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THE INFLUENCE OF CHLORIDE IONS CONTENT ON THE MECHANICAL PROPERTIES OF CONCRETE

WPŁYW ZAWARTOŚCI JONÓW CHLORKOWYCH NA WŁAŚCIWOŚCI MECHANICZNE BETONU

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Abstract

This paper presents an analysis of the effect of concrete salinity on the splitting tensile strength of specimens taken directly from the HC-500 floor slab and the flexural and compressive strength and the value of the modulus of elasticity of specimens made under laboratory conditions from lightweight concrete and ordinary concrete. The tests were carried out in two variants: in the first, chloride ions were introduced into the concrete by the migration method and in the second, as an additive introduced directly with the batch water. The analysis showed that the additive can affect certain mechanical properties of concrete both favorably and unfavorably. The results indicate that it is important to examine the issue of the influence of salinity on concrete's mechanical properties. This knowledge can be applied to the modeling of damage in reinforced concrete structures resulting from exposure to chloride-rich environments.

Keywords: prestressed structures, HC-500 floor slabs, concrete salinity, concrete strength, chloride ions, modulus of elasticity

Streszczenie

W niniejszej pracy przedstawiono analizę badań wpływu zasolenia betonu na wytrzymałość na rozciąganie przy rozłupywaniu próbek pobranych bezpośrednio z płyty stropowej HC-500 oraz wpływu zasolenia na wytrzymałość na zginanie i ściskanie oraz na wartość modułu sprężystości próbek wykonanych w warunkach laboratoryjnych z betonu lekkiego i betonu zwykłego. Badania przeprowadzono w dwóch wariantach: w pierwszym po wprowadzeniu jonów chlorkowych do betonu metodą migracyjną w próbkach pobranych z płyt HC-500 i wykonanych z betonu lekkiego i w drugim, jako dodatek wprowadzony bezpośrednio z wodą zarobową w próbkach z betonu zwykłego. Przeprowadzone badania porównawcze różnych betonów z dodatkiem NaCl wykazały, że dodatek ten może wpływać zarówno korzystnie, jak i niekorzystnie na niektóre właściwości mechaniczne betonu. Przeprowadzone badania wskazują, że istotne jest dokładniejsze rozpoznanie zagadnienia wpływu zasolenia betonu na jego właściwości mechaniczne, co może być następnie wykorzystane w procesie modelowania zniszczeń konstrukcji żelbetowych wywołanych oddziaływaniem środowiska zawierającego chlorki.

Słowa kluczowe: konstrukcje sprężone, płyty stropowe HC-500, zasolenie betonu, wytrzymałość betonu, jony chlorkowe, moduł sprężystości

1. INTRODUCTION

The impact of chloride ions on reinforced and prestressed concrete structures is complex in nature. It can pose a threat by destroying the cement matrix that forms the cover of the reinforcement, and also, it can initiate corrosion and destruction of the steel reinforcement [1]. The mechanism of the effects of reinforcement corrosion on concrete cover is now fairly well understood, while the effects of chloride ions on the cement matrix in concrete and the impact of

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these effects on the mechanical properties of concrete are usually ignored. Even small amounts of chlorides, contained in soft drinking water (up to 0.3 mg/L), can cause corrosion of the reinforcement of water tanks under unfavorable conditions [2]. Other times, they can cause the formation of products that increase in volume due to crystallization, causing tensile stresses [3]. The whole range of processes that occur in concrete under the influence of chloride ions will undoubtedly affect its mechanical properties. However, not enough research defining these relationships exists.

The mechanical properties of concrete depend on two basic hydration products: hydrated calcium silicate (C-S-H) and calcium hydroxide (CH). Moreover, there is a relationship between the Ca/Si ratio of C-S-H and the mechanical properties of concrete [4]. In [5], the mechanical properties of various Self-Compacting Concrete (SCC) concrete mixtures prepared from two types of cement: OPC (ordinary Portland cement) and PPC (Portland pozzolanic cement) were evaluated. Compressive strengths were determined after 28, 90 and 360 days of curing, which were compared with the Ca/Si ratio calculated by energy dispersive X-ray spectroscopy (EDX) and the amount of calcium hydroxide (%) calculated by thermogravimetric analysis (TGA). The effect of NaCl salt added directly to the batch water during the making of the concrete mix at 0%, 1%, 3% and 5% (by weight of the batch water) was studied. A control SCC concrete mix (0% NaCl) was compared with SCC mixes with chloride admixture (1%, 3% and 5% NaCl) for a given cement type. It was observed that the compressive strength decreased for concrete from OPC mixes while it increased for PPC concrete with chloride ion content. The average decrease in compressive strength of concrete from OPC mixes was 10.88%, while the average increase in compressive strength of chloride-doped PPC concrete was 8.92% with respect to the control SCC concrete mix. Both the Ca/Si ratio and compressive strength increased with maturation time for OPC at different concentrations of NaCl. However, in PPC-based SCC concretes, the compressive strength increased, while the Ca/Si ratio decreased with concrete maturation time. In SCC concretes prepared with OPC, both the calcium hydroxide content and the Ca/Si ratio increased with maturation age, while the opposite relationship of these parameters was observed in SCC concretes prepared with PPC.

In [6], there are presented tests of compressive strength and Young's modulus carried out after 3, 7 and 28 days of maturation of samples with different chloride contents of 0.00, 0.07, 0.60 and 1.20% (of the weight of cement). However, no significant changes in the mechanical properties of concretes in the early maturation period dependent on the addition of NaCl were observed.

However, in [7], the destructive force determined in the study of mechanical fracture parameters carried out with the use of a so-called „Brazilian" method, using a central notch in the centre of the cylindrical test specimen, was about 15% lower after 30 days of natural diffusion in specimens made of high-strength HPPC concrete saturated with chloride ions than in control specimens from this concrete. In contrast, indirect tensile tests conducted using the Brazilian method showed no differences in the strength values obtained in concrete subjected to diffusion penetration of chloride ions and in reference concrete.

The impact of concrete salinity on its mechanical properties is particularly significant, especially when modeling the durability of reinforced concrete structures. Variations in concrete characteristics, influenced by chloride ions – such as strength and modulus of elasticity – can alter the nature and location of cracks within the concrete matrix. This aspect has been largely overlooked in current concrete cracking models, and there is a scarcity of experimental studies addressing this concern.

The main objective of this pilot research work was to test the possibility of the effect of chloride ions on the mechanical characteristics of concrete. The effect of salinity of concrete on the splitting tensile strength of specimens taken directly from the HC-500 slab and exposed to chloride ions in an electric field was tested. The effect of salinity caused by chloride ions in an electric field on the flexural and compressive strengths and the value of the modulus of elasticity of specimens made under laboratory conditions from lightweight concrete was also investigated. The effect of the addition of NaCl to the batch water on the splitting tensile strength and on the value of the modulus of elasticity of specimens made from lightweight concrete was evaluated.

2. MATERIALS AND METHODS

Three types of samples were prepared for testing: 1) 5 cylindrical specimens with a diameter of Ø 95 mm and a height of 50 mm – taken with a crown drill directly from the HC-500 prestressed concrete slab; 2) 11 rectangular specimens with dimensions of 40 × 40 × 160 mm – made under laboratory conditions from ready dry concrete mixture; 3) 6 cylindrical specimens with a diameter of Ø 150 mm and a height of 300 mm made from ordinary concrete with the addition of NaCl directly to the batch water (in the amount of 1.5% to the weight of cement) and 6 of the same specimens without the addition of NaCl. Since the study is preliminary and the results of analogous studies available in the literature do not give clear answers as to the effect of NaCl content on the mechanical properties of concrete, different types of concrete were chosen.

To determine the composition of the ready-mix lightweight concrete, a sieve analysis of the aggregate was performed and the cement content was determined roughly. A super-plasticizer was added according to the manufacturer's recommendations. The preparation of beams for testing was carried out in accordance with PN-EN 196-1 [8]. The samples were unmoulded about 24 hours after the mixture was placed in the moulds. The finished beams were then left submerged in water for 56 days. Cylindrical specimens were cut from fragments of the floor, the age of which was determined to be 6 months at the time of testing based on the manufacturer's data. Cylindrical samples prepared from ordinary concrete were stored under laboratory conditions at a temperature of about 20°C and were unmoulded after 28 days. The quantitative composition of the tested concretes is shown in Table 1.

Table 1. Composition of tested concretes

Constituent of concrete	Concrete in HC-500 slabs	Lightweight concrete	Ordinary concrete
	kg/m³		
Type of cement	CEM II A-S 52.5 R	CEM I 42.5 R	CEM I 42.5 R
Mass of Cement	581	577	350
Aggregate	1597	250	1788
Silica fume	65	–	–
Foam glass	–	1012.80	–
Superplasticizer	22.95	30	–
NaCl	–	–	5.29
Water	180	370	192.5
w/c	0.31	0.64	0.55
γ_b kg/m³/ Volume weight	2621	826.95	2460

Figure 1 shows the particle size distribution of the tested concretes.

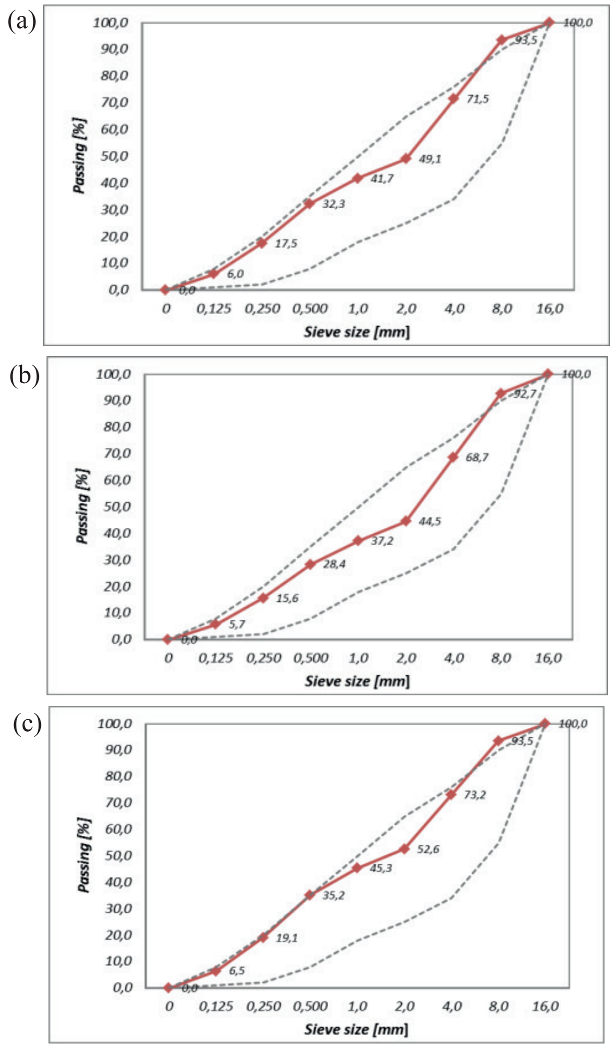

Fig. 1. Particle size distribution in: (a) HC-500 slab concrete and (b) lightweight concrete (c) ordinary concrete

Table 2 shows the chemical composition of the cements used.

Table 2. Chemical composition of the cements used

Components, % of mass	CEM I 42.5 R	CEM II A-S 52.5 R
SiO_2	19.38	21.1
Al_2O_3	4.57	5.63
Fe_2O_3	3.59	3.59
CaO	63.78	59.3
MgO	1.38	2.24
K_2O	0.58	0.59
Na_2O	0.21	0.6
Eq. Na_2O	0.59	0.2
SO_3	3.26	2.86
Cl	0.069	0.039

Figure 2 shows slabs with sampling locations for testing (2a) and a view of the slabs after sampling (2b). The sampling location was determined by taking into account the possibility of cutting the samples without reinforcement and the technical conditions for setting up the drilling rig. After cutting, the bottom surface of the samples was levelled with a diamond saw, setting the height of the samples at 50 mm.

In order to analyze the effect of salinity on the properties of concrete, an accelerated migration process of chloride ions assisted by an electric field was carried out. Prior to the migration process, both cylindrical samples cut from HC-500 slabs and cuboidal samples were stored in water for 72 hours. Two-plastic reservoirs with an epoxy resin-protected side surface (2) were tightly attached to the top surface of the cylindrical specimens (which is also the top edge of the ceiling) (1), and filled with a 3% NaCl solution. Perpendicular specimens (3) were similarly prepared, the side walls secured with waterproof glue and the previously prepared plastic tanks (4) slid onto the elements.

Cathodes (5) made of stainless steel and sized to fit the cross-section of the test piece were placed in the tanks filled with water, on a grid anode (6) made of platinum-coated titanium. The system was connected to a direct current source of U = 18 V (8). The electrical circuit was powered by a special bridge (7), which ensured stabilization of the flowing current and also distributed the voltage between the electrodes. The cylindrical samples were connected to the circuit for a period of one month, during which the NaCl solution was changed three times. Throughout the test period, the temperature of the solutions was constant at around 20°C – Figure 3a.

Perpendicular samples were tested for a week, during which the NaCl solution was replaced once after 3 days – Figure 3b.

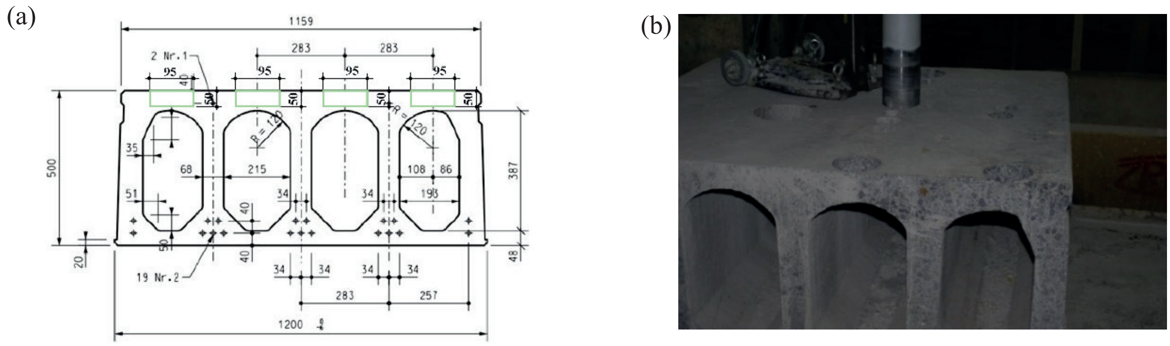

Fig. 2. (a) Drawing of the disc with the download locations marked and (b) view of the discs after they have been downloaded

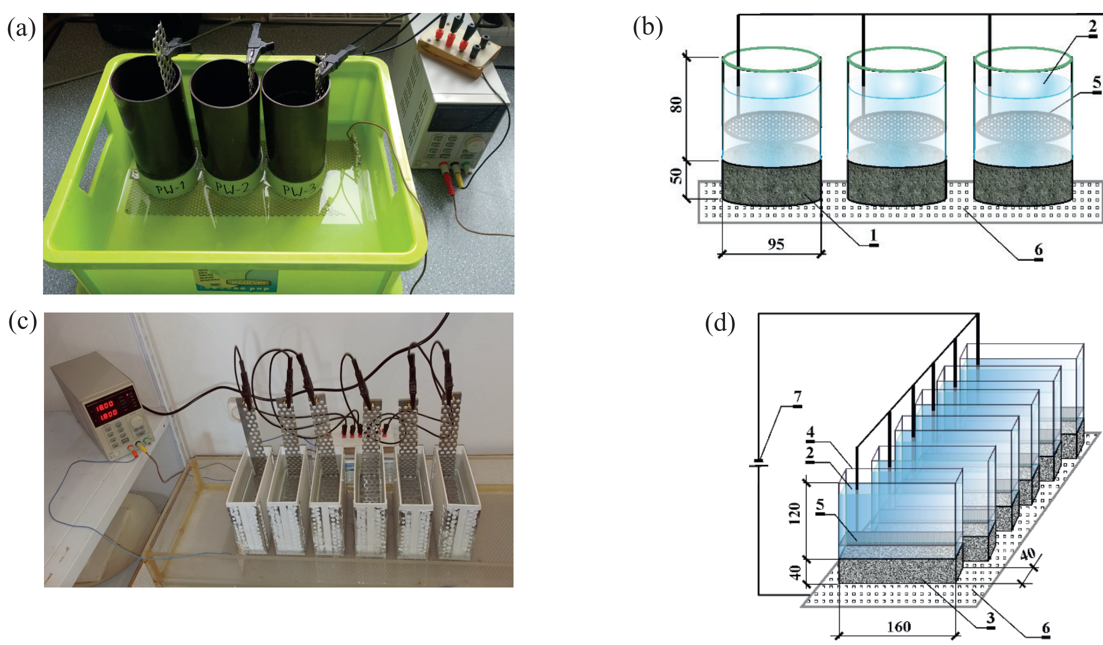

Fig. 3. Chloride migration test stands: a) view of test of cylindrical specimens cut from HC-500 slabs; b) schematic of test of cylindrical specimens cut from HC-500 slabs; c) view of test of lightweight concrete rectangular specimens; d) schematic of test of lightweight concrete rectangular specimens – description in text

After migration, the samples were left under laboratory conditions for 3 days. Then some of the samples were subjected to strength tests. In the remaining samples, the level of chloride ion concentration in the aqueous extract was determined using a multifunction meter CX-701 from Elmetron. This extract was obtained, from stratified ground concrete taken with the Profile Grinding Kit device, from layers 4 mm thick to a depth of 40 mm [9]. Table 3 summarizes the designations and dimensions of the samples, along with the tests to which they were subjected.

Strength tests of rectangular specimens were performed in accordance with PN-EN 196-1 [8] using a PILOT Controls Model 65-L27C12 device. The specimens were subjected to a load until the specimen broke. The bending strength of the rectangular specimens was calculated according to the formula:

$$R_t = \frac{1.5 \cdot F_t \cdot l}{b^3} \tag{1}$$

where:
R_t – flexular strength MPa,
b – lateral length of the beam cross-section, mm,
F_t – breaking load in the middle of the beam, N,
l – distance between supports, mm.

The part of the PILOT Controls Model 65-L27C12 responsible for compressive strength testing provided a load increment speed of 2400 (±200) N/s. The device indicated Fc – the value of the pressure reached when the barrel was crushed. The test was performed on halves of the beams. The prepared pieces were placed laterally on the center of the plate, with the accuracy of the ±0.5 mm in the longitudinal direction, so that the faces of the beam protruded about 10 mm beyond the plates. Throughout the test, the load was increased uniformly at a rate of 2400 N/s until crushing. The compressive strength was calculated according to the formula:

$$R_c = \frac{F_c}{1600} \tag{2}$$

In order to determine the tensile strength of cylindrical specimens, the indirect method of determining the tensile strength of brittle materials, the Brazilian method, was used, by compressing the cylinder on the side with two linear equivalent loads [10]. The test was performed using a specialized hydraulic press FORM+TEST Prufsysteme Model MEGA 3-3000-100 S – Figure 4.

The splitting tensile strength (Brazilian method) was calculated according to the formula:

$$f_t = \frac{2 \cdot P_{\max}}{\pi \cdot d \cdot h} \tag{3}$$

where:
f_t – splitting tensile strength MPa,
$P_{\max}$ – destructive force on the sample kN,
d – sample diameter, mm,
h – sample height, mm.

Testing of the modulus of elasticity of lightweight concrete beams was carried out using the guidelines provided in the ITB manual 194:98 [11]. All samples were divided into two equal halves (to reduce slenderness), and one of each was selected for further analysis. In order to measure deformation, two paper strain gauges, 20 mm each, were taped the samples, on opposite sides of the longitudinal beams. The test was performed using a specialized hydraulic press FORM+TEST Prufsysteme Model MEGA 3-3000-100 S.

Simultaneously, the pressure of the applied force and strain were checked for both strain gauges at a frequency of 0.5 s intervals. The pressure increment was 0.1 kN/s. The specimens were positioned axially in the testing press and loaded with an initial force, inducing a stress of $\sigma = 0.5$ MPa in the specimen. The press then increased the pressure on the specimen until it failed. The strain values were automatically measured and entered into a computer connected to the test press. Calculations of the modulus of elasticity for individual specimens were made using the formula:

$$E_{cmi} = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4}$$

where:
E_{cmi} – modulus of elasticity, MPa,
$\Delta\sigma$ – the difference in stress in the specimen between the stress corresponding to the initial load and the stress corresponding to the load with a value of $0.4 f_{cm}$, MPa,
$\Delta\varepsilon$ – the difference in the deformation of the specimen between the initial load and the final load with a value of $0.4 f_{cm}$, ‰.

3. RESULTS AND DISCUSSION

Table 4 shows the results of chloride ion concentrations determined in cylindrical samples cut directly from HC-500 slabs and samples made from lightweight concrete after accelerated penetration of chloride ions into the concrete. A higher value of chloride ion concentration obtained in cuboidal samples made of lightweight concrete was observed, compared to samples taken directly from HC-500 slabs, which results from the

Table 3. Distribution of chloride ion concentration values determined in cylindrical samples cut from HC-500 slabs and beams made from lightweight concrete

Rzędna obl./ Coordinate [mm]	Cl^- concentration in c^1 Solution [mg/dm^3]	Chloride content by cement mass [%]	Cl^- concentration in c^1 solution [mg/dm^3]	Chloride content by cement mass [%]
Concrete	Concrete in HC-500 slabs		Leight weight concrete	
2	246.8	0.270	699	0.20
6	45.9	0.05	152.1	0.043
10	20.1	0.023	74.6	0.021
14	17.1	0.019	51.3	0.015
18	16.1	0.018	46	0.013
22	15.8	0.017	37.5	0.011
26	15.4	0.017	31.2	0.009
30	15.6	0.017	27.3	0.008
34	15.0	0.016	22.3	0.006
38	14.9	0.016	18.9	0.005

more compact structure of cylindrical samples. After converting the chloride ion content expressed as a percentage by weight of cement, the concentration distribution obtained in cylindrical samples was slightly greater up to a depth of 10 mm. In contrast, as the depth increased, the predominance of chloride content in concrete cut from HC-500 slabs increased.

Figure 4 shows the results of strength tests on cuboid specimens made of lightweight concrete. It was observed that specimens PP-2-4, subjected to the penetration of chloride ions with the help of an electric field, obtained a lower average flexural strength (about 41% taking into account the arithmetic mean and 52% taking into account the median of the measured values) and at the same time a higher average compressive strength (about 19% taking into account the arithmetic mean and 18% taking into account the median) with respect to control specimens PP-5-7.

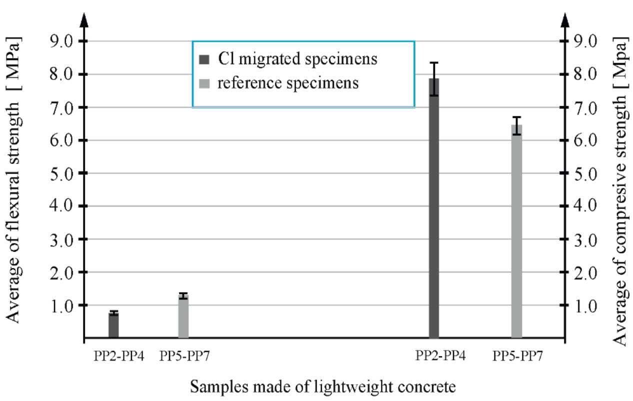

Fig. 4. Graph of average flexural and compressive strength of samples subjected to Cl migration and reference samples made of lightweight concrete

In [12] it was found that specimens cared for in water had higher flexural strength (by 15%) and lower compressive strength than specimens with lower moisture content cared for in a climatic chamber. Concrete in a moist state showed higher tensile strength than dry one, since water in the form of films on colloidal particles causes them to be bonded together more strongly [12]. The salt content of concrete, due to its hydrophilic properties, can bind water, causing it to "dry out" and loosen those bonds, entailing a reduction in flexural strength.

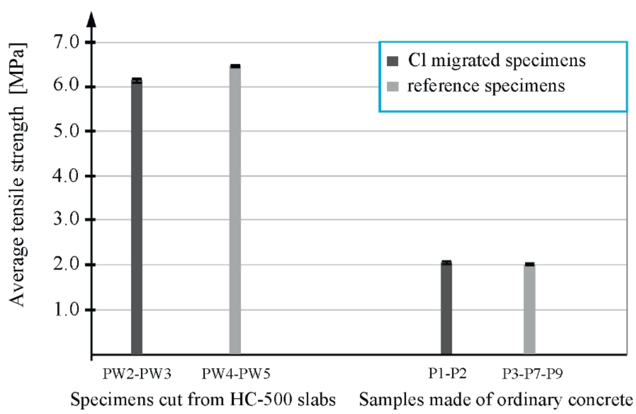

Fig. 5. Graph of average tensile strength of Cl migrated and reference specimens cut from HC-500 slabs and made of ordinary concrete

Figure 5 shows the results of tensile tests (Brazilian method) of cylindrical specimens cut directly from HC-500 slabs (PW-2, PW-3 treated with chloride ions in the process of migration and PW-4, PW-5 without the action of these ions) and cylindrical specimens made from ordinary concrete (P1-P3 made with NaCl addition and P7, P9 control specimens). It can be seen that in both types of samples the tensile strength almost did not change due to NaCl penetration.

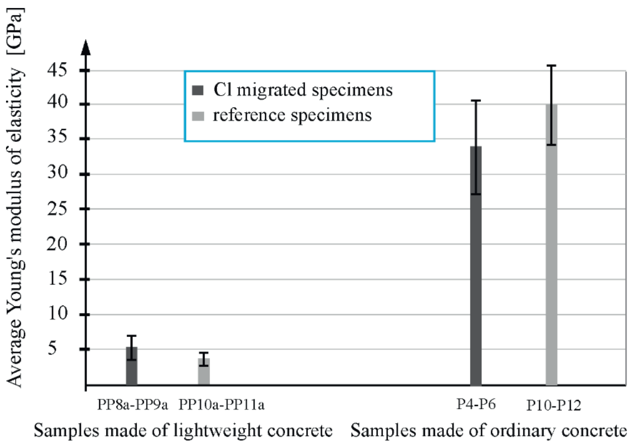

Fig. 6. Graph of average Young's modulus of elasticity of samples subjected to Cl migration and reference samples made of lightweight concrete and ordinary concrete

Figure 6 shows the results of tests on the modulus of elasticity of rectangular specimens made from lightweight concrete and cylindrical specimens prepared from ordinary concrete. It can be observed an increase of about 42% taking into account the arithmetic mean (about 64% taking into account the median) in the value of the modulus of elasticity of PP-8a-9a beams treated with chloride ions with respect to the control specimens PP-10a-11a. However, in the case of cylindrical specimens made of ordinary concrete, a reduction of about 17% taking into account the arithmetic mean (about 20% taking into account the median) in the value of the modulus of elasticity of P4-P6 beams treated with chloride ions can be observed with respect to P10-P12 control specimens. The figure also indicates the variance of the standard deviation calculated for each group of results. The dispersion of the results, as determined by the value of the standard deviation, can be considered average, but each time its value was less than or slightly exceeding 1/3 of the average value of the measured values. Of course, such tests should be carried out on a larger number of samples in order to reduce the dispersion of the values obtained and assess the effects of salinity on concrete.

4. CONCLUSIONS

Based on the conducted preliminary studies of the mechanical properties of various types of concrete, it can be concluded that:

- The flexural strength of lightweight concrete decreased about 41% taking into account the arithmetic mean and 52% taking into account the median of the measured values due to the addition of salt, in contrast to the compressive strength, which increased by about 19% taking into account the arithmetic mean and 18% taking into account the median. The flexural strength of the concrete is more sensitive to the salt content than the compressive strength, which may be related to a decrease in the moisture content of the tested concrete due to the hydrophilic properties of salt.
- Using the Brazilian method to evaluate the effect of salt content both added directly to the concrete mix and introduced by the migration method showed no change in tensile strength, similar to what was found in the [7].
- Tests of the modulus of elasticity of ordinary concrete indicate a slight decrease (about 17% taking into account the arithmetic mean (about 20% taking into account the median) in Young's modulus associated with the addition of chlorides directly to the concrete mix.
- On the other hand, a definite increase about 42% taking into account the arithmetic mean (about 64% taking into account the median) in the value of elastic modulus was obtained in lightweight concrete in samples treated with chloride ions in an electric field, which confirms the dependence of elastic modulus on compressive strength contained in the standard [13].

The findings suggest the importance of conducting additional research on the mechanical properties of various types of concrete, including the study of microstructure and chemical composition, in particular, the content of Ca/Si and the amount of calcium hydroxide. Such studies would allow for more accurate modelling of concrete cracking under corrosive conditions induced by chloride ions, examining both the variations in the volume of reinforcement corrosion products and the changes in the mechanical properties of chloride-contaminated concrete.

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