

AN INNOVATIVE APPROACH FOR REPAIRING OF CORRODED REINFORCED CONCRETE INDUSTRIAL STRUCTURES IN AGGRESSIVE ENVIRONMENT BY HIGH-TECH HYBRID REINFORCED SPRAYED CONCRETE WITH CAPILLARY CRYSTALLINE ADMIXTURE

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Abstract: Solvay Sodi JSC, Devnya, Bulgaria, is the biggest calcite soda production plant in Europe. It is built in 1974 and it works in three-shift production regime up to present days. The exploitation environment is highly influenced by numerous factors, acting corrosively on main reinforced concrete structures – active atmospheric processes (in continental type moderate climate), sea water born chloride-aerosols, as well chemical attack caused by carbon dioxide and nitric acid, presented in the air in form of evaporation. The most reinforced concrete structures need urgent remedial measures to restore the load-bearing capacity of its components.

The "light soda" silos are reinforced concrete facilities (cylindrical shells) which repair has to be executed during continuous production process. The options for repair of these structures and restoration of their load bearing ability by specially designed innovative high-tech hybrid reinforced sprayed concrete, containing capillary crystalline admixture, are discussed in the report.

The in-situ tests and wide-range comparative studies are carried out, covering basic physical and mechanical structural characteristics of the proposed sprayed concrete for wet spraying and another one - based on proportioned dry ready mix.

The original scientific results concerning strength-deformation properties, phase composition and structure of hardened sprayed concrete, directly related to the durability in aggressive environment, are obtained by X-ray diffraction (XRD), differential thermal analysis (DTA), mercury porosimetry, low temperature gas adsorption (BET-method) and computer X-ray tomography.

The static and dynamic analysis of the structure is performed using the test results obtained and the fully specified engineering solution has been presented to restore the load-bearing capacity of the structures with a guaranteed service life of at least 50 years.

Keywords: CORROSION, HYBRID REINFORCED SPRAYED CONCRETE, CAPILLARY CRYSTALLINE ADMIXTURE, X-RAY DIFFRACTION (XRD), DIFFERENTIAL THERMAL ANALYSIS (DTA), MERCURY POROSIMETRY, LOW TEMPERATURE GAS ADSORPTION (BET-METHOD) AND COMPUTER X-RAY TOMOGRAPHY

1. Introduction

Currently, silos for light-weight soda silos "4" and "5" are used for temporary storage and subsequent distribution of the product. Serious corrosion damages are observed on the concrete wall, visible corroded areas of the steel-reinforcement, too. (Photo 1).



Photo 1 Silo's concrete structures visualization

The design for repair should be based on the principle of reasonable sufficiency, without providing for a change in the geometry of the existing sections of the building structure and partial or complete closure of the technological openings in the structure.

According SOLVAY SODI JSC preliminary experience such structures were repaired by dry-shotcreting by "MC Bauchemie" dry ready mix, type "Torkret W81" (MC). The method used should be optimized to avoid some disadvantages - very expensive dry mixture, technical requirements for very thin shotcrete single layer (up to 2 cm), need for at least three layers to reach the design repairing thickness of about 6-7 cm, possible dusting during work, relative large rate of rebound, etc.[1,2,3].

All mentioned above gave me enough reason to propose different type of repairing approach based on wet technology technical and technological basic advantages - high performance productivity (3-5 m³/h), single layer thickness – up to 20 cm (all repairing concrete section deep will be executed in single stage!!!), rebound reduced (up to 15%), possible to used special designed high-performance fiber-reinforced fine-grained sulfate-resistant sprayed concrete, strict control of concrete mix design (fresh concrete mixed at batching plant under control), possibilities to incorporate in concrete mix different type of fibers (control the shrinkage processes in different hydration stages and dramatically increases resistance to brittle fracture, increase the residual strength after the first crack strength of fatigue in long-term load and impact strength, which ensures the integrity of the concrete even in partial depletion of bearing capacity) and incorporated in concrete mix special deep crystallization admixtures (self-healing, water-proof concrete, 4G - impermeable concrete).

A special repair wet-shotcreting mix WS is designed for this purpose. The mix consists of polymer-modified hybrid fiber-reinforced concrete (maximal size of large aggregate $D_{max}=8$ mm) and internal-crystallizing chemical admixture (Table 1).

Table 1: Wet-shotcreting mix design, type WS

| Ingredients | Quantity, kg/m ³ |
|---|-----------------------------|
| Sulfate resistant portland cement CEM I 42,5 SR5 | 550 |
| River sand, SILISTRA, "Polaris - 8", 0-4 mm | 745 |
| Crashed washed sand, ESKANA, "Sini vir", 0-4 mm | 300 |
| Crashed stone, PATSTROY, Karnobat, 4-8 mm | 505 |
| Highly water reducing admixture DYNAMON SX, MAPEI, Italy – 0,6% of cement mass | 3,30 |
| PP fibers FM150, Propex Concrete Systems, USA | 0,900 |
| PP fibers FM300, Propex Concrete Systems, USA | 0,900 |
| KMC – thixotropic polymer modifier increasing mix compactness (water solution of 10% dry compound – conforming to a prescription) | 10,00 |
| Internal-crystallization chemical admixture KRYSTALLINE Add +, Spain | 6,0 |
| Mixing water for dry aggregates | ~190 |
| Consistency (regarding to slump test), cm | S1 |

2. Test sampling

Under SOLVAY SODI JSC requirements before design procedure starting, an approved test program is performed. The main purpose of the tests planned was to compare in parallel the basic technical characteristics of **MC** and **WS** shotcretes, established in real production conditions (Photo 2).



Photo 2 WS mix wet site-shotcreting

5 days after shotcreting was performed standard preparation of samples from the fragments (test panels) fabricated via experimental deposition of both types of shotcrete in the casing forms (boxes). This was done by extraction of a coordinated number of cores with diameter of 100 mm and height equal to the thickness of the deposited shotcrete layer – 150 and 200 mm, respectively (Photos 3 and 4).

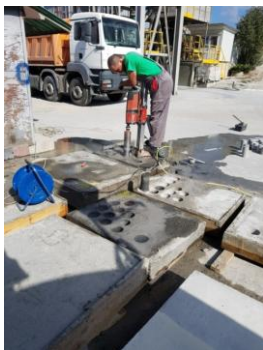


Photo 3 Cores boring



Photo 4 Samples taken

All samples taken were stored before testing on 7- and 28 days of age under respective EN standard requirements.

3. Test performed

Pursuant to the agreed test program the following standard tests [4,5,6] were performed:

- Volume density and compressive strength;
- Speed of ultrasound propagation;
- Static modulus of deformation;
- Depth of water penetration under pressure;
- Splitting tensile strength;
- Frost resistance;
- Adhesion to old concrete.

The standard tests visualization are given on Photos 5-12.

Trying to emphasize the differences between **MC** and **WS** mixes a set of additional high-tech structural tests were performed by using direct physical methods [7,8,9]:

- X-ray diffraction (XRD);
- Differential thermal analysis (DTA);
- Mercury porosimetry;
- Low temperature gas adsorption (BET-method);

- Computer x-ray tomography.



Photo 5 Volume density



Photo 6 Compressive strength



Photo 7 Speed velocity



Photo 8 Elastic modulus



Photo 9 Water penetration



Photo 10 Splitting tensile strength



Photo 11 Frost resistance



Photo 12 Weight lost

The structural tests visualization are given on Fig. 1-15 and Photos 13-16.

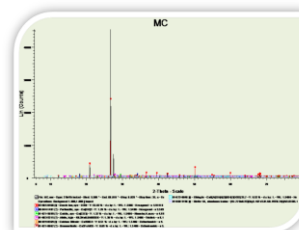


Fig. 1 X-ray MC – 7 days

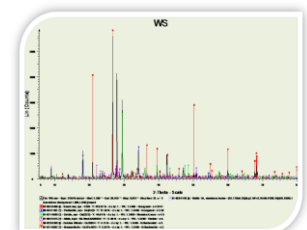


Fig. 2 X-ray WS – 7 days

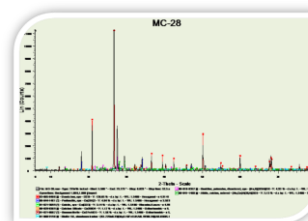


Fig. 3 X-ray MC – 28 days

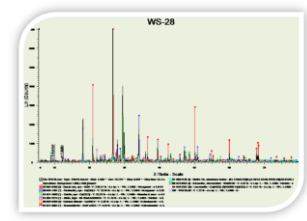


Fig. 4 X-ray WS – 28 days

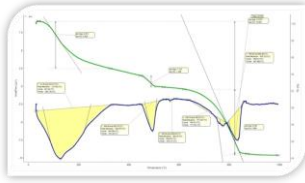


Fig. 5 DTA MC - 7 days

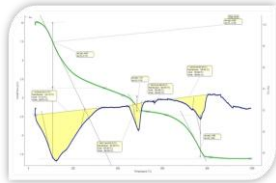


Fig. 6 DTA WS - 7 days

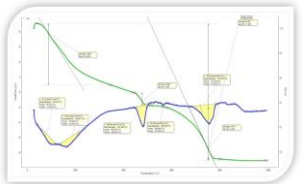


Fig. 7 DTA MC - 28 days

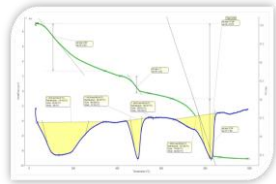


Fig. 8 DTA WS - 28 days

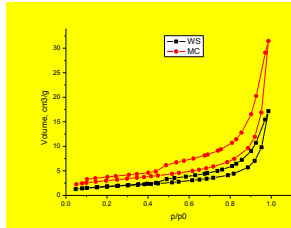


Fig. 9 BET Total porosity at 7 days of age

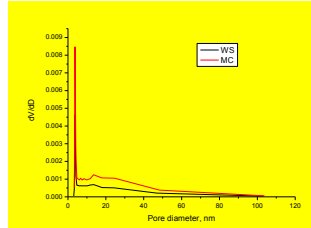


Fig. 10 BET Pore diameter size distribution at 7 days of age

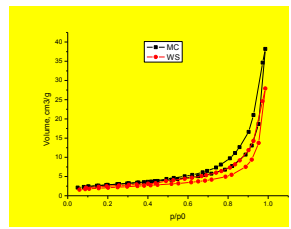


Fig. 11 BET Total porosity at 28 days of age

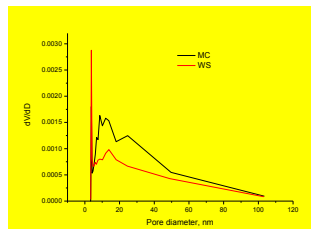


Fig. 12 BET Pore diameter size distribution at 28 days of age

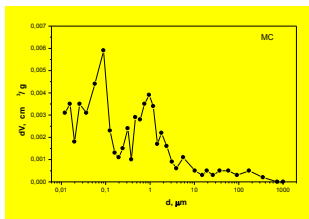


Fig. 13 MC- Pore volume distribution by pore diameter

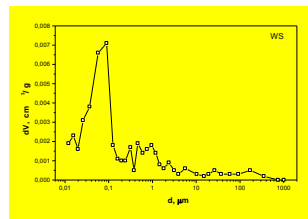


Fig. 14 WS- Pore volume distribution by pore diameter

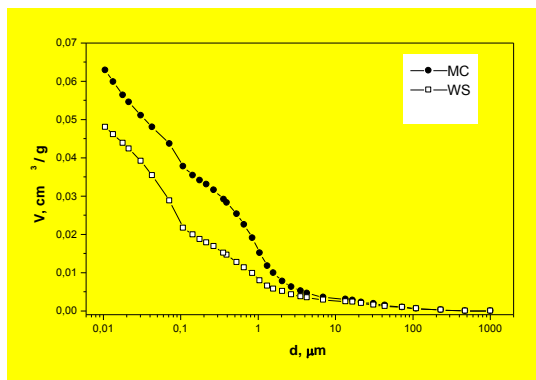


Fig. 15 Integral distribution curves of pore volume for samples MC and WS



Photo 13 X-ray computer tomography, type Nikon XT H 225

Photo 14 Concrete sample tomography testing

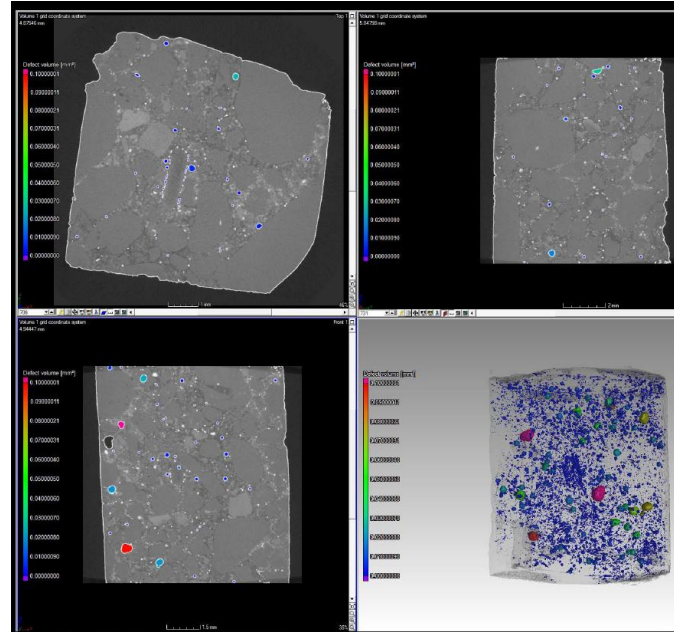


Fig. 15 MC - 28 days of age

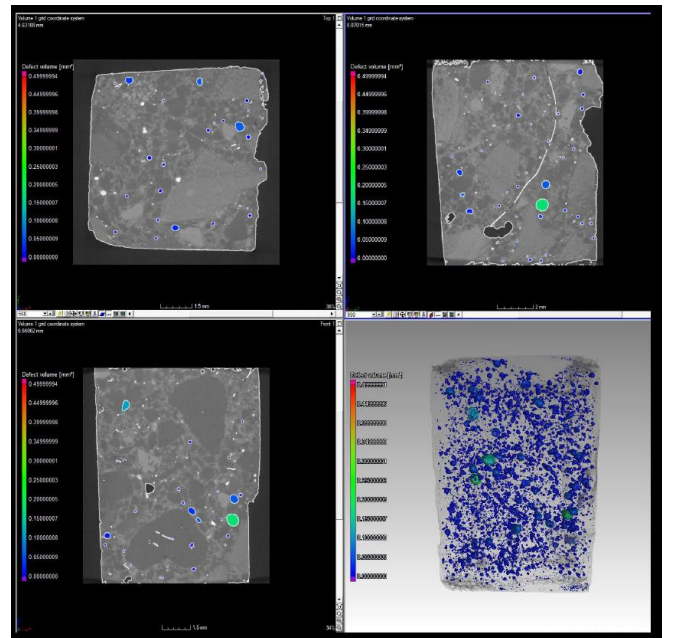


Fig. 16 WS - 28 days of age

4. Test results

In Tables 2 and 3 all test results are presented and compared by two different mixes (MC and WS).

Table 2: SUMMARY RESULTS from the tests conducted of MS and WS - PHYSICO-MECHANICAL CHARACTERISTICS

| Index tested | Composition | |
|---|-------------------------|-------------------------|
| | MC | WS |
| Volume density (kg/m ³), at: - 7 days - 28 days | 2230 2230 | 2320 2300 |
| Compressive strength (MPa), at: - 7 days - 28 days | 34,00 44,20 | 51,90 60,10 |
| Ultrasonic speed velocity (km/s), at: - 7 days - 28 days | 4,202 4,333 | 4,450 4,509 |
| Static modulus of elastic deformation (MPa), at: - 7 days - 28 days | 24,00 28,80 | 35,80 37,20 |
| Water penetration depth (mm), at: - 7 days - 28 days | 44 35 | 35 20 |
| Splitting tensile strength (MPa), at: - 7 days - 28 days | 2,02 3,18 | 2,39 3,39 |
| Calculated mean bending strength (MPa), at | 2,795 | 3,965 |
| Frost resistance class (cycles passed), C _{fr} | (4) C _{fr} 150 | (5) C _{fr} 200 |

Table 3: SUMMARY RESULTS from the tests conducted of MS and WS - STRUCTURAL CHARACTERISTICS

| Index tested | Composition | |
|--|--|--|
| | MC | WS |
| X-ray – portlandit (%), at: - 7 days - 28 days | 7 10 | 10 20 |
| DTA - C-S-H (%), at: - 7 days - 28 days | 3,944 4,164 | 7,685 7,893 |
| DTA - Total loss of chemically set water (integral hydration characteristic) (%), at: - 7 days - 28 days | 12,765 11,095 | 15,942 18,879 |
| Low temperature gas adsorption (BET-method) – pore structure parameters at 7 days of age: - specific pore surface S _{BET} , m ² /g - total pore volume V _t , cm ³ /g - mean pore diameter D _{av} , nm | 11 0,05 18 | 6 0,03 17 |
| Low temperature gas adsorption (BET-method) - pore structure parameters at 28 days of age: - specific pore surface S _{BET} , m ² /g - total pore volume V _t , cm ³ /g - mean pore diameter D _{av} , nm | 10 0,06 24 | 7 0,04 23 |
| X-ray computer thomography - (pore volume in interval 0,02-0,10 mm) at: - 7 days - 28 days | 0,394515- 0,000539= 0,394 0,50994- 0,00025= 0,510 | 0,465127- 0,002693= 0,462 0,39748- 0,00040=0,397 |

5. General conclusion

The analysis of the experimentally found physico-mechanical and structural characteristics of the analyzed mixes for shotcreting yields the following **CONCLUSION**:

The physico-mechanical and structural characteristics of the proposed of the repair mix **WS** for "wet" shotcreting significantly surpass those of mixes used for the repair of silos for heavy soda MC.

The WS mix for "wet" shotcreting displays strength-deformation and structural characteristics typical for performance shotcrete of the newest generation - high strength, elasticity modulus and degree of frost resistance. The mix properties combined with its high impermeability to aggressive agents (inclined to increase during exploitation) makes it entirely applicable from a technical-economical point of view in the repair-recovery of silos "4" and "5" for light soda.

All mentioned above gave enough reason SOLVAY SODI JSC to make a decision to assign respective structural design to be performed in accordance to all BG-standards.

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