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Structure and Environment 2021, vol. 13, (4), pp. 104-112, Article number: el 012
https://doi.org/10.30540/sae-2021-012

Structure and Environment
ISSN 2081-1500
e-ISSN 2657-6902
https://content.sciendo.com/sae
https://sae.tu.kielce.pl

Kielce University of Technology

DOI: 10.30540/sae-2021-012

ASSESSMENT OF THE POSSIBILITY OF USING THE EXISTING FOUNDATIONS FOR THE CONSTRUCTION OF A STEEL SILOS

OCENA MOŻLIWOŚCI WYKORZYSTANIA ISTNIEJĄCYCH FUNDAMENTÓW DO BUDOWY SILOSÓW STALOWYCH

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Abstract

The article presents an assessment of the possibility of using the existing reinforced concrete foundations as foundations for a new battery of steel silos for storing rape and soybean in the factory of fats. Visual tests of the reinforced concrete mantle were performed, as well as destructive and non-destructive tests of concrete strength, tests of the location of reinforcement, concrete carbonation and the degree of steel corrosion. On the basis of the conducted analyzes, final conclusions and recommendations concerning the conditions of further operation were formulated.

Keywords: foundations, silos, damages, scratches, cracks, non-destructive testing, destructive testing, durability

Streszczenie

W artykule przedstawiono ocenę możliwości wykorzystania istniejących fundamentów żelbetowych jako fundamentów pod nową baterię silosów stalowych do magazynowania rzepaku i soi w zakładach tłuszczowych. Wykonano badania wizualne płaszcza żelbetowego, niszczące i nieniszczące badania wytrzymałości betonu, badania lokalizacji zbrojenia, karbonatyzacji betonu i stopnia korozji stali. Na podstawie przeprowadzonych analiz sformułowano wnioski końcowe oraz zalecenia dotyczące warunków dalszej eksploatacji.

Słowa kluczowe: fundamenty, silosy, uszkodzenia, zarysowania, spękania, badania nieniszczące, badania niszczące, wytrzymałość

1. THE EXISTING CONDITION OF FOUNDATIONS FOR THE SILOS

The reinforced concrete foundations of the seven silos, made in the early 1990s, are located in the north-west part of the plant. Originally, the construction of reinforced concrete silos for rapeseed grain was planned on the foundations. Due to the change in the socio-economic situation, only the foundations in question were constructed (Fig. 1).

These are cylindrical structures founded on 80 cm thick reinforced concrete foundation slabs in the shape of a regular octagon. The inner diameter of the circle formed by the existing foundation walls is 18.85 m, and their thickness is 40 cm. The height of the foundation walls is 4.00 m from the top of the foundation slab. The ordinate of the foundation slab is 209.60 m above sea level. Originally, two reinforced concrete tunnels with a clearance of $2.30 \cdot 2.0$ m and a wall thickness of 40 cm were designed in each chamber.

The archival design included a reinforced concrete structure of the slab, foundation walls and tunnels

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Fig. 1. General view of the foundations for the silos from the south

made of B17.5 class concrete, reinforced with A-I (St3SX) class steel smooth bars. Substrate made of lean concrete of class B10 with a design thickness of 20 cm.

2. THE SOIL AND WATER CONDITIONS

The soil and water conditions found in the substrate are varied: favorable and moderately favorable, and the substrate is lithologically heterogeneous and predominantly horizontally geo-technically stratified. No groundwater was found up to the recognize depth, i.e. 8.0 m.

The soil and water conditions found in the subsoil are diverse: favorable and moderately favorable, and the subsoil is not homogeneous in terms of terms and predominantly horizontally geotechnically stratified. No groundwater was found up to the exploration depth, i.e. 8.0 m.

Under the berms with a thickness of 1.42 ÷ 2.2 m are: fine sands with ID < 0.35; dusty sands, fine sands with ID = 0.50; fine sands with interlayers of clay sand with ID = 0.70; sandy dust with IL = 0.15; sandy dust and silty loam with marl crumbs with IL = 0.25; dusty clay boundary dust with IL = 0.35; dusts with IL = 0.50; clay rubble (dusty loam with marl crumbs) and weathered (dusty loams with marl crumbs), IL = 0.00.

In the open pit, the foundation of the silo foundation was found on a bedding made of fine sand and crushed stone, laid on the native soil – medium-compacted fine sands with lamination of clay sand. Foundation condition – good (Fig. 2).

Fig. 2. The exposed foundation plate No. 7

3. SCOPE OF TESTS

During the preparation of the expertise, visual tests of the reinforced concrete mantle were carried out, as well as destructive and non-destructive tests of concrete strength, tests of the location of reinforcement, concrete carbonation and the degree of steel corrosion. Concreting of the structures in question was carried out most probably in the years 1991-1992, hence the age of the concrete was estimated at around 28-29 years. Concrete during this period has already reached full strength, but also exhibited gradual corrosion under the influence of changing weather conditions. The elements of the structure have undergone detailed visual tests, the markings and locations of which are shown in Figures 3-5.

During the tests of the current technical condition of the foundations for silos, the following were made:

3.1. Visual tests of damages and cracks of the reinforced concrete coat

Based on the visual assessment, the following damages were found:

1. Visible white efflorescence on the surfaces of the concrete plinths walls of the foundations (Fig. 3 and Fig. 5).

Fig. 3. Fragment of foundation No. 6. On the left, a narrow fragment of foundation No. 7

Fig. 4. Delaminated (impacts on concrete) samples. Right: a sample with poorly mixed concrete components – visible aggregate (sand) inside

According to the standards and technical literature [1], efflorescence, as a rule, does not have a detrimental effect on the properties and use of concrete products. They also do not affect the durability of such an element. They are therefore not considered essential from a technical point of view. The formation of efflorescence on concrete surfaces is normal. They are formed on all porous materials, and concrete belongs to them too.

Efflorescence can be saline and calcareous. Salt efflorescence most often arises as a result of the action of water on salts soluble in it, which may be contained in concrete. In the case of salt, water is not only a solvent but also a means of transport. In order for salt efflorescence to be visible on the surface of the material, water is necessary for this, which penetrates into the building material and dissolves the salts contained therein, crystallizing on the surface. Saline efflorescence is usually white, but there are also other colors.

Lime efflorescence is due to the calcium hydroxide content in the cement. Under the influence of dissolution in water and capillary pull-ups after rainfall, it comes to the surface and, after reacting with carbon dioxide in the air, transforms into calcium carbonate. After the water has evaporated, a white coating remains on the surface.

The intensity of the efflorescence depends on the amount of water entering the building material. Therefore, the most effective form of protection against efflorescence is the impregnation of the surface and protect it from excess water.

2. Concrete scratches and cracks – especially above the openings intended for the passage of tunnels in the plinth walls of the foundations – Figure 3. On the left – a narrow fragment of the foundation No. 7 – visible delamination of concrete along the corroded reinforcing bar at the top.
3. Degraded upper surface (crown) of all foundation walls – Figure 5.

Fig. 5. Fragment of foundation No. 7 – visible salinity in concrete cracks, exposed corroded reinforcing bars and a trace of a break in concreting: no bonding of concrete placed earlier (lower) with concrete placed later. Darker color of the concrete surface. Degraded upper surface of the foundation wall

4. Traces of breaks in concreting: no bonding of the concrete placed earlier (lower) with the concrete placed later (Fig. 3 and Fig. 5).

Table 1. Compressive strengths of concrete on samples-boreholes obtained from destructive tests

Object – Foundation No.	Sample No.	Average compressive strengths of samples (boreholes) from the testing machine $f_{m(n),is}$ [MPa]	Standard deviation s from $f_{is,cyl}$ [MPa]	Coefficient of variation $v_{fis,cyl}$ [%]	Characteristic strengths $f_{m(n),is} - 1.48s$ [MPa]	Concrete strength class according to PN-EN 13791 [6], [MPa]	Uniformity of strength (quality) of concrete
1.	1÷6	51.4	8.0	15.6	39.6	C45/55	Sufficient
2.	7÷12	53.7	7.0	13.0	43.3	C50/60	Average
3.	13÷18	40.6	5.5	13.5	32.5	C35/45	Sufficient
4.	19÷24	48.7	9.7	19.9	34.3	C40/50	Insufficient
5.	25÷30	66.1	5.8	8.7	57.5	C60/75	Good
6.	31÷36	52.8	14.8	28.1	30.9	C35/45	Insufficient
7.	37÷42	43.7	13.6	31.2	23.6	C25/30	Insufficient

5. Discoloration – a darker color of the concrete surface, observed especially in the area of shading foundations with the existing, adjacent silos – Figure 5.
6. Exposed reinforcing bars, vertical and horizontal, intended for further concreting of the structure, with visible surface corrosion – Figure 3 and Figure 5.
7. A visible delamination of concrete in the structure (Fig. 7) and a very easy delamination of concrete samples taken from the structure during impact tests (samples hitting concrete – Fig. 4).

3.2. Compressive strength (destructive) tests of concrete from the structure and sclerometric (non-destructive) tests of concrete strength and uniformity

Non-destructive tests of concrete strength were performed with a Schmidt N-type sclerometer, in accordance with [2, 3], ITB Instruction No. 210 [4] and PN-EN 12504-2: 2013-03 [5] and PN-EN 13791: 2008 [6]. According to point 7.2 of PN-EN 13791, the largest, practically possible number of boreholes should be made. The "practically possible" number of boreholes was the number agreed by the contracting authority, ie 42 boreholes – 6 boreholes for each tested foundation. In accordance with the recommendations of PN-EN 12504-1 [7], cylindrical boreholes were taken (Fig. 4) with a diameter and height of 100 mm – such samples are representative, because according to this standard, the strength of samples with such a proportion of dimensions corresponds to the strength determined on cubic samples with a side of 150 mm.

To evaluate the class of concrete on the basis of the rebound numbers of the sclerometer, the correlation relationships contained in [8, 9], in the Instruction [4] were used and the results from the computer program attached to the Schmidt hammer were taken into account. This program, however, does not take into account the correction factor for converting strength from old cylindrical samples ($D = L = 16$ cm) to current cubic samples #15 cm and does not calculate the correlation (base curve) according to PN-EN 13791: 2008 only according to the ITB Instruction [4]. Therefore, the base curve was determined according to PN-EN 13791: 2008 based on own calculations.

The results of compression tests of samples-boreholes performed in the accredited Laboratory of the Faculty of Civil Engineering and Architecture of Lublin University of Technology are presented in Table 1. These results were prepared in accordance with the above-mentioned PN-EN standards in terms of correlation with sclerometric tests. Before drilling in these places, $3 \cdot 9$ measurements of the rebound numbers were made with a Schmidt N-type hammer.

In addition, 18 measurement places were selected in each foundation, where 9 readings of the reflection numbers were made, a total of over 1.320 measurements of the reflection numbers.

Based on the results of tests of concrete samples (Table 1) and the accompanying earlier sclerometric tests carried out at the sampling sites with a Schmidt hammer, the base curve was scaled, on the basis of which a corrected correlation curve was developed, and then it was the basis for determining the strength of concrete tested with a Schmidt hammer in the remaining parts of the foundation, which made it possible to determine the actual strength (class) of concrete (Table 2) of individual structures (foundations).

The classification of concrete uniformity in terms of compressive strength was given according to PN-75/B-06250 – Normal concrete [12] (Table 12) and according to the literature [13].

Table 2. The strengths of concrete in the tested objects determined from the correlation of destructive and nondestructive tests

Object – Foundation No.	The test area Sample No.	Characteristic compressive strength after correlation f_{ck} [MPa]	Designed compressive strength after correlation f_{cd} [MPa]	Coefficient of variation $v_{fis,cyl}$ [%]	Concrete strength class according to PN-EN 13791 [6] after correlation	Uniformity of strength (quality) of concrete
1.	1÷6	23.2	15.5	18.5	C20/25	Sufficient
2.	7÷12	32.3	21.5	13.8	C30/37	Sufficient
3.	13÷18	23.8	15.8	11.3	C20/25	Good
4.	19÷24	29.2	19.5	11.2	C25/30	Average
5.	25÷30	53.4	35.6	6.8	C50/60	Very good
6.	31÷36	16.1	10.7	19.3	C12/15	Insufficient
7.	37÷42	13.9	9.2	24.2	C12/15	Insufficient

The determination of the concrete strength on the basis of the compressive strength tests of the concrete boreholes and of the measurements of rebound numbers with of the Schmidt hammer was performed separately for each foundation.

As the comparison of the two tables above shows, the concrete strength class determined on the samples-boreholes is much higher than the concrete class determined on the basis of the correlation of strength from destructive and non-destructive tests. Taking into account the time and weather conditions to which the structures were exposed, it can be concluded that the real values are shown in Table 2.

3.3. Reinforcement course tests using the FERROSCAN system

The tests of cover thickness, spacing and reinforcement diameters are shown in Table 3. Two-

Table 3. Results of measurements of concrete cover, spacing and diameters of reinforcing bars determined by the FERROSCAN system

Object – Foundation No .	The test area Scan No.:	Spacing of horizontal bars φ 20 [mm]	Average test area cover [mm]	Average cover in the foundation [mm]	Spacing of vertical bars φ 12 [mm]	Average test area cover [mm]	Average cover in the foundation [mm]
1.	FS1_000868.XFF	80÷150	63	49	220÷270	47	36
	FS1_000869.XFF		45			32	
	FS1_000875.XFF		40			30	
2.	FS2_000866.XFF	100÷170	77	54	80÷270	52	37
	FS2_000867.XFF		42			25	
	FS2_000876.XFF		42			35	
3.	FS3_000865.XFF	80÷150	32	40	100÷270	17	22
	FS3_000877.XFF		37			19	
	FS3_000878.XFF		51			30	
4.	FS4_000870.XFF	100÷150	79	51	150÷300	51	31
	FS4_000879.XFF		37			22	
	FS4_000880.XFF		38			20	
5.	FS5_000881.XFF	100÷180	33	42	150÷270	22	38
	FS5_000882.XFF		66			64	
	FS5_000886.XFF		29			29	
6.	FS6_000872.XFF	70÷150	71	68	150÷270	52	52
	FS6_000887.XFF		59			43	
	FS6_000888.XFF		74			62	
7.	FS7_000873.XFF	100÷150	73	55	170÷300	59	39
	FS7_000874.XFF		45			29	
	FS7_000885.XFF		48			28	

way (cross) reinforcement with smooth bars was found: horizontally – φ 20 mm, vertically – φ 12 mm. The results of measurements of the concrete cover of reinforcing bars (Table 3) indicate that in each case the cover thicknesses are sufficient and comply with the standards applicable at the time of construction.

3.4. Research on the degree of carbonation

Carbonation is one of the main causes of destruction (corrosion) of reinforced concrete elements and hardened concrete. Carbon dioxide (CO_2) in the air reacts with the products of cement hydration. Primarily calcium hydroxide Ca $(OH)_2$ undergoes the carbonation reaction, resulting in the formation of calcium carbonate ($CaCO_3$). Carbonation is a threat to concrete structures that use steel reinforcement. By lowering the pH level in the vicinity of the reinforcement, the layer protecting against corrosion (passivation) on the reinforcing steel is lost.

Chemical tests of the degree of loss of protective properties of concrete against corrosion of reinforcing steel – carbonation depth: spraying the moistened side surface of the core of the borehole or the concrete forging surface with an alcoholic solution of phenolphthalein (concrete pH > approx. 8.3÷9.3) dyes red-purple. The uncolored concrete layer is carbonated. The reinforcement located in this layer is exposed to corrosion. Figure 6 shows a carbonated (non-colored) layer of concrete about 4÷5 cm thick. The same photo also shows non-carbonated samples with "imprints" on the reinforcing bars – it can be concluded from this that the carbonation of the concrete did not proceed evenly and, just like the strength, is very varied (heterogeneous). Some of the structural concrete underwent carbonation, but many samples showed virtually zero carbonation.

3.5. Research on the degree of corrosion of reinforcing steel and the load-bearing cross-section of the reinforcement

The reaction product (iron oxide – rust), increasing its volume, generates stresses causing concrete cracking and even delamination of concrete along corroded reinforcing bars. The situation shown in Figure 7 is repeated in practically every hole in the foundation walls, both on the lower surface, as well as on vertical and upper surfaces.

The inspection of cutting-cores from the structure together with sections of reinforcing bars did not show any corrosion of these bars. Observed corroded surfacelly vertical rods projecting from the foundation walls to be connected originally proposed reinforcement of the silos walls of reinforced concrete and horizontal rods shown in Figure 5 as well as vertical rods projecting from the bottom plates to connect the designed reinforcement of walls of tunnels (Fig. 4 – shown in second plan). Despite the quite significant passage of time, the corrosion of these bars is not advanced, there are no visible pits or visible diameter losses.

Fig. 6. Concrete carbonation tests

Fig. 7. Concrete delamination along a corroded reinforcing bar

In technical publications, e.g. ([10], p. 52) one can find relationships linking the corrosion rate of steel obtained during polarization measurements with the assessment of the intensity of the corrosion hazard of the reinforcement in the structure. The most frequently used criteria for assessing the degree of corrosion risk are presented in Table 4.

Table 4. The degree of corrosion risk of the reinforcement of the structure depending on the corrosion rate according to [10]

Steel corrosion rate [µm/year]	The degree of corrosion risk
<0.01	Irrelevant (passivity)
<0.1	Low
1÷10	Moderate
10÷30	High
>30	Very High

The PN-EN 206+A1:2016-12 standard [11] provides „Concrete exposure classes related to environmental impact". According to this classification, the structures in question should in principle be classified into the following classes: XD1 – Moderately moist. Concrete surfaces exposed to chlorides from the air or XC2 – Wet, occasionally dry. Concrete surfaces exposed to prolonged contact with water. Most often foundations.

The table quoted in [10]: „Average corrosion rate $V_{corr,\ REP}$ depending on the exposure classes according to EN 206-1" for both these classes (XD1 and XC2) predicts the corrosion rate: $V_{corr,\ REP}$ = 4 m/year, i.e. moderate the degree of corrosion risk.

After 29 years of exposure of the foundations in question under the above-mentioned conditions, the loss caused by corrosion could hypothetically amount to: 29 [years] · 4 [mm/year] = 116 µm, which means that it is a size of the order of 0.1 mm, so practically.

The actual diameter of the reinforcement bars for φ 12 mm, taking into account this loss, is: 12 – 2 · 0.1 = 11.8 mm, and for φ 20 mm: 20 – 2 · 0.1 = 19.8 mm and such diameters can be assumed for static analysis of existing foundations from loads with new steel silos with their content.

4. CONCLUSIONS

4.1. Strength of structural

It was found that the foundations of silos No. 6 and No. 7, apart from the low strength, also the uniformity of concrete strength, tested both on compressed samples of cores and in the correlation of these results with the sclerometric method, is insufficient (Table 2).

Insufficient uniformity of concrete and large spread of compressive strength could be caused by improper compaction of concrete or even lack of compaction, which seems to confirm the lack of bonding of concrete placed earlier with concrete placed later (Fig. 3 and Fig. 5).

Static analyzes showed that the utilization of the load-bearing capacity of the existing horizontal tension reinforcement is 86.2% for rapeseed, and 87.7% for soybean [14].

The foundations of silos with sufficient and higher concrete uniformity (Table 2) may be used for the foundation of the newly designed steel silos.

When planning a technology that generates significant dynamic loads when emptying newly designed steel silos, it is necessary to consider the use of the existing foundation walls as a lost formwork and the construction of new walls for steel silos.

4.2. Necessary repair works with specification of the technology of their implementation

The scope of necessary repair work is given in the expert opinion. Overall, it included: cleaning the entire surface of the walls and foundation slabs after the foundations were discovered; hydro-sandblasting of the concrete substrate; forging the crown of foundation walls on the thickness of the layer of corroded concrete and reinforcing steel; forging a layer of corroded concrete in places of necessary repairs along corroded and exposed reinforcing bars and under them, abrasive blast cleaning from corrosion of exposed external rebars; anti-corrosion protection of cleaned reinforcing steel; reconstruction of the foundation wall crown (concreting); substrate re-profiling: filling the cavities in concrete with a repair mortar and leveling the surface; puttying of concrete repair layers; execution of anti-moisture insulation in some of the walls subject to be back filled again with soil.

The last, seventh steel silo is mounted on the foundations – the lowest one in Figures 8 and 9.

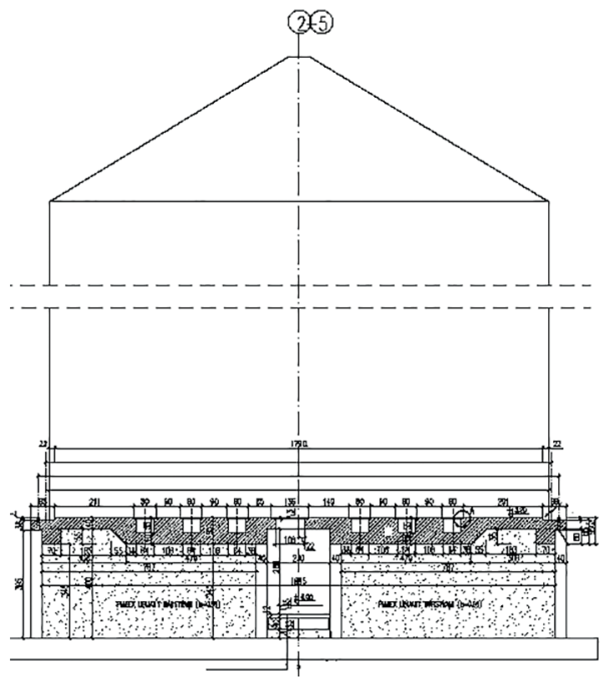

Fig. 8. General view of the silos from the west

Fig. 9. General view of the silos from the west

4.3. Conditions for further operation

Regarding the further operation of the structures in question as foundations for the newly designed steel silos [15], the entry in the original documentation of reinforced concrete silos should be maintained: "In order to maintain parameters, especially tilts, a controlled filling of chambers is required in the first year of operation".

The technological design should include instructions for the 1st year of silos operation.

5. COMPARISON OF CONCRETE STRENGTH ACCORDING TO PN-EN 13791: 2019-12 AND PN-EN 13791: 2008

During the preparation of this article, the standard [17] – PN-EN 13791: 2019-12 – Assessment of concrete compressive strength in structures and prefabricated concrete products was published. Therefore, an attempt was made to compare the concrete strength results obtained on the basis of the standard [6] and the new standard [17], namely Annex B (informative) to this standard: "Example of the general relationship between the rebound number and the compressive strength class". This appendix provides an example (or in fact tables) which is taken from the procedure given in the German National Annex to EN 13791: 2006.

The following conditions should be met in order to be able to adopt the concrete compressive strength class (column 3) related to the rebound numbers (col. 1 and 2):

- the concrete is normal-weight concrete;
- controlled permeability formwork or surface hardeners were not used;
- a Type N rebound hammer having an impact energy of 2.207 Nm was used for measuring the rebound number based on the rebound distance (R) or by energy or velocity measurements (Q);
- the carbonation depth does not exceed 5 mm;
- the rebound numbers meet both the criteria in column 1 and column 2 of Table B.1 (rebound distance) or both the criteria in column 1 and column 2 of Table B.2 (energy or velocity differential).

As shown in Table 5, the compressive strength classes of concrete determined only on the basis of the rebound numbers do not take into account the very important property of concrete, which is its uniformity. This may result in imprecise estimation of the concrete class and its unjustified overestimation or understatement. It is especially visible in silos No. 6 and No. 7, where the concrete class is overstated several times.

The most reliable data is presented in Table 2, in which the concrete strength in the structure of the tested objects was determined on the basis of the correlation of destructive and non-destructive tests, taking into account both the standard deviation, the coefficient of variation and the heterogeneity of the concrete. The significantly lower strength, visible in foundations No. 6 and No. 7, was also confirmed by visual tests.

Table 5. The relationship between the rebound number and the class of concrete compressive strength [17]

Object – Foundation No.	Sample No.	Lowest rebound number from all test locations in the test region *R*	Median of the rebound numbers for the test region *R*	EN 206 compressive strength class [MPa]
1.	1÷6	40.0	50.0	C30 / 37
2.	7÷12	42.0	46.0	C30 / 37
3.	13÷18	36.0	42.0	C20 / 25
4.	19÷24	40.0	46.0	C30 / 37
5.	25÷30	44.0	52.0	C35 / 45
6.	31÷36	40.0	50.0	C30 / 37
7.	37÷42	44.0	54.0	C35 / 45

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