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УТИЦАЈ ВРСТЕ И ПРИМЈЕНЕ КОМПОНЕНТНИХ МАТЕРИЈАЛА НА САДРЖАЈ ХЛОРИДА У САМОУГРАЂУЈУЋЕМ БЕТОНУ

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Резиме: Обзиром да су, један од најчешћих узрочника корозије арматуре, а тиме и деградације бетонских конструкција, хлор јони, од изузетне је важности познавање њихове концентрације у бетону. У раду су приказана ограничења садржаја хлор јона у бетонима и класе према европској регулативи, те спроведено експериментално истраживање о величини утицаја примијењених компонентних материјала на садржај хлор јона у различитим врстама самоуграђујућих бетона.
Истраживањем се показало да на повећање садржаја хлор јона у бетону доминантан утицај има цемент, а затим и примјена рециклираног агрегата, произведеног од отпадног бетона. Примјена минералних додатака – кречњачког филера и електрофилтерског пепела и ријечног агрегата утиче на смањење концентрације хлорида у бетону.
Путем факторијалне анализе, извршено је моделирање фунционалне зависности садржаја хлорида и примјене различитих врста компонентних материјала.

Кључне ријечи: хлориди, самоуграђујући бетон, експериментална истраживања.

THE INFLUENCE OF COMPONENT MATERIALS TYPES AND APLICATION ON THE CHLORIDE ION CONTENT IN SELF-COMPACTING CONCRETE

Abstract: Considering that one of the most common causes of reinforcement corrosion, and consequently degradation of concrete structures, are chloride ions, it is of utmost importance to know their concentration in concrete. This paper presents the limitations of the chloride ions content in concrete and classes according to European regulations, and the experimental research on the magnitude of the influence of applied component materials on the chloride content in various types of self-compacting concrete.
The research presented that the dominant influence in respect of the increase of the chloride ions content in concrete, is of cement and then of a recycled concrete aggregate. The application of additions - limestone filler and fly ash and river aggregate results in the reduction of the chloride concentration in the concrete.
Through factorial analysis, modeling of the functional dependence of chloride content and application of different types of component materials was performed.

Keywords: chloride, self-compacting concrete, experimental research.

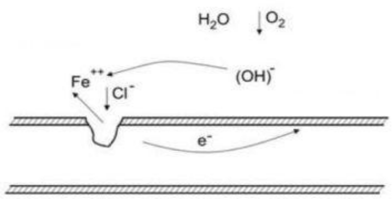
1. INTRODUCTION

When designing concrete constructions, in accordance with the European regulations, it is necessary to consider the environmental conditions which are expected to occur during constructions working life (XO, XC, XD, XS, XF, XA), as well as possible special forms of aggressive or indirect effects, which may exist at the site of application. These special effects imply:

- chemical attack, arising from, for example: the use of the construction (storage of aggressive liquids etc), solutions of acid or sulfate salts (EN 206, ISO 9690), chlorides contained in concrete (the class of the chloride content in the concrete Cl - Table 1, according to EN 206) and alkaline-silicate reaction of aggregates (EN 206, SRPS B.B2.009);
- physical attack, arising from, for example: temperature changes, abrasion (class of abrasion of concrete XM according to EN 1992-1-1) and water penetration (EN 206) [1,2,3].

Researches [4,5,6,7,8,9] have shown that a significant cause of many degradations of concrete constructions is a reinforcement corrosion, which may be result of various chemical and electrochemical processes. It has been shown that an excessive amount of chloride ions, which can be found in the composition of concrete mix-design components, by many researches, is a significant and frequent cause of depassivization of the reinforcement, and thus its corrosion. Hence, their content in concrete, by applying new European regulations, is determined and limited, as shown in the Chapter 2.

When due to the presence of chloride ions, depassivization of the reinforcement is present, locally activated surface of the steel, in the presence of water and oxygen, behaves as an anode, while the entire remaining reinforcement may be a corrosion cell cathode (Picture 1).



Picture 1. Schema of electrochemical corrosion due to chloride effects

The cathodic reaction is reduction of oxygen passing through the concrete layer. Due to the large difference between the surfaces of the electrodes (small anode, and a large cathode) corrosion is extremely intense on anode. Metal ions, which are generated by the dissolution of metals in an anode reaction, make corrosion products, so called rust, which occupies considerably larger volume than the original metal [10,11].

The appearance of degraded concrete, on which the cover layer has ruptured due to pressure from reinforcement corrosion products, is shown in the Picture 2.

Picture 2. Degradation of concrete due to excessive chloride content

In order to prevent a degradation of concrete constructions due to the subject aggression, it is important to determine the influence of the application, and the magnitude of this influence, of component materials on the chloride ions content in self-compacting concrete - as shown in the experimental study given herein. Also, it is of great importance that in this experimental research are applied recycled materials and by-products of thermal power plants, in addition to component materials from the domestic resources used for making self-compacting concrete (still a contemporary concrete composite on the domestic market).

According to research of *B. Beeralingegowd-a* and *V. D. Gundakalle* [12], the content of chlorides in self-compacting concrete depends on the type of additions used and their mutual ratio. In this respect, it has been demonstrated that by application of limestone filler, in relation to the application of fly ash, the concrete with lower chloride content are gained. In doing so, research by *K. Audenaert* and *G. De Schutter* [13], *P. R. da Silva* and *J. de Brito* [14], show that self-compacting concrete, because of the generally better compactness of the cementitious stone, has better resistance to the aggressive effect of chloride ions, compared to conventional concrete, which is compacted by vibration.

2. CHLORIDE CONTENT IN CONCRETE

The chloride content in concrete, which is expressed as the percentage of chloride ion relative to the mass of cement, is determined as the sum of the individual contributions of chlorides from component materials, by one of the following methods or their combination:

- calculation based on the maximum content of chloride in component materials, either as permitted by the standard for that material or as the one declared by the manufacturer of each component and
- calculation based on chloride content in component materials, calculated monthly from mean value for the last 25 determination of chloride content in sum with product of 1.64 times calculated standard deviation for each component material.

The second method is particularly applicable in the case of aggregates extracted from the sea, as well as in cases where no declared or standardized maximum value is available.

Table 1 shows the classes of chloride content in concrete, according to EN 206: 2013, with the maximum permissible percentage of chloride ion in relation to cement mass, as well as examples of particular concrete class application.

Table 1. Classes of chloride content in concrete, EN 206:2013 [1]

<table>
<tr><th>Chloride content class[1)]</th><th>Maximum content of Cl^- by mass of cement [2)]</th><th>Concrete use</th></tr>
<tr><td>Cl 1,0</td><td>1,0 %</td><td>Not containing steel reinforcement or other embedded metal, with the exception of corrosion resistant lifting devices</td></tr>
<tr><td>Cl 0,20</td><td>0,20 %</td><td rowspan="2">Containing steel reinforcement or other embedded metals</td></tr>
<tr><td>Cl 0,40</td><td>0,40 %</td></tr>
<tr><td>Cl 0,10</td><td>0,10 %</td><td rowspan="2">Containing prestressing steel for reinforcement in direct contact with concrete</td></tr>
<tr><td>Cl 0,20</td><td>0,20 %</td></tr>
<tr><td colspan="3">[1)] For the specific concrete use, the class to be applied depends on the provisions valid in the place of us of concrete.
[2)] If type II additions are used and if they are taken into account in determening the amount of cement, the chloride content is expressed as the percentage chloride ion by mass of cement plus total mass of additions.</td></tr>
</table>

Calcium chloride and admixtures based on chloride should not be added to concrete containing steel reinforcement, prestressed steel reinforcement or other embedded metal.

3. AUTHORIZED EXPERIMENTAL RESEARCH

3.1. EXPERIMENTAL RESEARCH PROGRAM

Experimental research, which includes laboratory tests on several different types of self-compacting constructive concrete, is realized in two laboratories:

- Laboratory for testing of building materials, Department of Civil Engineering and Geodesy, Faculty of Technical Sciences, University of Novi Sad and
- Laboratory of the Institute for Urbanism, Civil Engineering and Ecology of Republic of Srpska, in its business unit the Institute for Material and Construction Testing of the Republic of Srpska, Banja Luka.

Eight mixtures of self-compacting concrete were designed, with different types of aggregates (river and recycled concrete aggregate), with or without the use of different types of additions. All concrete mixtures are made of a threefraction aggregate, with nominally largest grain of 16 mm, with a continuous granulometric curve. From additions, limestone filler was used (addition type I), fly ash (addition type II), as well as their combination. Portland-composite high-strength cement was used as the basic binder, and a new generation superplasticizer was used as an admixture. Water used is potable water.

The starting criteria for all mix design, as it is customary for all self-compacting concrete, were chosen regarding the characteristics of the fresh concrete, and they were as follows:

- achieving "complete compactness", without the use of mechanical means for embedding, shaking or vibration; the entrapped air in fresh concrete is limited to a value of 3 to 5%,
- achievement of the consistency class SF2, for which the slump flow value ranges from 660 to 750 mm; according to this request, the amount of superplasticizer is determined, but also according to the manufacturer's recommendation.

Additional common features of the concrete mixtures were:

- concrete mixtures contain, in average, large amount of powder component (for self-compacting concrete it is within the range from 450 to 550 kg/m^3),
- approximately the same total amount of cement and addition for all mixtures is applied, in amount of 483,5 ± 7,4 kg/m^3, i.e. approximately the same amount of powder component: cement, addition and aggregates with grains of less than 0,125 mm, in the amount of 497,9 ± 8,1 kg/m^3, with different combinations of additions being applied, namely:
  - concrete mixtures B-1 and B-2, without additions,
  - concrete mixtures B-3 and B-4, with limestone filler,
  - concrete mixtures B-5 and B-6, with fly ash and
  - concrete mixtures B-7 and B-8, with a mixture of limestone filler and fly ash in equal amount,
- the total amount of aggregate is 1571,6 ± 99,4 kg/m^3, where aggregates of different origin are used:
  - concrete mixtures B-1, B-3, B-5 and B-7, with a river aggregate and
  - concrete mixtures B-2, B-4, B-6 и B-8, with a mixture of river sand and coarse recycled concrete aggregate.
- the amount of superplasticizer is 0,0060 ± 0,0007 m^3 in 1 m^3 of concrete,
- water-cement ratio 0,487 ± 0,075.

For the above-mentioned concretes, labels with a brief description are given as follows:

- B-1 self-compacting concrete with a river aggregate, without the use of additions,
- B-2 self-compacting concrete with a mixture of river sand and coarse recycled concrete aggregate, without additions,
- B-3 self-compacting concrete with a river aggregate and limestone filler,
- B-4 self-compacting concrete with a mixture of river sand and coarse recycled concrete aggregate and limestone filler,
- B-5 self-compacting concrete with a river aggregate and fly ash,
- B-6 self-compacting concrete with a mixture of river sand and coarse recycled concrete aggregate and fly ash,
- B-7 self-compacting concrete with a river aggregate, limestone filler and fly ash and

- B-8 self-compacting concrete with a mixture of river sand and coarse recycled concrete aggregate, limestone filler and fly ash.

The following characteristics were tested on the designed concretes:

- the air entrapped, according to SRPS U.M1.031:1982 [15] (SRPS ISO 4848:1999) and EN 12350-7:2009 [16],
- bulk density of fresh concrete, according to SRPS U.M1.030:1982 [17],
- consistency – slump-flow test, according to EN 12350-8:2010 [18],
- bulk density of hardened concrete, according to SRPS U.M1.009:1993 [19],
- compressive strength determination after 28 days, according to SRPS U.M1.020:1992 [20] and EN 12390-3:2009 [21] and
- chloride content, according to EN 206:2013 [1].

For all concrete mixtures, concrete preparation, making and curing specimens was carried out in the same way and under the same thermohygrometric conditions.

3.2. CHARACTERISTICS OF COMPONENT MATERIALS AND COMPOSITION OF CONCRETE MIXTURES

3.2.1. Characteristics of component materials

For the design of self-compacting concrete, the following components were used:

- portland-composite cement with moderate portland-cement clinker content, of high class with ordinary early strength, marked as CEM II/B-M (S-LL) 42,5 N, "Dalmacijacement", of manufacturer "Cв. Jypaj" from Split (Kaštel Šućurac); specific and bulk density, in loose and compacted state, are respectively, 3140, 1100 and 1480 kg/m^3,
- limestone filler of manufacturer "Japra" ldt. Novi Grad; with specific density of 2780 kg/m^3,
- fly ash of thermal power plant "Nikola Tesla B" from Obrenovac, with the original composition, obtained as a by-product from the thermal power plant (fly ash was not sieved before use, so that grains larger than 0.125 mm contribute to the fine fraction of concrete aggregate); specific density is 2400 kg/m^3,
- aggregate from Sava river, from manufacturer "RTC Luka LEGET" from Sremska Mitrovica, washed and separated into fractions: 0/4, 4/8 and 8/16 mm (when making concrete B-1, B-3, B-5, B-7 all three mentioned fractions are used, while for concrete B-2, B-4, B-6 and B-8 only the first fraction was used); specific density is 2700 kg/m^3, while the bulk density of the grain, for fractions I, II and III are, respectively, 1608, 1555 and 1535 kg/m^3,
- recycled concrete aggregate labeled as RA-N obtained by crushing of wasted concrete MB30 and MB40 (raw materials for the aggregate concerned were concrete cubes, previously used for pressure strength testing and a prefabricated reinforced concrete pillar made with inadequate dimensions); crushing is realized in two phases – the first was the so-called primary crushing, where the elements mentioned above are roughly crushed, using a pneumatic hammer, then, so-called, secondary crushing, or fine shredding, using a rotary crusher was performed; the aggregate is separated into standard

fractions, whereby for the subject research, fractions II and III were used, i.e. fractions of coarse aggregate 4/8 and 8/16 mm); the specific density is 2500 kg/m^3, while the bulk density of the grain, for fractions II and III are, respectively, 1359 and 1309 kg/m^3,

- new generation superplasticizer admixture "Cementol®Zeta Super S", of manufacturer "TKK", Srpenica, Slovenia, based on a modified polycarboxylic ether polymer, declared as a high ranged water reducing admixture HRWRA, according to EN 934-2:2009+A1:2012,
- potable water.

For concrete B-1, B-3, B-5 and B-7, fully designed with a river aggregate, a mixture of aggregates M-1 is applied, whose granulometric composition is shown in the Table 2.

For concrete B-2, B-4, B-6 and B-8, designed using the river aggregate in first fraction and the recycled concrete aggregate in the second and third fraction, a mixture of aggregates M-2 is applied, whose granulometric composition is shown in the Table 3.

Table 2. – Particle size distribution of aggregate mixture M-1

Fraction		Sieve opening d [mm]									
		дно	0,125	0,25	0,5	1	2	4	8	16	31,5
Passing Y [%]	0/4	0	2,1	25,4	65,4	76,9	85,5	94,5	100	100	100
	4/8	0	0	0,1	0,2	0,3	0,8	9,5	92,2	100	100
	8/16	0	0	0	0	0	0	0	4,4	90	100
$Y_i \cdot x_i$ [%]	0/4	0	0,9	10,9	28,1	33,1	36,8	40,6	43,0	43	43
	4/8	0	0	0	0	0,1	0,2	2,1	20,3	22	22
	8/16	0	0	0	0	0	0	0	1,54	31,5	35
M-1 [%]		**0**	**0,9**	**10,9**	**28,2**	**33,1**	**36,9**	**42,7**	**64,8**	**96,5**	**100**

Table 3. – Particle size distribution of aggregate mixture M-2

Fraction		Sieve opening d [mm]									
		дно	0,125	0,25	0,5	1	2	4	8	16	31,5
Passing Y [%]	0/4	0	2,1	25,4	65,4	76,9	85,5	94,5	100	100	100
	4/8	0	0	0	0	0	0,5	21,1	100	100	100
	8/16	0	0	0	0	0	0	0,2	23,7	100	100
$Y_i \cdot x_i$ [%]	0/4	0	0,9	11,2	28,8	33,8	37,6	41,6	44	44	44
	4/8	0	0	0	0	0	0,1	2,1	10	10	10
	8/16	0	0	0	0	0	0	0,1	10,9	46	46
M-2 [%]		**0**	**0,9**	**11,2**	**28,8**	**33,8**	**37,7**	**43,8**	**64,9**	**100**	**100**

3.2.2. Concrete mix-design

Concrete mix-design and concrete bulk density are given in table 4.

Table 4. – Concrete mix-design

Concrete mixture				B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8
Cement			[kg/m³]	490,9	483,6	403,6	404,2	391,8	393,1	394,1	394,5
Limestone filler			[kg/m³]	–	–	85,6	85,7	–	–	42,2	42,2
Fly ash			[kg/m³]	–	–	–	–	84,2	84,5	42,2	42,2
Aggregate	River	0/4 mm	[kg/m³]	718,5	697,3	715,3	702,0	659,6	647,8	689,8	676,4
		4/8 mm	[kg/m³]	367,6	–	366,0	–	337,4	–	352,9	–
		8/16 mm	[kg/m³]	584,8	–	582,2	–	536,9	–	561,5	–
	Recycled	4/8 mm	[kg/m³]	–	158,5	–	159,6	–	147,2	–	153,7
		8/16 mm	[kg/m³]	–	729,0	–	733,9	–	677,2	–	707,2
HRWRA			[kg/m³]	7,36	7,29	6,05	6,06	5,88	5,9	5,91	5,92
Water			[kg/m³]	202,2	200,3 +17,1	201,8	202,1 +17,0	220,2	220,9 +16,9	201,8	202,0 +16,9
Bulk density			[kg/m³]	2371,4	2295,8	2360,6	2310,6	2236,0	2193,5	2290,4	2241,0

3.2.3. Results of experimental research

Testing of fresh concrete showed that designed self-compacting concrets are with high-compactness, with the entrapped air to 3,8%, normal weigth concrete with bulk density from 2193 to 2371 kg/m^3, consistency class SF2, with slump-flow from 690 to 740 mm, which is suitable for the usual, i.e. the most common application; eg. for the execution of walls and pillars.

By testing of hardened concrete on cube samples with edge length of 15 cm, the values of the bulk density within the range of 2213 to 2392 kg/m^3 and compressive strength within the range of 44,4 to 60,1 MPa are obtained.

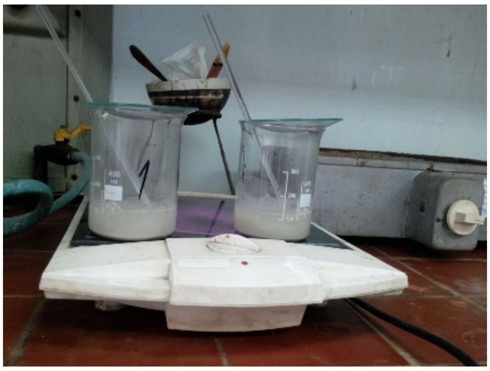
Chlorides content in concrete, shown in Table 5, was determined through the chloride ions content in component materials. It is expressed as the percentage chloride ion by mass of cement plus total mass of addition of type II, for concrete B-5, B-6, B-7 and B-8, for which, as such type of addition, fly ash is applied.

Table 5. Results of chloride content test

Concrete mixture	Chloride ions content in concrete	The chloride ions content in relation to the mass of cement	The chloride ions content relative to the mass of cement and fly ash
	m_{Cl}	m_{Cl} / m_c	$m_{Cl} / (m_c + m_{ma\text{-}II})$
	[g/m^3]	[%]	[%]

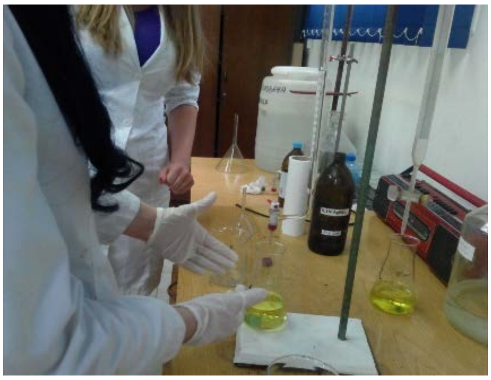
Concrete mixture	Chloride ions content in concrete	The chloride ions content in relation to the mass of cement	The chloride ions content relative to the mass of cement and fly ash
	m_{Cl}	m_{Cl} / m_c	m_{Cl} / (m_c + m_{ma-II})
	[g/m^3]	[%]	[%]
B-1	105,11	0,021	–
B-2	166,42	0,034	–
B-3	98,76	0,024	–
B-4	161,62	0,040	–
B-5	99,64	0,025	0,021
B-6	157,85	0,040	0,033
B-7	98,28	0,025	0,023
B-8	158,80	0,040	0,036

On Pictures 3-6. the chemical test is shown, performed in order to determine the content of chloride in limestone filler. At the first picture, boiling of samples is shown, which are previously mixed with destilated water. Picture 4 shows filtering through the medium density filter paper. On Pictures 5 and 6 is shown, respectively, titrating with standard silver-nitrate solution ($AgNO_3$) and the visage of the filtrates, collected in conical bottles according to Erlenmajer. The visage of the titrated filtrate, with a noticeable transition from yellow to darker shades and the visage of a non titrated filtrate, with standard (starting) yellow color is shown on Picture 6.



Picture 3. Testing of Cl^- content in a limestone filler – samples boiling in destilated water

Picture 4. Testing of Cl^- content in a limestone filler – samples filtering



Picture 5. Testing of Cl^-content in a limestone filler – samples titration

Picture 6. Testing of Cl^- content in a limestone filler – titrated and non titrated filtrates

3.2.1. Analysis of experimental research

The analysis and discussion of the experimental research was carried out through the examination of the simultaneous influence of the applied type of aggregates and the application of additions to the chloride ion content in the designed self-compacting concrete using a multi-parameter analysis. For the multi-parameter analysis, the so-called method of factorial experiment is used. The above method tested the hypothesis about the existence of a link between the content of chloride in concrete and varied influencing factors. In addition, it has been determined which of the selected parameters has the greatest impact on the analyzed property, and how much the relative sizes of the impact of these parameters are. Also, by testing the level of significance of the relative magnitudes of influence, through Student's test for factor polynomial coefficients, analytical forms of the connection "chloride content in concrete - influential parameters" were formulated. Conclusions were made according to the conducted analysis with a probability of safety of 0,95.

Table 6. gives the input data needed for calculating the coefficients of the polynomial of the factorial experiment, which describes the effect of the applied type of aggregate and the application and type of addition on the value of the chloride ion content in the designed concrete.

Table 6. Chloride ion content in concrete in the function of variables

N	Concrete mixture	Z_1	Z_2	Z_3	Chloride ion content in concrete
		Type of agreggate	Limestone filler	Fly ash	
			$m_{ma,I}$	$m_{ma,II}$	m_{Cl}
			[kg/m^3]	[kg/m^3]	[g/m^3]
1	B-1	river	0	0	105,11
2	B-2	recycled	0	0	166,42
3	B-3	river	85,6	0	98,76
4	B-4	recycled	85,7	0	161,62
5	B-5	river	0	84,2	99,64
6	B-6	recycled	0	84,5	157,85
7	B-7	river	42,2	42,2	98,28
8	B-8	recycled	42,2	42,2	158,80

Based on the above and the application of the expression for determining the value of the polynomial coefficients, which defines the functional dependence of the analyzed property on the variable parameters, by the factorial experiment method, the values of the polynomial coefficients are obtained, as given in Table 7.

Table 7. Coefficients of polynomial for functional dependence $m_{Cl} = m_{Cl}(Z_1,Z_2,Z_3)$

Coefficients of polynomials	b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{123}
Value coeff. polynomial	130,81	30,36	-1,45	-2,17	0,48	-0,68	1,34	0,09

The functional dependence of the chloride ion content in concrete and the simultaneous effect of varied influential parameters is given by the expression:

$$m_{Cl} = 130{,}81 + 30{,}36x_1 - 1{,}45x_2 - 2{,}17x_3 + \\ + 0{,}48x_1x_2 - 0{,}68x_1x_3 + 1{,}34x_2x_3 + 0{,}09x_1x_2x_3 \quad [g/m^3] \qquad (1)$$

The calculated values of the coefficients of the factor polynomial have the following physical meaning:

- b_0 defines the average value of the chloride ion content of all tested concrete,
- b_1 defines the influence of the application of the type of aggregate on the chloride ion content in concrete (the sign "-" refers to the influence of the application of the river aggregate, and the sign "+" on the impact of the application of the recycled concrete aggregate),
- b_2 defines the influence of limestone filler on the chloride ion content in concrete (the sign "-" refers to the concrete mixed without limestone filler and the "+" sign on the concrete mixed with limestone filler),
- b_3 defines the influence of the application of fly ash on the chloride ion content in concrete (the sign "-" refers to concrete mixed without fly ash, and the sign "+" on concrete mixed with fly ash),
- b_{12} defines the additional influence of the interaction of the applied type of aggregates and limestone fillers on the chloride ion content in concrete (the sign "-" refers to concrete mixed with river aggregate and limestone filler, as well as concrete with recycled concrete aggregate, without limestone filler, and the sign "+" on concrete mixed with a river aggregate, without limestone filler, as well as concrete with recycled concrete aggregate and limestone filler),
- b_{13} defines the additional influence of the interaction of the applied type of aggregate and fly ash on the chloride ion content in concrete (the sign "-" refers to the concrete mixed with the river aggregate and fly ash, as well as concrete with a recycled concrete aggregate, without fly ash, and the sign "+" on concrete mixed with river aggregate, without fly ash, as well as concrete with recycled concrete aggregate and fly ash),
- b_{23} defines the additional influence of limestone filler and fly ash interaction on the chloride ion content in concrete (the sign "-" refers to concrete mixed only with one addition (limestone filler or fly ash), while the other is omitted, and the sign "+" on concrete mixed with both additions, as well as concrete made without additions) and
- b_{123} defines the additional influence of the interaction of the applied type of aggregates, limestone fillers and fly ash on the chloride ion content in concrete (the sign "-" refers to concrete mixed with a river aggregate and both additions or are both omitted, as well as concrete mixed with a recycled concrete aggregate and only with one addition, and the sign "+" on concrete prepared with a river aggregate and with only one addition, as well as concrete with a recycled concrete aggregate and both additions or both are omitted).

The absolute value of the polynomial coefficients describes the influence of the varied factor on the value of the chloride ion content - a higher absolute value indicates a significant influence of the variable factor on the value of the chloride ion content in the concrete.

Values, that can be calculated by using the given expression (1), are identical with the obtained experimental values of the chloride ion content in concrete.

By analyzing the polynomial coefficients in Table 7, it is concluded:

- The most important influence on the value of chloride ion content is the choice of the type of aggregate. By using a river aggregate, they receive less, ie, using a recycled concrete aggregate, a higher value of the chloride content in the concrete. Considering the obtained value of the coefficient of polynomial $\boldsymbol{b_1}$ in the amount of 30,36, it is concluded that, in the case of the application of a recycled concrete aggregate, an average increase in the chloride ion content in concrete in the amount of about 60,7 g/m^3 is achieved, about 46,4%, compared to the case of the river aggregate.
- The effects of the application of additions are significantly lower in relation to the effect of selecting the type of aggregate. The coefficients of the polymers $\boldsymbol{b_2}$ and $\boldsymbol{b_3}$ are negative, which indicates that the application of any of the relevant additives affects the average reduction in the value of the chloride ion content in the concrete, compared to the cases where they are eliminated. Namely, it has been shown that the use of limestone filler reduces the amount of chloride ions in concrete in the amount of about 2.9 g/m^3, or about 2.2%, on average, while it decreases with the use of fly ash in the amount of about 4, 3 g/m^3, or about 3.3%.

Additional effects from the combined effect of variables (expressed in coefficients b_{12}, b_{13}, b_{23} and b_{123}), reflect the change in the value of the chloride ion content in concrete for a sum of at most ± 2.6 g/m^3, ie for a maximum of 4%, which, in relation to the total value of chloride content, shows that these combined effects are practically negligible. However, it is noted that the coefficient b_{23}, which describes the interaction effect of additions, is significantly higher than other coefficients of interaction (the value of this coefficient is greater than the sum of other coefficients), which has proved to be frequent in analyzes of other properties mentioned above.

In order to simplify the forms of functional dependence of the chloride ion content in concrete and variables, and in accordance with the analysis of the values of the coefficients of the polynomial, the coefficients of interaction b_{12}, b_{13} and b_{123} are rejected, so that the given function has the form:

$$m_{Cl} = 130{,}81 + 30{,}36 \cdot x_1 - 1{,}45 \cdot x_2 - 2{,}17 \cdot x_3 + 1{,}34 \cdot x_2 \cdot x_3 \quad [\text{g/m}^3] \qquad (2)$$

By rejecting the mentioned coefficients of the polynomial $m_{Cl} = m_{Cl}(Z_1,Z_2,Z_3)$, the differences between the experimentally determined values of the chloride content in the concrete and the values calculated by the factorial analysis are increased. The stated differences, expressed in percentage terms, are given in Table 8, are obtained by means of the expression:

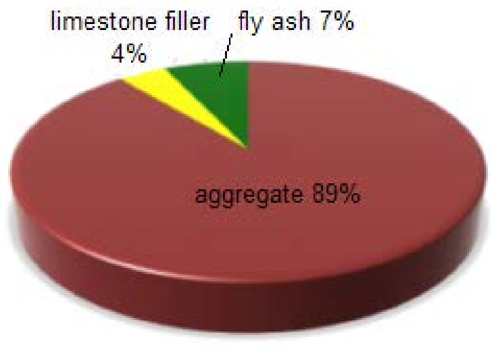
$$\Delta = \frac{\Delta m_{Cl}}{m_{Cl}} \cdot 100 = \frac{m_{Cl} - m_{Cl\text{-}R}}{m_{Cl}} \cdot 100 \qquad [\%] \qquad (3)$$

By analyzing the above differences, they are found to have absolute values within acceptable limits, which implies that the shape function (2) can be used with great reliability to display and analyze the chloride ion content in concrete, depending on the type of aggregate used and the application of limestone filler and/or fly ash.

Table 8. Differences between real and design (applying $m_{Cl} = b_o+b_1x_1+b_2x_2+b_3x_3+b_{23}x_2x_3$) values of the chloride ion content in concrete

N	Concrete mixture	Z_1	Z_2	Z_3	Chloride ions content		Differ. betw. tests and designs values of chloride content	
		Type of agreggate	Limestone filler	Fly ash	tests (real)	designed (theory)		
			$m_{ma,I}$	$m_{ma,II}$	m_{Cl}	m_{Cl-R}	Δm_{Cl}	Δ
			[kg/m^3]	[kg/m^3]	[g/m^3]	[g/m^3]	[g/m^3]	[%]
1	B-1	river	0	0	105,11	105,403	-0,292	-0,3
2	B-2	recycled	0	0	166,42	166,128	0,292	0,2
3	B-3	river	85,6	0	98,76	99,828	-1,068	-1,1
4	B-4	recycled	85,7	0	161,62	160,553	1,068	0,7
5	B-5	river	0	84,2	99,64	98,383	1,257	1,3
6	B-6	recycled	0	84,5	157,85	159,108	-1,258	-0,8
7	B-7	river	42,2	42,2	98,28	98,178	0,102	0,1
8	B-8	recycled	42,2	42,2	158,8	158,903	-0,103	-0,1

Picture 7. shows the percentage of participation of varied parameters in their joint influence on the chloride ion content in concrete. As can be seen, the dominant influence of the variables on the value of the chloride content is dominated by the type of applied aggregate, with 89% of the joint effect, then the fly ash with 7% of the total influence, and at least of all variables, the effect of the application limestone filler, specifically in the amount of 4%.



Picture 7. Partial fraction of the influence of variables on the

4. CONCLUSION

The higher content of the component material, which contain a higher concentration of chloride ions, causes the increase of these ions in concrete. In addition, it is shown that a significant influence on the amount of chloride contained in concrete has the ratio of the applied amounts of powder component and aggregates, as well as the type of applied aggregate. Namely, in the case of designed concretes, the difference in the content of chloride in the river and recycled concrete aggregate was significant (higher amount of chloride ions in the recycled concrete aggregate), and significant differences in the chloride ions content in the concrete were obtained. Specificaly, when comparing the use of a river aggregate (for which no chloride content is found) and a recycled concrete aggregate (with 0.007% of chloride ions), it is obtained that in the case of the application of a recycled concrete aggregate, an average increase in the chloride ion content in concrete is from about 60.7 g/m^3, i.e. about 46.4%, compared to the case of use of the river aggregate. In addition to the above, a much smaller impact, but still significant, has the use of additions. By their application, the amount of cement, or the amount of the component with the highest chloride content, decreases, thus reducing the total content of chloride in the concrete. Specifically, for the addition in the amount of 21%, compared to the mass of the cement, it has been found that by using limestone filler chloride ion content is averagely reduced the in the concrete for about 2.9 g/m^3, i.e. about 2.2%, while by using fly ash, the average decreases by about 4.3 g/m^3, i.e, about 3.3%.
A multi parameter analysis carried out has established a functional dependence of the content of chloride in concrete and the application of various types of additions and aggregates.
It was also concluded that by using concrete components materials from the domestic resources, for self-compacting concrete technology, it is possible to design concrete class Cl 0.10 according to EN 206-1:2013, which is applicable for all types of reinforcement plans, i.e. to meet even the strictest criteria, which are required when applying prestressing steel.

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