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Condition assesment of concrete pier after three decades of exposure to sea water

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Preliminary note

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This paper presents the effects of long-term exposure of concrete structures to marine environment using as an example concrete blocks of a pier exposed to seawater for more than three decades. The blocks were tested to determine their mechanical characteristics (compressive strength), durability (gas permeability and capillary absorption), homogeneity (sclerometer rebound and ultrasound passage velocity) and chemical properties (quantity of chloride and sulphate ions). In addition, concrete behaviour in sea water was modelled using software packages Stadium and Conclife.

Key words:
Marine environment, sulphate corrosion, chlorides, condition assessment

Prethodno priopćenje

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Ocjena stanja betonskog obalnog zida izloženog djelovanju morske vode više od 30 godina

U radu su prikazane posljedice dugotrajnog izlaganja betonskih konstrukcija morskom okolišu, na primjeru betonskih blokova obalnog zida koji se nalaze u moru više od 30 godina. Na blokovima je provedeno ispitivanje mehaničkih (tlačna čvrstoća) i trajnosnih (plinopropusnost i kapilarno upijanje) svojstava, svojstava homogenosti (odskok sklerometrom i brzina prolaska ultrazvuka) te kemijska analiza (količina kloridnih i sulfatnih iona). Osim ispitivanja, provedeno je modeliranje ponašanja betona u morskoj vodi uz pomoć programskih paketa Stadium i Conclife.

Ključne riječi:
morski okoliš, sulfatna korozija, kloridi, ocjena stanja

Vorherige Mitteilung

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Zustandsbeurteilung von Ufermauern bei über 30-jähriger Meerwassereinwirkung

In dieser Arbeit werden die Folgen langzeitiger Einwirkungen aus der Meerwasserumgebung auf Betonkonstruktionen dargestellt und am Beispiel von Betonblöcken einer Ufermauer, die sich über 30 Jahre im Meerwasser befinden, erläutert. An den Blöcken wurden Versuche zur Ermittlung mechanischer (Druckfestigkeit) sowie mit der Beständigkeit(Gasdurchlässigkeit, kapillare Saugfähigkeit) und mit der Homogenität zusammenhängender Eigenschaften (Sklerometerabprall, Ultraschallgeschwindigkeit) durchgeführt und chemische Analysen (Anteil von Chlorid- und Sulfat-Ionen) abgeschlossen. Außerdem wurde das Verhalten des Betons im Meerwasser mittels der Programme Stadium und Conclife modelliert.

Schlüsselwörter:
Meerwasserumgebung, Sulfat-Korrosion, Chloride, Zustandsbeurteilung

1. Introduction

Marine environment is one of the most aggressive and complex environments that a concrete structure can be exposed to [1]. It influences concrete structures through various physical, chemical, mechanical, and biological processes, which cause deterioration of the concrete microstructure. Some of the major concrete infrastructure facilities in Croatia are situated in the vicinity of the Adriatic Sea, as well as in many marinas and ports [2, 3]. Knowledge about the extent of the long term influence of the Adriatic Sea on concrete structures is therefore of extreme importance.

The main reason for aggressiveness of marine environment is the chemical composition of seawater, which consists of different amounts of dissolved salts, oxygen, carbon dioxide, and sulphates. On an average, seawater contains 3.5 – 4 % of dissolved salts, mainly sodium chloride [4]. An average salt content of the Adriatic seawater is 38.3 g/l, which is more than an average salt content in other world seawaters. Besides chlorides, concrete deterioration can also be caused by chemical attack induced by Mg^{2+}, acid, and sulphate ions, which are also present in The Adriatic seawater, Table 1.

Table 1. Concentration of aggressive ions in the Adriatic Sea

Dissolved ions		SO_4^{2-}	Mg^{2+}	Ca^{2+}	Na^{+}	K^{+}
Concentration	g/l	2,97	1,42	0,46	21,25	0,39

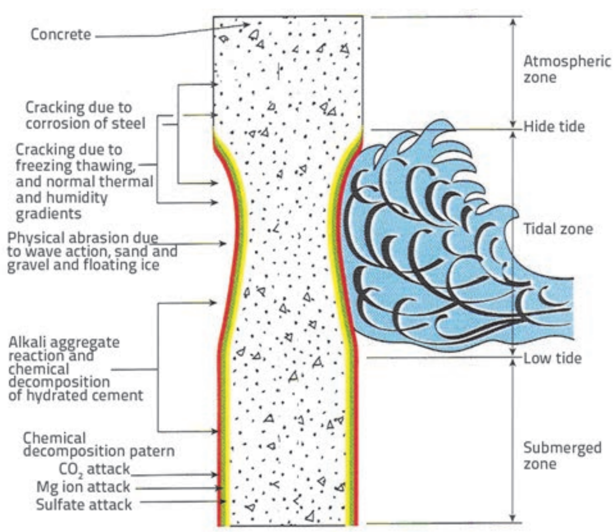


Figure 1. Type of attack on concrete sea structure for different exposure conditions [4]

Concrete structures exposed to marine environment are also influenced by a vast number of physical, chemical, and biological degradation mechanisms, such as the drying-wetting cycles, temperature changes, erosion, and different microorganisms that can grow in the microstructure of concrete and cause its deterioration [4-6]. Given the complexity of the degradation mechanisms in marine environments, the interdependence and synergy between individual degradation mechanisms should be taken into account. The type and severity of attack on a concrete sea structure depends on the conditions of exposure. Main physicasl and chemical reactions are presented in Figure 1.

1.1. Physical causes of concrete deteriorations

In the case of unreinforced concrete structures, physical causes of concrete deterioration involve four basic mechanisms: cavitation, erosion, salt crystallization, and freeze/thaw cycles [1]. In the Mediterranean climate, all of the above mentioned degradation mechanisms can be expected, with the exception of freeze/thaw cycles. During the wetting and drying cycles, salts from the sea (Na_2SO_4, Na_2CO_3, NaCl) penetrate deeper into the pores of concrete. An increase in volume due to salt crystallization exerts an additional pressure on the cement matrix of concrete. If the stress caused by crystallization of salt exceeds the tensile strength of concrete, the appearance of cracks on concrete surface, flaking or spalling is inevitable [4].

The progressive loss of mass on concrete surface can occur due to erosion and cavitation, as a result of wave action. These types of degradation are more frequent in cold seas where ice carried by waves causes damage to concrete surface.

1.2. Chemical causes of concrete deterioration

Small quantities of dissolved CO_2, derived mainly from absorption of atmospheric CO_2, and magnesium salts that are always present in seawater, can enter into deleterious chemical reactions with hydration products. Under normal circumstances, concrete structures are protected by aragonite, one of the most stable minerals in seawater environment [4]. In the splashing zone, aragonite is removed from concrete surface by wave action. If higher concentrations of CO_2 are present (for instance in bay waters), aragonite is transformed to calcium bicarbonate, which is leached away [1]. This results in an increased porosity of the structure and reduced concrete strength. The concentration of magnesium sulphate in sea water (up to 2000 mg/l) is more than sufficient for the sulphate corrosion of concrete [4]. The sulphate attack is related to an expansive character of gypsum or to ettringite formation by reaction of external sulphate with hydrated calcium aluminate of the hardened cement matrix [7]. The presence of sulphates causes transformation of calcium hydroxide into gypsum and/or ettringite. This process is accompanied by volume change, which is responsible for disruptive expansion of the concrete structure [4, 7]. One should be aware that, in case of permeable concrete, the normal amount of CO_2 present in seawater is sufficient for disintegration of cementitious products [1].

1.3. Biological causes of concrete deterioration

Biological deterioration of concrete caused by marine growth such as barnacles, molluscs, and different types of algae, is present in all seawaters [8, 9]. Fungi and lichens require less moisture, and can be found in splashing zones where cycles of wetting and drying are more pronounced. Algae are found in the parts of concrete structures that are constantly immersed in the sea, where they form fibrous, green or brown cover on concrete and fill the surface pores, partially preventing penetration of water into concrete.

The most common biological mechanism of concrete degradation is the activity of various molluscs and barnacles that inhabit the surface of concrete, eventually eroding it. Over time, these organisms drill through concrete and create „tunnels" that weaken the concrete structure. Up to date inspection of concrete structures located at Kvarner Gulf shows that six species usually settle on the concrete surface in this area, including sponges *Cliona vastifica*and and *Cliona vermifera*, shells *Rocellariadubia*, *Hiatellarugosta*, and *Irusirus*, and urchins *Paracentrotuslividus* [10, 11].

2. Old Brajdica pier

The Brajdica Container Terminal is a part of the largest Croatian port of Rijeka, which is situated at the northern coast of The Adriatic Sea. The old Brajdica pier consists of massive unreinforced concrete blocks measuring 2.5 m x 3 m x 8 m, placed up to the height of 15 meters measured from the sea bottom. The sea next to the pier is 12 m in depth. The terminal was built in the 1980s, and so the blocks were exposed to aggressive marine environment for more than 30 years.

The documentation from the construction phase of this pier is quite scarce, and the only available data is the specified strength class MB30 which, according to current standards, corresponds to the strength class of C25/30. No durability criteria were considered during construction. According to current requirements for concrete structures exposed to marine environment, as contained in HRN EN 206-1 [12], the minimum compressive strength should be C35/45, and the w/c ratio should be lower than 0.45.

The evaluation was conducted during reconstruction of the container terminal, when one part of the blocks were taken out of the sea and placed on the terminal platform to be surveyed, while other blocks were left in the sea, Figure 2. A comprehensive

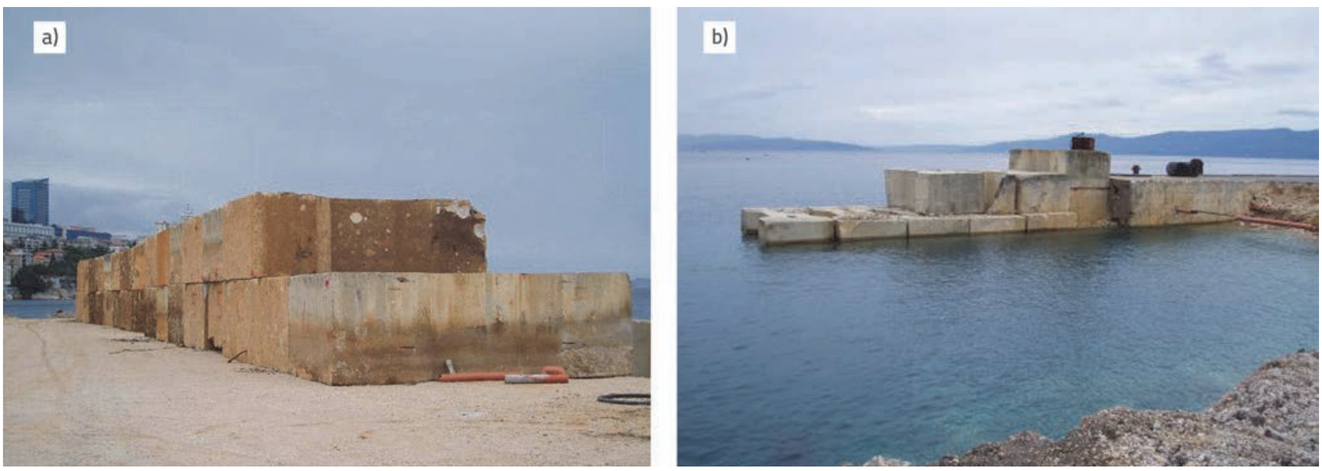


Figure 2. a) Concrete blocks taken out of seawater; b) concrete blocks left in seawater

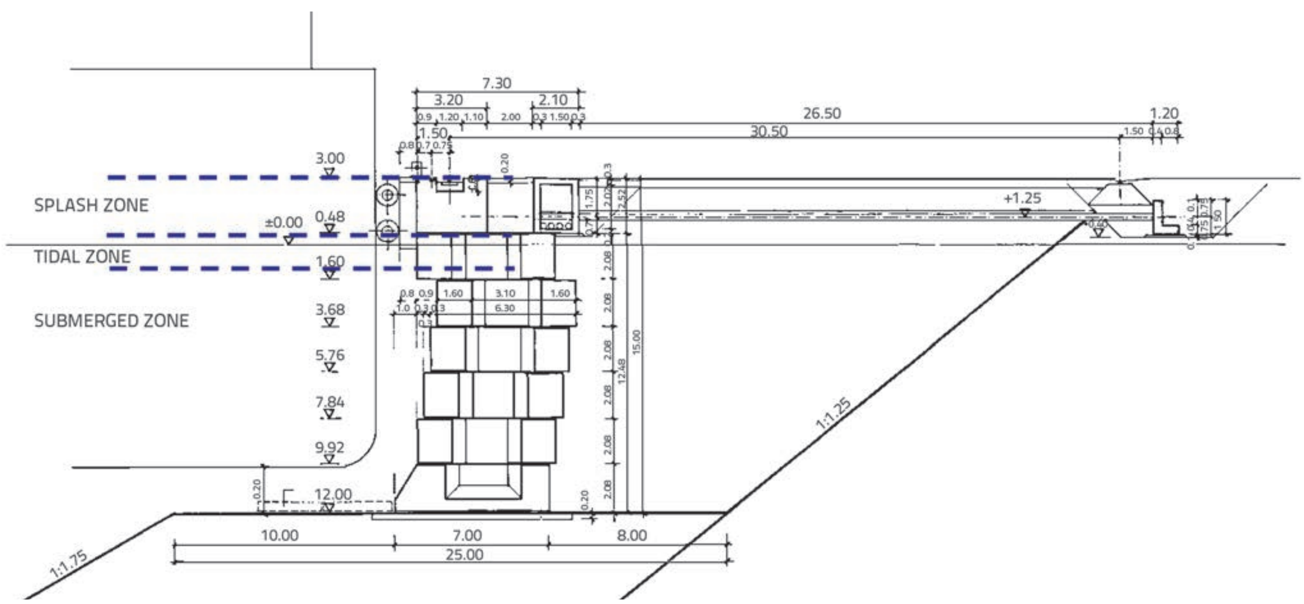


Figure3.Cross-section of concrete block wall

assessment was done in order to evaluate the condition of blocks and their possible subsequent use in the new pier. Figure 3 shows the cross-section of the wall, with the bottom part submerged in the 12 m deep sea, the central part exposed to shifts in sea level due to the tides, and the top part exposed to splashing of the sea water under the action of strong marine wind.

This paper presents consequences of all indicated environmental loads, as established during condition survey of massive unreinforced concrete blocks originating from an old pier of Brajdica Container Terminal on the Adriatic Coast, near the city of Rijeka, which were exposed to seawater action for over thirty years. The aim of this condition assessment was to collect the real-scale data on the long-term performance of concrete exposed to the Adriatic seawater. Therefore, a thorough testing was performed to evaluate the influence of sea water on the properties of concrete, at different levels of exposure.

3. Assesment metodology and testing

The assessment methodology consisting of preliminary inspection and preliminary (on-site) and detailed (laboratory) testing is schematically presented in Figure 4.

The available documentation, mainly construction drawings and basic material property (compressive strength), was obtained during preliminary inspection. Based on exposure conditions during service life, and different mechanisms and intensity of sea environment influence on concrete, the blocks under study were divided into three groups of exposure: splash, tidal, and submerged zone.

Each available block was visually inspected from both exposed sides. The damage and defects established in this way were classified into 5 categories, depending on the level of damage, all according to standards and recommendations for quantitative visual inspection [13-15], Table 2. Each block was also evaluated based on the non-destructive on-site test results. The surface toughness and the homogeneity of all blocks were obtained by rebound hammer and ultrasonic pulse velocity method, respectively. Based on visual inspection and non-destructive on-site test results, blocks were subdivided into 6 groups.

Three concrete cores (Ø 100 mm) were drilled for each group of blocks and these cores were used for further detailed laboratory testing. Since no information is now available on concrete properties during initial casting, there are no data that could be used to evaluate the long term influence of environment on concrete properties. For that reason, the influence of environment was determined on the first 5 cm of depth from the exposed surface, while further 10 cm were used for the evaluation of compressive strength. Samples of unexposed concrete were taken at the depth 15 cm below the exposed surface of concrete blocks, since it was expected that concrete is not exposed to seawater attack at this depth.

The detailed testing included determination of mechanical properties (compressive strength), homogeneity (rebound index and ultrasonic pulse velocity), and durability properties (gas permeability and capillary absorption). Additionally, concrete powder was collected for chemical analysis (chloride and sulphate ions content). The list of on-site and laboratory testing

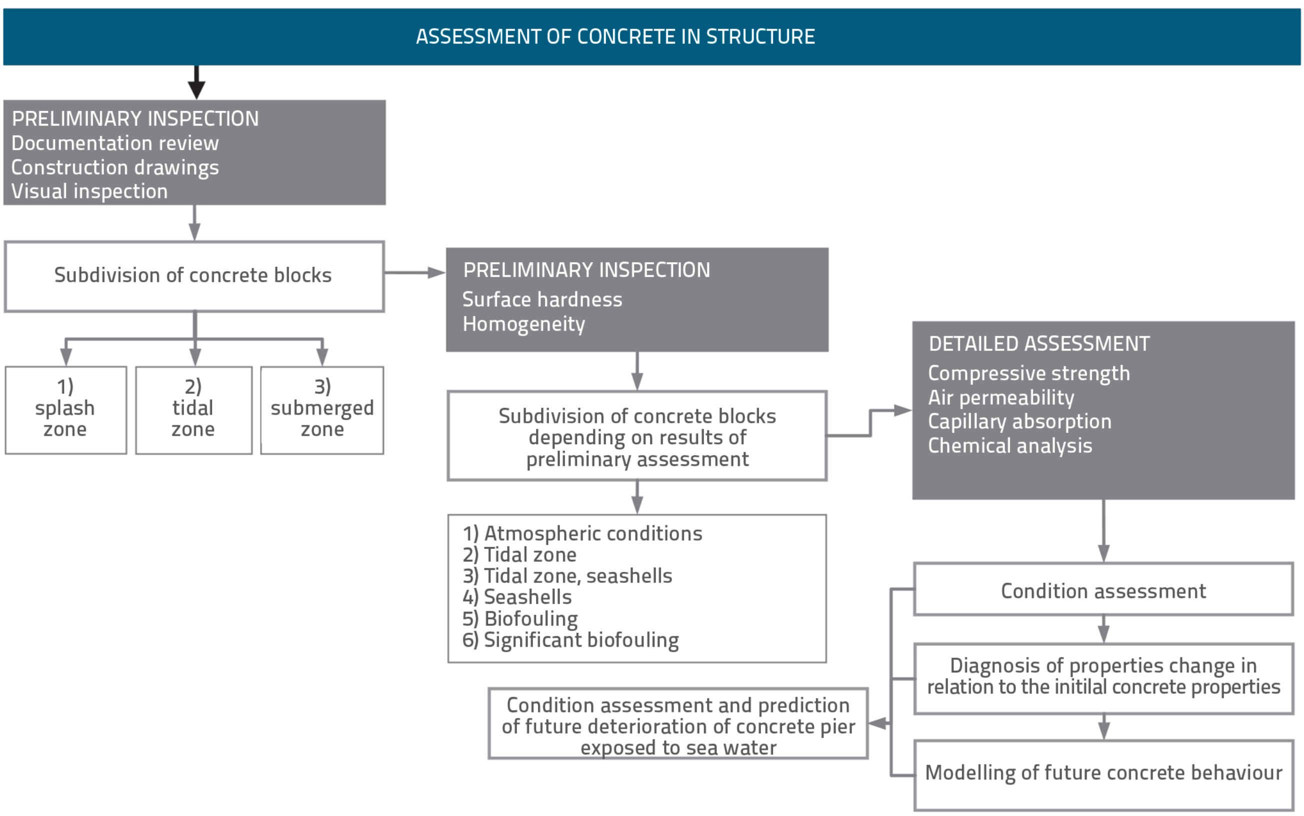


Figure 4. Schematic view of condition assessment methodology

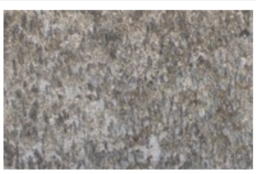
Table 2. Assessment of structural condition and classification of defects

Category	Description
0	Deterioration of thin layers of concrete cover, without any voids
I	Deterioration of thin layers of concrete surface sown to 1 mm in depth, thin scars in concrete surface, partly loose fine sand grains, surface cracks
II	Deterioration of concrete surface layer down to 4 mm in depth, scars in concrete surface, loose larger sand grains, deterioration of concrete cover due to seashells
III	Damages of concrete surface down to 10 mm in depth, loose large sand grains, scaled cement mortar between grains, deterioration due to seashells and seaweed
IV	Delamination of concrete cover, reduction of cross section
V	Odlamanje većeg površinskog dijela betona, smanjenje poprečnog presjeka

Table 3. List of testing performed, number of testing sites and standard according to which the testing was performed

Testing	Number of testing sites	Dimensions of specimens [mm]	Norma [15-22]
Visual inspection	80	-	DIN 1076
Schmidt hammer	80	-	HRN EN 12504-2
Ultrasonic pulse velocity	80	-	HRN EN 12504-4
Compressive strength	18	ø100/100	HRN EN 12390-3
Capillary absorption	36	ø50/100	HRN EN 13057
Gas permeability	36	ø50/100	RILEM TC 116
Chemical analysis (chloride and sulphate ions content)	16	prah	HRN EN 196-2

Table 4. Characteristic surfaces of concrete blocks and categorization of surfaces (% of exposed surface)

Exposure	Group	Surface deterioration	Classification of defects, % of exposed area					
				I	II	III	IV	V
Splash zone	1		57	19	0	24	0	0
Tidal zone	2		4	4	61	30	0	1
	3		8	3	37	48	4	0
Submerged zone	4		0	0	0	94	1	4
	5		1	1	0	31	62	5
	6		0	0	0	0	97	2

and standards used for particular testing are presented in Table 3. After testing and analysis of results, the level of damage to massive blocks was evaluated, properties were compared to reference properties, and future behaviour and service life of blocks was predicted.

4. Results and analysis

4.1. Preliminary inspection – visual inspection

During visual inspection, it was established that each of the six groups of blocks has a specific type of damage, characteristic for the level of the exposure to seawater action. Characteristic surface for each group of concrete blocks is shown in Table 4 together with its exposure conditions.
Visual inspection results show that the above sea level blocks (group 1) exhibit mostly shallow surface defects (surface cracks or thin scars). This type of physical deterioration mechanism is caused by wetting and drying cycles and salt crystallization [23]. The second group of concrete blocks in the tidal zone (groups 2 and 3) exhibits deterioration in terms of mapped cracks on exposed surfaces, which is probably caused by physical deterioration due to salt crystallization stresses.
A greater extent of deterioration was found on concrete blocks situated in the transition zone between the tidal zone and the submerged zone (group 4). This kind of chemical deterioration is mostly caused by the presence of sulphate ions and seashell activity [24]. Seashells caused heavier deterioration of the concrete surface layer leaving deeper holes and allowing easier penetration of aggressive agents further into concrete. Although the exact determination of seashell types was not conducted in the scope of this research it can be assumed, due to a similar surface appearance, that concrete degradation was caused by species similar to those found on other submerged structures in Kvarner Gulf [10, 11].Concrete blocks situated in the submerged zone (groups 5 and 6) exhibit significant biofouling on exposed surfaces, which is dependent on chemical dissolution of hydration products causing higher permeability. The defect categorisation summary based on visual inspection of concrete blocks is given for each group in the following table (Table 4).

4.2. Preliminary assessment - results of on-site testing

After preliminary inspection, an on-site testing campaign was performed on locations selected during visual inspection as recommended in [25]. The on-site testing included estimation of surface hardness and homogeneity using the rebound hammer and the ultrasonic pulse velocity method, respectively. According to results obtained by this testing, the concrete block surfaces were classified as medium quality surfaces (groups 1, 2, 3, 5) or good quality surfaces (groups 4, 6). Classification criteria are given in [12].
As could have been expected, results show that concrete quality is better in blocks placed in deeper zones of the sea, because at such depths they were not exposed to factors that can provoke deterioration of concrete.

4.3. Detailed assessment - results of laboratory testing

In order to perform a detailed analysis of concrete properties, cores were taken from 18 different sites. The following tests were performed on the drilled cores: compressive strength, capillary absorption, and gas permeability.
Results obtained by laboratory testing are presented in Table 6. The coefficient of capillary absorption and the coefficient of gas permeability are expressed for the unexposed and exposed concrete surfaces, respectively. Unexposed surfaces were used as reference for the evaluation of changes in concrete microstructure. If exposed and unexposed surfaces are compared, the most profound influence on permeability can be seen in the block groups 2 and 3. This implies that certain degradation processes were present in the tidal zone. Surface cracks arising from wetting and drying cycles and subsequent salt crystallization were determined as the factor causing an increased permeability. It is followed by chemical interactions between the seawater and hydration products where leaching of hydration products has a detrimental effect on increased porosity. During evaluation of these results, the age of the structure should also be considered because a very

Table 5. Results of surface hardness and ultrasonic pulse velocity methods

Exposure	Group	Rebound index	Pulse velocity [m/s]	On-site quality of concrete surface [6]
Splash zone	1	37,3 ± 5,1	3526,7 ± 160,7	medium
Tidal zone	2	35,6 ± 0,2	3313,3 ± 1006,5	medium
	3	42,5 ± 1,2	3823,3 ± 769,6	medium
Submerged zone	4	41,2 ± 3,4	4128,4 ± 823,0	good
	5	40,1 ± 1,9	3581,4 ± 871,8	medium
	6	46,5 ± 7,3	4730,0 ± 389,6	good

Table 6.Results of laboratory testing performed on cores (compressive strength, capillary absorption, gas permeability)

Exposure	Group	Compressive strength [MPa]	Coefficient of capillary absorption [kg/m^{2}h^{0,5}]		Coefficient of gas permeability [x10^{-16} m^2]	
			unexposed	exposed	unexposed	exposed
Splash zone	1	39,0 ± 10,6	0,35 ± 0,17	0,39 ± 0,19	1,75 ± 1,07	11,2 ± 3,40
Tidal zone	2	36,3 ± 4,7	0,22 ± 0,07	0,97*	6,49 ± 3,32	-**
	3	44,9 ± 5,7	0,20 ± 0,03	0,53 ± 0,04	10,9 ± 6,20	22,4*
Submerged zone	4	49,9 ± 6,0	0,24 ± 0,04	0,33 ± 0,08	1,83 ± 2,38	2,61 ± 2,58
	5	41,5 ± 8,6	0,25 ± 0,08	0,61 ± 0,35	2,38 ± 7,78	6,59 ± 7,12
	6	52,9 ± 10,0	0,22 ± 0,14	0,51 ± 0,15	1,45 ± 6,92	7,20 ± 5,03

* tested on one sample; ** unable to test

low compressive strength class (C25/30), together with a high w/c ratio, do not comply with current durability requirements and are certainly one of the reasons for a high coefficient of gas permeability, which was obtained even for unexposed concrete. The permeability of exposed surfaces was from 1.5 to 4 times higher compared to unexposed surfaces, for both capillary absorption and gas permeability.

In the splashing and tidal zones, the protective layer of aragonite ($CaCO_3$) is reduced due to wave action [1, 4]. Here, a chemical reaction between the aragonite and seawater is present and causes development of calcium bicarbonate. Highly soluble in water, calcium bicarbonate can be associated with the loss of materials and weakening of the hardened cement paste. This decomposition of hydration products can further be connected with lower compressive strengths in these zones, if compared with the submerged zone where such degradation mechanisms are not present (Table 6). This results in the loss of mass from erosion of concrete by wave action.

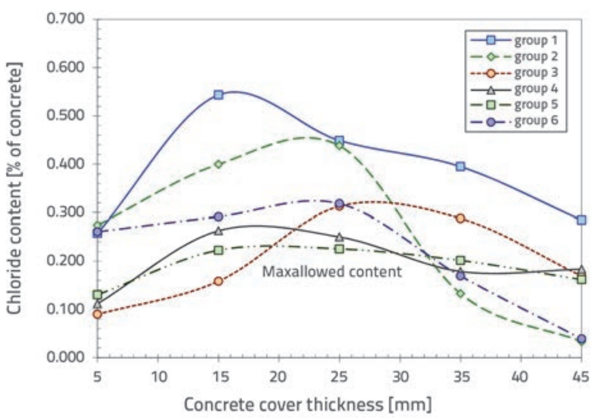


Figure 5. Chloride ions content for each group of concrete blocks (% wt of concrete)

The chemical analysis was performed on concrete powder samples and included determination of the chloride and sulphate ions content. Chemical analysis results are presented in Figures 5 and 6. According to the obtained results, there is a certain dependency between the block position and ions content. The highest amount of chloride ions can be found in the splashing zone (group 1) where wave and wind activities ensure a high amount of chloride ions in surface layers.

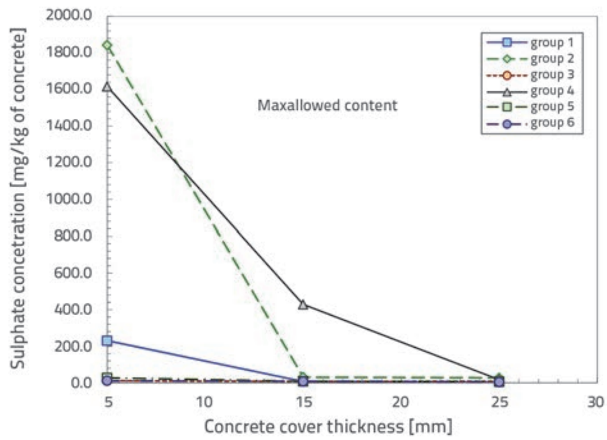


Figure 6. Sulphate ions content for each group of concrete blocks (% wt of concrete)

Chloride profiles for the splash and tidal zone (groups 1 – 3) confirm that the cracks found on concrete surface during visual inspection are caused by the crystallisation pressure of salts, which produced stresses large enough to cause cracking [1]. Although the concrete blocks used in this study are not reinforced, the information on chloride profiles can be used to predict future behaviour of reinforced concrete exposed to similar aggressive environment.

The content of sulphate ions (progressive decrease in strength and mass loss) was identified in order to determine the extent of possible deterioration by these ions, Figure 6. Sulphate profiles confirm that concrete in tidal zone is mostly susceptible to formation of gypsum and ettringite, which is due to the exposure of the old concrete block pier in Brajdica terminal to seawater action. However, according to literature, the expansion associated with ettringite formation is unlikely to occur in seawater due to presence of chlorides [1]. Lower density of gypsum with respect to calcium hydroxide, can cause volume increase [7]. Gypsum is highly soluble in seawater and, as such, it can be linked to the increased permeability of concrete and to a higher content of both chloride and sulphate ions in first few centimetres of the surface [1].

5. Prediction of future behaviour

5.1. Modelling with Conclife Software

Conclife is a software program for modelling service life of structures exposed to sulphate attack or freezing/thawing cycles. It was developed by the Building and Fire Research Laboratory, Federal Highway Association (FHWA), as a tool for the performance based design of concrete pavements and slabs [26]. The program enable control of ambient conditions (temperature, humidity, rainfall, precipitation) and concrete properties (modulus of elasticity, Poisson's coefficient, surface concentration of sulphate, concrete humidity, capillary absorption), and it assumes capillary suction as the main mechanism of water transport.
Conclife uses three concrete models, data on concrete properties, and external ambient conditions to estimate the time at which the concrete spalls. The software uses laboratory testing results for measuring concrete sorptivity, annual precipitation, and estimated rates of concrete spalling. The sulphate attack model is based on the model developed by Atkinson and Hearne [27] considering that sulphate ions are transported via sorption from external environment. The following basic equation was developed by Atkinson and Hearne:

$$X_{spall} = \frac{2\alpha\gamma_f(1-\nu)}{E(\beta\, C_E)^2}) \quad (1)$$

where:
C_E - concentration of reacted sulphate as ettringite [mol/m³]
E - Young's modulus [GPa]
X_{spall} - concrete spalling depth [m]
α - roughness factor for fracture path (default value is one)
β - llinear strain caused by reaction of sulphate ions to form one mole of ettringite m³/mol (default value of $1{,}8 \cdot 10^{-6}$)
γ_f - fracture surface energy of concrete [N/m]
ν - Poisson's ratio of concrete (e.g., 0.3).

The basic assumption of the model is that the deleterious expansion and cracking is due to formation of expansive ettringite within the concrete. The strain produced by the growing ettringite crystals exceeds the fracture energy of concrete causing failure and spalling of a thin Xspall layer from the concrete surface [28].
A deterministic numerical analysis is performed for three main exposure zones: splash zone, tidal zone and submerged zone. For comparison purposes, the analysis is also performed for sound concrete simulation. For all groups of exposure, input parameters are concrete properties presented in Table 6, while the output parameter is the time needed for crack initiation (caused by expansion due to sulphate attack) in the first 1 cm of concrete cover. An example of the tidal zone output information obtained with Conclife software is presented in Figure 7.

5.2. Modelling with Stadium Software

Stadium is a software program developed by SIMCO Technologies for service life modelling of structures exposed to a variety of aggressive environments, such as sea action, sulphate attack, soil, freezing/thawing, etc. [29]. It should be noted that a demo version of STADIUM, with a predefined material database and restricted mixture parameters, was used during this investigation.
A deterministic numerical analysis is performed for three main exposure zones: splash zone, tidal zone, and submerged zone. For all groups of exposure, the input parameters (materials, mixture parameters) are selected from the offered database, while the output parameter is the content of substances

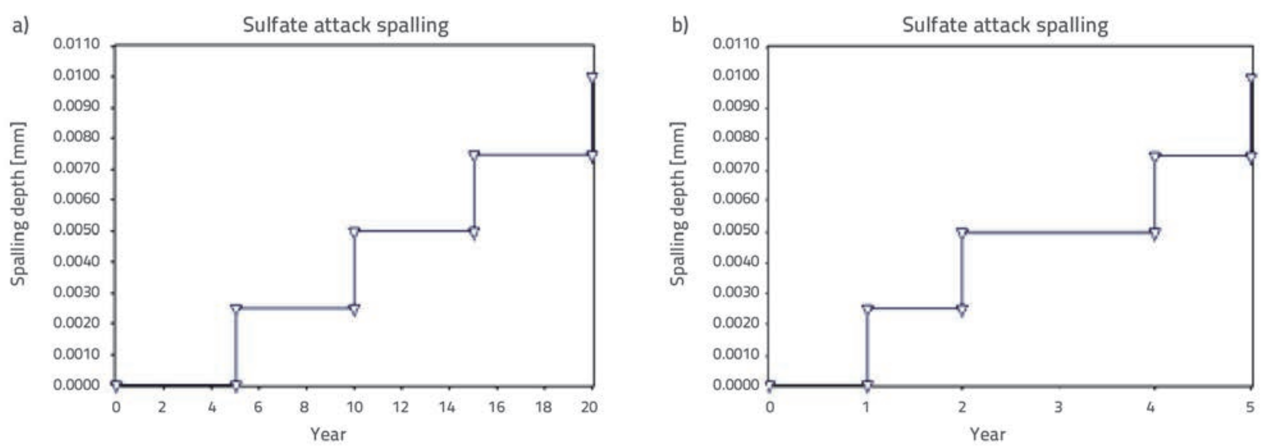


Figure 7. Example of tidal zone output information obtained with Conclife software: a) time to cracking of unexposed concrete; b) time to cracking of sulphate contaminated concrete

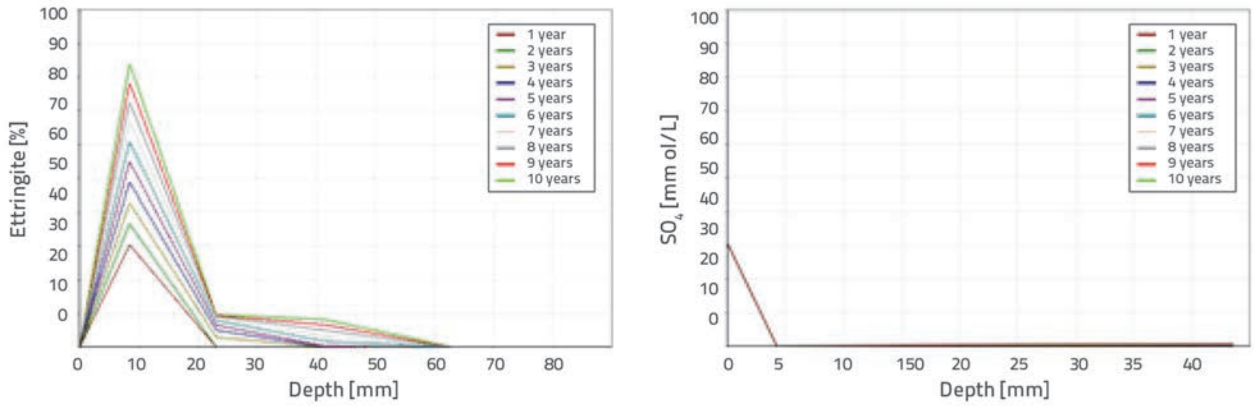


Figure 8. Example of output information for concrete exposed to tidal zone, obtained with Stadium software: a) chloride content; b) sulphate content

that are responsible for physical and chemical deterioration of concrete (Friedel's salt, chlorides, sulphates, magnesium, brucite, ettringite) after 10 years of exposure.

The results obtained by numerical modelling (Figure 8) show that sulphate attack is the most likely mechanism of deterioration of blocks in the splash and tidal zones (groups 1 – 3). The sulphate and chloride ion values obtained by modelling were compared with values obtained by testing in laboratory (Figures 5-8). This comparison shows that the above mentioned software is a useful tool for predicting the content of chemically aggressive substances in concrete exposed to different conditions in marine environment, and that it can therefore be used for performance-based design of concrete structures in marine environment.

6. Conclusions

Massive concrete blocks, which form the coastal wall of Brajdica terminal, have been exposed to aggressive marine environment for more than 30 years. The condition assessment of the exposed structure, and comprehensive testing of mechanical properties (on-site and laboratory testing of compressive strength), durability properties (gas permeability and capillary absorption), and chemical properties, were performed In order to evaluate influence of the aggressive marine environment on concrete properties.

The investigation conducted in the scope of this study shows that main mechanisms that are responsible for deterioration of concrete blocks are dependent on the concrete pier's exposure zone. These mechanisms include:

1. Salt crystallisation (physical cause of deterioration)
- The most exposed zone: splashing zone where seawater is brought by waves and wind; the chloride content determined for groups 1-2 is higher than allowed for unreinforced concrete (> 0.15 % wt cement).
- Mechanisms: salts from seawater are crystallized in concrete structure causing tensile stresses in the concrete structure;
- Consequences: surface cracks, deterioration of mechanical properties and homogeneity, increased surface permeability of concrete.

2. Sulphate attack and leaching of hydration products (chemical cause of deterioration)
- The most exposed zone: tidal zone where a low amount of chlorides and a certain amount of sulphates are present; the sulphate content determined for groups 2-4 is higher than allowed (> 0.14 % wt cement)
- Mechanisms: sulphate ions react with hydration products of the hardened cement paste, which results in formation of the mineral ettringite. Due to a higher concentration of CO_2 (i.e. bay water) and wave action, aragonite is transformed to calcium bicarbonate and leached away.
- Consequences: concrete cracking; however, the presence of chloride ions from seawater delays expansion of ettringite, increases porosity of concrete, and reduces strength.

3. Seashells and marine grass (biological cause of deterioration)
- The most exposed zone: tidal and submerged zones where seawater is always present and concrete is completely saturated;
- Mechanism: seashells induce surface holes in the cement matrix close to aggregate particles, while marine grasses use hydration products in their metabolism, thus weakening concrete microstructure;
- Consequence: surface holes 2 cm in depth, increased surface permeability of concrete.

Modelling with ConcLife software shows that an accelerated deterioration of surface layers (around 5 years) can be expected if blocks are returned to the same positions in the wall. Surface layers (up to 5 cm in depth) exhibit an increased permeability and the amounts of chloride and sulphate ions are higher than allowed in unreinforced concrete. Parts of concrete blocks that are 5 cm below can be considered as undamaged concrete, because significant amounts of chloride and sulphate ions have not been found. The gas permeability testing shows that concrete quality ranges from medium to good. Measured chloride and sulphate ion values were confirmed by modelling with the commercially available Stadium software. Based on this calculation, the time of crack occurrence obtained with the ConcLife program package has been confirmed.

A general conclusion of this study is that evaluated blocks are suitable for use in marine environment, but exclusively in zones under the water surface where deterioration mechanisms progress very slowly or are unlikely to occur due to the reduced availability of oxygen.

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