bonding layers are applied according to the 'wet on wet' principle, i.e. after the application of the bonding layer, prior to its bonding and drying, the surface should be repaired. This technological requirement hinders the execution of repairs. Defective execution of repairs decreases their efficiency and durability. Additionally, the effectiveness of repairs is worsened by the low strength and chemical contamination of concrete. In order to ensure long-term protection of the elements of the tower in a contaminated environment, it was necessary to find a more effective solution than the solution used previously. Among other proposals, the possibility of making an outer coating, made of stainless steel, was considered. Finally, the system of a reputable supplier of construction chemistry, not requiring the use of an additional bonding layer, was applied. After the removal of the corroded concrete particles and thorough cleaning of the concrete surface and reinforcing steel, it was recommended that the extensive loss of concrete be replaced with fine-grained, thixotropic repair mortar with controlled shrinkage, reinforced by synthetic fibers with an average compressive strength of 30 MPa (Fig. 9a – mortar '1'). The mortar is usally applied in layers with thicknesses of up to 25 mm. After the re-profiling of concrete cavities, the reinforced protective coating of 5–6 mm was applied all over the surface of the prefabricated wall. For this purpose, a two-component cement mortar with high strength and plasticity dedicated to strengthening of masonry structure (mortar "2") was used. This mortar includes fine aggregate, special additives and an aqueous dispersion of synthetic polymers. Due to the high content of synthetic resin, it forms a stable and durable layer which is impermeable to water and the aggressive components present in the atmosphere, and it is not a barrier to water vapour diffusion. The protective layer was reinforced with an alkali-resistant glass fibre mesh with meshes of 25 × 25 mm and a weight of 225 g/m^2, tensile strength of 45 kN/m and strain at rapture of less than 3%. Given the poor adhesion of the protective coating applied to the corroded concrete, the anchoring to the original wall of the tower was applied with the support of nail anchors spaced at not more than 400 mm in both directions.

Reinforced concrete foundation columns were encased in a 3mm thick steel layer (Fig. 9b) after all loose and cracked concrete parts were forged together. After prior reinforcement of concrete filling of a steel casing in accordance with Fig. 9b (4mm vertical bars ϕ 16, pasted into the parent concrete, transverse stirrups and pasted bonding inserts), the inside of the casing was flooded with self-compacting concrete.

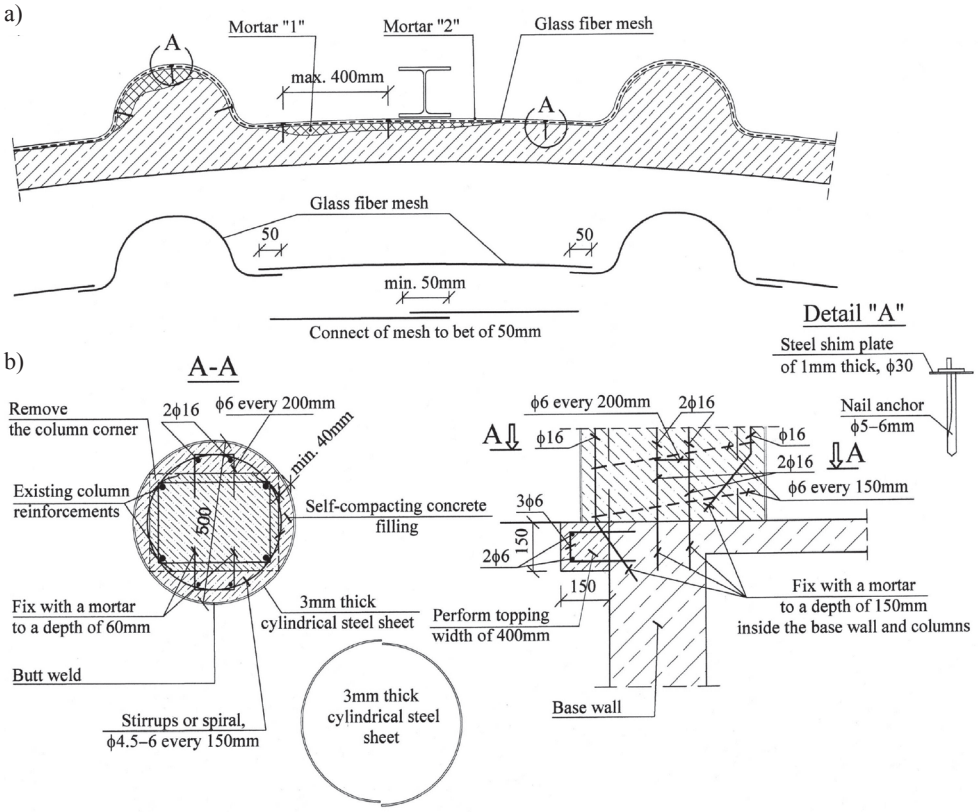


Fig. 9. a) details of protection of prefabricated concrete shell; b) reinforcement of foundation columns

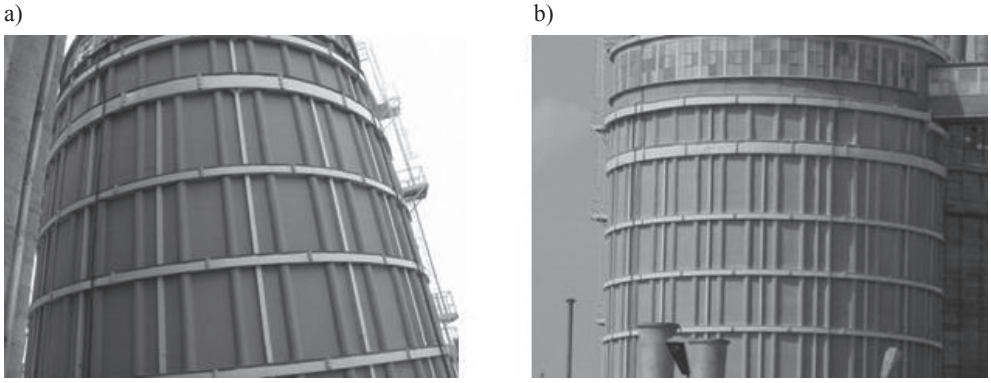


Fig. 10. a) the granulation tower shortly after renovation (mid-2012); b) the same tower after 2.5 years of operation

In addition to the complete repair and securing of protective coating, additional reinforcement was designed to increase the stiffness and stability of the wall. The number

of vertical HEA 160 steel posts was increased from 10 to 20 during the previous repair. Moreover, 6 reinforced peripheral tie beams with cross-sections of 300 × 300 mm, evenly spaced at 3.2 m, were designed. The tie beams were made from steel formwork (Fig. 10), armed longitudinally and transversely, and combined with the concrete wall.

7. Summary and conclusions

Taking into consideration the long-term, twelve-year use of the towers in the very aggressive environment and the sustainability of previously used methods of corrective repairs, a comprehensive but costly protection system was designed and implemented in one of the towers used for the granulation of fertilisers. The proposed technology has been accepted by the user of the building and executed under the supervision of designers and experts from the technical department of the manufacturer of the used construction chemistry products. Figure 10 shows a view of the tower shortly after renovation in mid-2012 (a) and at the beginning of 2015 (b). The inspection of the tower carried out after 2.5 years of operation showed no damage (cracks or delamination) to the protective layer. The results of the inspection bode well for the applied protection technology for the projected period of use until 2024. Keeping the tower in good condition will require only the renovation of the anticorrosion coating of steel elements.

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