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NEW FRESH CONCRETE CHEMICAL ADMIXTURE FOR TUNNEL LINING DESIGN IN THE EXTREME WINTER CONDITIONS***

Abstract

A new type of calcium-nitrate and urea-based chemical admixture is proposed, in order to maintain the compressive strength of fresh concrete exposed to very low temperatures (below to – 25^0C), including a sudden transition to positive temperatures at an early age. The applied admixture has no negative effect on compressive strength of specimens cured in water at 20^0C. When it is cured under three different frost regimes, concrete specimens with admixture show over three times higher compressive strength, in comparison to specimens without admixture. The implications of such improved concrete composition are discussed in reference to the tunnel lining design.

***Keywords**: frost protection, compressive strength, anti-freezing admixture, tunnel lining*

INTRODUCTION

Tunnel advance in weak rock masses requires an appropriate lining design, in order to prevent high inward displacements of rock masses, tunnel roof collapse or jamming/damage of tunnel boring machines, before the final support is installed. The process of supporting the rock mass usually initiates with adequate distribution of rock bolts, modifying the properties of rock mass in much the same way as reinforcement does in concrete. In the same time, since the final support is typically installed after some time elapsed from the excavation, and at some distance from the excavation point (using the "longitudinal arch" effect), a thin layer of shotcrete (sprayed concrete) is usually installed with the main task to reduce displacement and number of yielded bolt elements (regarding the elastic-perfectly plastic behavior of rock mass) [1]. Properties of such shotcrete are determined according to specific tunnel design and geological conditions. However, an important issue that has to be considered is the time - dependent properties of the shotcrete layer. For example, if the tunnel lining, consisting of rock bolts and shotcrete with steel lattice girders, is installed right behind the tunnel face and

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activated immediately, the rock-bolts and lattice girders respond to the deformation of the rock mass surrounding the tunnel as soon as the tunnel advances. However, the shotcrete is only one day old at this stage, and it has not yet developed its full capacity, so the current load may be sufficient to induce failure in the shotcrete. Considering this, it is important to assure that shotcrete reaches the expected short-term value of compressive strength by protecting it from the unfavorable outdoor conditions, e.g. sudden freezing and thawing cycles. It should be noted that for tunnel advance in frost conditions, it is not necessary to use the shotcrete mixture which provides freeze/thaw resistant hardened concrete, but to have a fresh concrete mixture resistant to possible freezing [2-3]. According to [4], concrete has to be protected against freezing until the degree of saturation is significantly reduced due to hydration process, corresponding to the time when concrete reaches a compressive strength of 3.5 MPa [5], which is typically achieved in the first 24 h for concrete mixtures with W/C ratio below 0.6 and exposed to t=20ºC. If concrete is exposed to freezing before this time, its compressive strength will be sig-nificantly reduced [6]. Considering this, it is of special interest to investigate the frost resistance of fresh concrete in winter months, when minimum recorded daily temperatures may reach even below -10ºC with up to 15 days with the average daily temperature below zero [7]. In such cases, water freezing in fresh concrete could permanently damage the structure of newly formed cement matrix.

Even though, there are many previous studies on the impact of low temperatures on compressive strength of concrete [8-11], none of them investigate the influence of severe frost on fresh concrete, with temperatures down to -25ºC, including the effect of quick temperature changes, with amplitude up to 45ºC in just several days. The main motivation for performing such research lies in the justified need for an anti-freeze admixture, considering the real temperature regimes recorded in Belgrade, with frequent cases of severe frost. Such extreme frost conditions could have happened during the TBM excavation of hydrotechnical tunnel in Višnjica near Belgrade, leading to the possible machine jamming.

The aim of research is to develop a reliable admixture, which could enable tunnel lining without frost protection even in such severe climate conditions. Considering this, the impact of different amount of proposed chemical admixture (4% and 8%) is investigated on compressive strength of fresh concrete under three different frost regimes: one-day frost (-10ºC), three-day frost (-10ºC, -5ºC and -15ºC), and seven-day frost (oscillating from 0ºC up to -25ºC).

DURATION OF FROST IN REAL CONDITIONS

In order to motivate a need for field application of such an anti-freeze admixture, a review on the climatic properties in Belgrade for period 1993-2012 is given according to the observations made by the Republic Hydrometeorological Service of Serbia [7]. In order to justify the testing of concrete under the first and second frost regime, the extreme examples of sudden warming for December, January, February and March in the period 1993-2012 were analyzed. Maximum temperature amplitudes (up to 16.8ºC in February 1996) are shown in Figure 1 only for those days with sudden transition from negative to positive temperatures in two consecutive days.

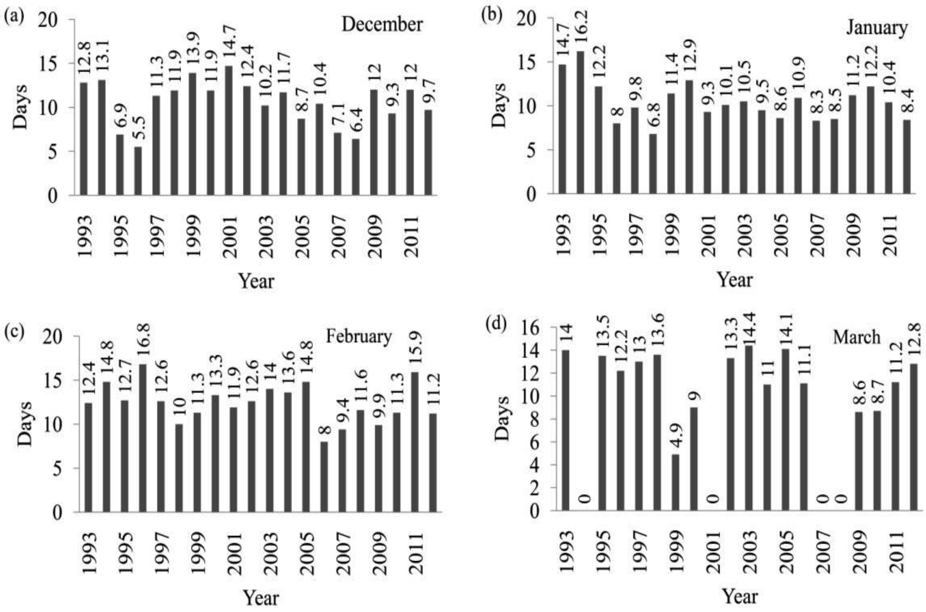

Figure 1 *Maximum daily temperature amplitude with sudden transition from negative to the positive values for two consecutive days in the period 1993-2012 for the following months: (a) December, (b) January, (c) February; (d) March. Zero value is assigned for months without a transition from negative to positive temperature*

On the other hand, maximum number of consecutive days with frost is shown in Figure 2 (14 days in January 2009 and February 2012), which legitimizes the testing of concrete in the third frost regime, with seven-day continuous frost.

EXPERIMENTAL PART

In the first phase of research, the concrete compressive strength was determined with and without admixture after curing in water at the room temperature (20ºC). The second stage of the study comprises the analysis of admixture effect (4% and 8%) on compressive strength of concrete specimens and after that they were exposed to three different frost regimes. The main constitutive elements of concrete were (Table 1): cement (CEM I 42.5 R, Lafarge Cement Factory Beočin, Serbia), andesite aggregate (crushed, quarry Šumnik, Serbia) and admixture ("T-25 ºC"). Cubic concrete specimens (10x10 cm) were formed in a laboratory counter-current concrete mixer, with the mixing period of 3 minutes for all mixtures. Casting was performed at a vibrating table until a complete consolidation was achieved.

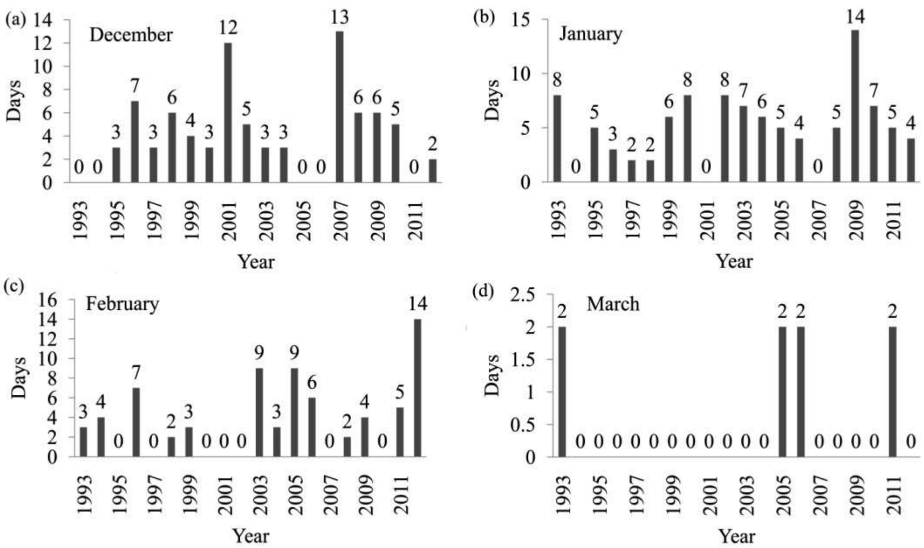

Figure 2 *Number of consecutive days with the temperature below 00C in the period 1993-2012 for the following months: (a) December, (b) January, (c) February; (d) March (only two or more days are taken into account)*

Table 1 *Proportions of concrete mixtures*

constituent per 1m^3 of concrete	admixture 0%	admixture 4%	admixture 8%
cement: CEM I 42,5 R	417 kg	411 kg	408 kg
andesite aggregate 0 - 2 mm (30%)	574 kg	567 kg	563 kg
andesite aggregate 2 - 4 mm (10%)	192 kg	189 kg	188 kg
andesite aggregate 4 - 8 mm (10%)	192 kg	189 kg	188 kg
andesite aggregate 8 -11 mm (20%)	383 kg	378 kg	375 kg
andesite aggregate 11 -16 mm (30%)	575 kg	568 kg	563 kg
admixture	-	16,4 kg	32,6 kg
water	167 kg	148 kg	139 kg
W/C ratio	0.40	0.36	0.34
unit weight	2500 kg/m^3	2467 kg/m^3	2456 kg/m^3

Concrete specimens for the first set of tests (isothermal curing conditions) were prepared as described above and cast in steel moulds. After 24 hours, the reference samples were taken out of the moulds and cured under the same conditions in water at 20ºC. The compressive strength was determined after 3, 7 and 28 days. In the second phase of the experimental part of the research, test specimens were made in the same way as in the previous test (10x10 cm cubes). The temperature of mixtures during casting was 20ºC. Immediately upon casting, metal moulds with fresh concrete were put in the acclimatization chamber at -10ºC, and exposed to three different frost regimes: (a) frost regime 1 simulates temporary one-day frost, with specimens exposed to -10ºC on the first day and cured in water at 20ºC during the following day; (b) frost regime 2 simulates several-day frost, with first-day exposure to -10ºC, second-day exposure to -5ºC, third-day exposure to -15ºC and, during the fourth day, the specimens were cured in water at 20ºC; (c) frost regime 3 simulates a long, seven-day period of frost, with first-day exposure to -10ºC, second-day exposure to -5ºC, third-day exposure to -15ºC, fourth-day exposure to -25ºC, fifth-day exposure to -10ºC and sixth-day and seventh-day exposure to -5ºC. From the eighth to twenty-eighth day, test specimens were cured in water at 20ºC.

EXPERIMENTAL RESULTS

Results of the first phase of research are shown in Table 2. It is clear that concrete compressive strength with admixture after 3 days is larger when compared to the specimens without admixture. However, after 7 days, a slightly larger compressive strength is observed for the concrete with 4% of admixture, while significantly lower strength is determined for the concrete with 8% of admixture. On the other side, after 28 days compressive strength increases for the concrete with 4% of admixture and then slightly drops for samples with 8% of admixture, but it is still higher when compared to the specimens without admixture. The testing proved that the addition of admixture had no negative effect on the concrete hardening after 28 days.

Table 2 *Properties of concrete samples with different % of admixture cured in water at 20ºC**

Sp. No.	Age (days)	0% admixture		4% admixture		8% admixture	
		γ (kg/m^3)	σ_c (MPa)	γ (kg/m^3)	σ_c (MPa)	γ (kg/m^3)	σ_c (MPa)
1	3	2470	52.0	2405	57.5	2490	61.0
2		2460	52.0	2420	58.0	2480	62.0
3		2460	51.0	2490	54.5	2480	65.0
4	7	2470	77.4	2470	74.5	2420	66.2
5		2580	73.8	2450	78.0	2460	64.0
6		2450	72.0	2450	72.0	2440	68.5
7	28	2460	88.5	2450	93.0	2470	83.7
8		2470	70.6	2470	84.0	2470	96.5
9		2440	81.0	2450	90.0	2430	81.6

**Sp. No. denotes specimen number, γ represents unit weight and σ_c denotes compressive strength of concrete.*

In the second stage of analysis, concrete compressive strength was determined under the various frost regimes up to -25ºC. Firstly, the effects of water freezing in fresh concrete without chemical admixtures are tested (Table 3).

Table 3 *Properties of concrete samples without admixture*

Sp. No.	frost regime	age (days)		equivalent age (t_e)*	concrete without admixture			
		< 0°C	= 20°C		γ (kg/m^3)	average	$σ_c$ (MPa)	average
1	1	1	1	1	2455	2478	7.9	8.2
2	1	1	1	1	2500		8.5	
3	2	3	1	1	2430	2420	10.1	10.2
4	2	3	1	1	2410		10.4	
5	3	7	1	0.83	2410	2400	11.8	12.1
6	3	7	1	0.83	2390		12.4	
7	3	7	1	0.83	2355		16.7	
8	3	7	3	2.83	2530	2425	19.0	17.6
9	3	7	3	2.83	2390		17.1	
10	3	7	3	2.83	2390		21.0	
11	3	7	7	6.83	2410	2397	21.8	21.5
12	3	7	7	6.83	2390		21.8	
13	3	7	7	6.83	2525		31.0	
14	3	7	28	27.83	2410	2440	28.0	29.3
15	3	7	28	27.83	2385		29.0	

equivalent age (t_e) is determined according to the Saul model [12]

The results of experimental research on concrete specimens with 4% and 8% of admixture are shown in Tables 4 and 5. In both cases, compressive strength of concrete specimens is much higher, even over three times (for frost regime 1 from 8.2 MPa to 25.9 MPa with 4% of admixture), when compared to the concrete strength without the admixture (Table 3).

Table 4 *Properties of concrete samples with 4% admixture*

Sp. No.	frost regime	age (days)		equivalent age (t_e)	concrete with 4% admixture			
		< 0°C	= 20°C		γ (kg/m^3)	average	$σ_c$ (MPa)	average
1	1	1	1	1	2440	2445	25.8	25.9
2	1	1	1	1	2450		26.0	
3	2	3	1	1	2470	2460	15.2	15.6
4	2	3	1	1	2450		16.1	
5	3	7	1	0.83	2440	2445	26.0	25.2
6	3	7	1	0.83	2450		24.3	
7	3	7	1	0.83	2380		31.0	
8	3	7	3	2.83	2380	2390	31.5	31.5
9	3	7	3	2.83	2410		32.0	
10	3	7	3	2.83	2370		45.0	
11	3	7	7	6.83	2410	2390	39.5	43.1
12	3	7	7	6.83	2390		44.8	
13	3	7	7	6.83	2440		50.7	
14	3	7	28	27.83	2460	2453	53.8	53.6
15	3	7	28	27.83	2460		56.4	

Table 5 *Properties of concrete samples with 8% admixture*

Sp. No.	frost regime	age (days)		equivalent age (t_e)	concrete with 8% admixture			
		< 0°C	= 20°C		γ (kg/m³)	average	σ_c (MPa)	average
1	1	1	1	1	2440	2440	17.0	17.6
2	1	1	1	1	2440		18.1	
3	2	3	1	1	2430	2445	24.0	23.8
4	2	3	1	1	2460		23.7	
5	3	7	1	0.83	2430	2435	38.7	39.4
6	3	7	1	0.83	2440		40.2	
7	3	7	1	0.83	2410		41.0	
8	3	7	3	2.83	2385	2402	40.0	40.5
9	3	7	3	2.83	2410		40.5	
10	3	7	3	2.83	2410		46.3	
11	3	7	7	6.83	2420	2403	46.5	47.9
12	3	7	7	6.83	2380		51.0	
13	3	7	7	6.83	2430		56.1	
14	3	7	28	27.83	2450	2443	69.4	61.0
15	7	7	28	27.83	2450		57.4	

It is necessary to emphasize that the difference in behaviour of concrete specimens with 4% and 8% admixture is rather small, indicating that further increase in admixture dosage would not significantly increase the concrete compressive strength. On the other hand, even though there is a significant increase of compressive strength when compared with the case without admixture (Tables 3, 4 and 5), the recorded values are still lower in comparison to the concrete specimens cured under isothermal conditions (Table 2). In order to compare the compressive strength of concrete samples under different frost regimes (with and without chemical additives) to the compressive strength of concrete specimens cured under isothermal conditions, the compressive strength of concrete is estimated after the following days: 0.83, 1, 2.83, 6.83 and 27.83, which represent the equivalent age for all tested cases (fourth column in Tables 3, 4 and 5). The compressive strength at target days was estimated using the Plowman model (Figure 3), which expresses the relationship between compressive strength of concrete cured under isothermal conditions and maturity by the Saul:

$$S_p = a + b \times \log M_s,$$

where

- S_p - is the strength prediction value by the Plowman equation [13],
- M_s - is the maturity by the Saul model [12] and
- a and b are constants.

Maturity of concrete M_s was determined on the basis of equivalent age, which takes into account the combined effect of time and curing temperature on strength development [14]:

$$t_e = \left(\sum_{1}^{n} (T - T_0) \times \Delta t_i \right) / (T_r - T_0),$$

where

- t_e - is the equivalent age,
- T - is temperature at which concrete hardens in the time interval Δt_i,
- T_0 - indicates the reference temperature (–10ºC),
- T_r - represents the concrete curing temperature (20 ºC), and
- Δt_i - represents the observed time interval.

It is obvious, based on Figure 3, that the Plowman model gives a reasonable estimation of experimental results, with high coeficient of correlation ($r > 0.8$) and small root mean squared error ($RMSE \leq 7.14$). Thus the values of compressive strength at target days could be read from these diagrams with reliable accuracy (fourth column in Tables 3, 4 and 5).

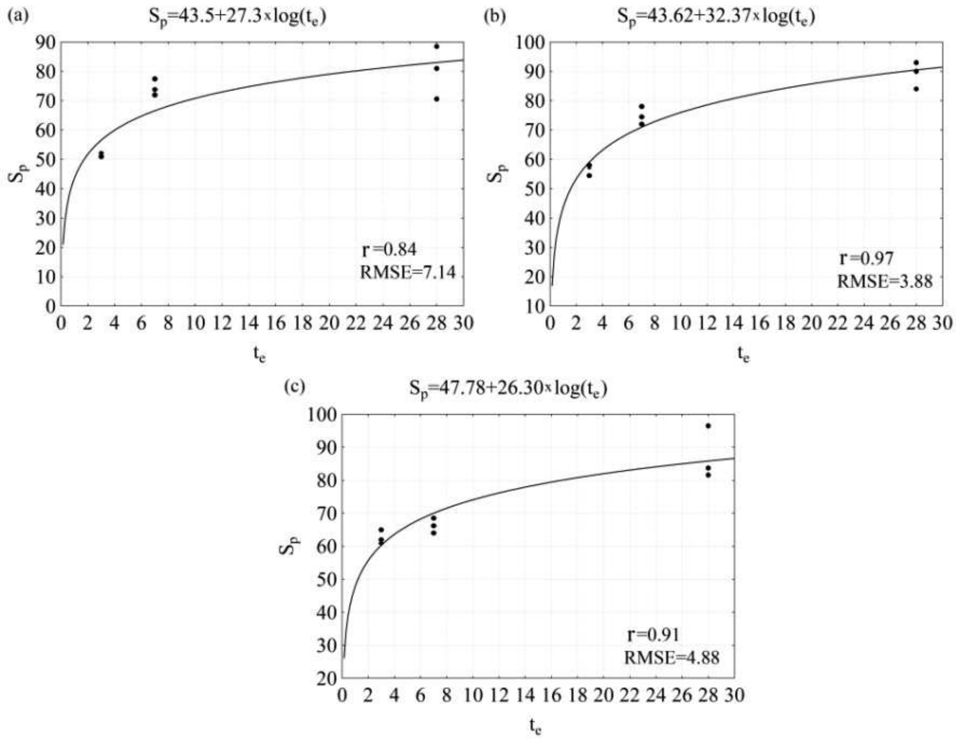

Figure 3 *Regression results of the Plowman model for concrete specimens with different amount of admixture, cured under the isothermal conditions (in water at 200C): (a) 0% of admixture; (b) 4% of admixture; (c) 8% of admixture*

Comparison of concrete compressive strength cured under isothermal conditions and after different frost regimes is shown in Table 6. It is clear that concrete specimens with 8% of admixture achieve 86.3% of the target compressive strength, for the third frost regime with seven days of frost and only one day of thawing. The same specimens achieve 71.1% of the target compressive strength for the third frost regime with seven days of frost and 21 days of thawing. In all other cases, the concrete specimens achieve less than 70% of the compressive strength of reference samples cured under isothermal conditions.

Table 6 *Decrease of compressive strength of concrete with and without admixture cured under the isothermal conditions and exposed to different temperature regimes*

equivalent age (t_e)	σ_c (MPa) with 0% admixture			σ_c (MPa) with 4% admixture			σ_c (MPa) with 8% admixture		
	Isothermal	After different frost regimes	% of isothermal σ_c achieved	Isothermal	After different thermal regimes	% of isothermal σ_c achieved	Isothermal	After different thermal regimes	% of isothermal σ_c achieved
0.83	41.29	12.1	29.3	41.00	25.2	61.5	45.65	39.4	86.3
1	43.50	8.2-10.2	18.9-23.5	43.62	15.6-25.9	35.8-59.4	47.78	17.6-23.8	36.8-49.8
2.83	55.83	17.6	31.5	58.24	31.5	54.1	59.66	40.5	67.9
6.83	66.28	21.5	32.4	70.63	43.1	61.0	69.73	47.9	68.7
27.83	82.94	29.3	35.3	90.38	53.6	59.3	85.77	61.0	71.1

CONCLUSION

This work analyzes the effect of chemical admixture on compressive strength of concrete specimens under differrent frost regimes. In all three cases, concrete with admixture achieved considerably higher compressive strength (even 200% higher for some regimes), when compared to the samples without admixture. The results of this analysis confirm that the use of chemical admixtures prevent breakage of fresh shotcrete tunnel lining even in such severe winter conditions.

It should be noted that comparison of recorded concrete compressive strength (Table 6) was carried out using the regression analysis, which could lead to ambiguous interpretations. However, relatively high value of correlation coefficient (r>0.8) points out that possible error in estimated value lies in the range of a measurement error. On the other side, the present analysis was limited by the small number of concrete samples: for some regimes three concrete samples are tested, as it is common in laboratory testing, while in the other cases, properties of only two specimens were determined. However, even with large number of samples the significantly different results should not be expected from the standpoint of the achieved compressive strength.

Regarding the future research, further analysis of the proposed admixture effect should be carried out especially regarding the target of compressive strength. Certainly, this should be related to the economic benefits, aiming at low-cost percentage of admixture with maximum concrete compressive strength. These experiments would certainly be performed *in situ*, at excavated contour, which would also involve the impact of progressive inward displacement of rock masses on the development of shotcrete compressive strength. In that way, the effect of chemical admixture on the stability of fresh shotcrete tunnel lining would be evaluated more closely.

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NOVI HEMIJSKI DODATAK SVEŽEM BETONU ZA IZVOĐENJE TUNELSKE OBLOGE U EKSTREMNIM ZIMSKIM USLOVIMA***

Izvod

U radu se predlaže novi tip hemijskog dodatka betonu na bazi kalcijum-nitrata i uree, sa ciljem održavanja čvrstoće na pritisak svežeg betona izloženog vrlo niskim temperaturama (do -25^{0}C), uključujući i uticaj iznenadnih velikih temperaturnih amplituda (prelaze od negativnih ka pozitivnim temperaturama). Primenjeni dodatak ne utiče nepovoljno na čvrstoću na pritisak uzoraka betona negovanih u izotermalnim uslovima na temperaturi od 20^{0}C. Kada se svež beton izloži uticaju različitih režima mraza, uzorci sa dodatkom pokazuju gotovo tri puta veću pritisnu čvrstoću u poređenju sa uzorcima bez dodatka. Primena betona sa predloženim aditivom u praksi razmatra se u odnosu na postojanost i stabilnost tunelske obloge sa prskanim betonom.

Ključne reči: *zaštita od mraza, čvrstoća na pritisak, dodatak protiv zamrzavanja, obloga tunela*

UVOD

Izvođenje tunela u „slabim” stenskim masama zahteva pravilno projektovanje tunelske obloge, radi sprečavanja velikih pomeranja po konturi iskopa, provaljivanja krovine ili zaglavljivanja, odnosno oštećenja tunelske mašine pre postavljanja finalne podgrade. Proces podgrađivanja stenske mase obično započinje ugradnjom ankera odgovarajućih svojstava, i u tačno određenom rasporedu, sa ciljem poboljšanja mehaničkih svojstava stenske mase. S obzirom na to da se izvođenju finalne podgrade pristupa tek nakon određenog vremena od iskopa, kao i na određenoj udaljenosti od čela (koristeći longitudinalni efekat luka), najpre se postavlja tanak sloj prskanog betona (torkreta) po konturi iskopa, sa ciljem redukovanja pomeranja stenske mase i broja deformisanih ankera (pod pretpostavkom elastičnog-idealno plastičnog ponašanja stenske mase) [1]. Svojstva takvog betona se određuju prema zahtevima projekta i lokalnim geološkim uslovima, pri čemu je neophodno imati u vidu i vremenski promenljivo ponašanje betona. Naime, ukoliko se obloga tunela,

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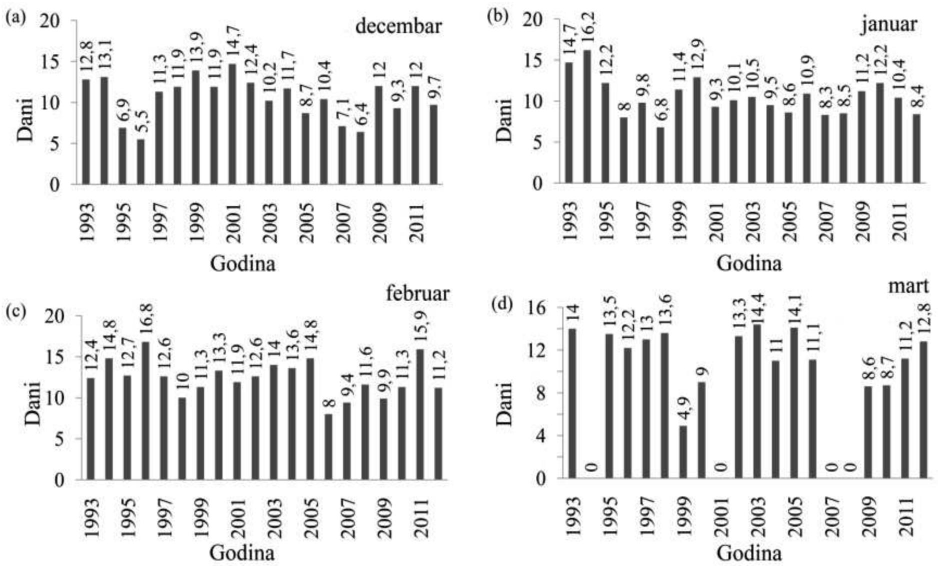
sastavljena od ankera i prskanog betona sa čeličnim rešetkastim nosačima, postavlja neposredno iza čela iskopa, ankeri i rešetkasti nosači će "odgovoriti" na deformaciju stenske mase po konturi iskopa istovremeno sa daljim napredovanjem tunela. Međutim, u ovom stadijumu, starost prskanog betona je vrlo mala, i beton nije uspeo da razvije svoju punu nosivost, tako da trenutno opterećenje od stenske mase u ovoj fazi iskopa može da dovede do njegovog loma. Shodno tome, neophodno je pristupiti zaštiti betona od nepovoljnih spoljašnjih uslova, poput iznenadnog zamrzavanja i otkravljivanja, kako bi dostigao očekivanu vrednost pritisne čvrstoće u tako kratkom vremen-skom intervalu. Neophodno je naglasiti da, u ovom slučaju, izvođaču radova nije potrebna smeša betona koja daje očvrsli beton otporan na zamrzavanje/otkravljivanje, već sveža smeša betona koja je otporna na moguće zamrzavanje [2-3]. Prema Uputstvu Američkog Instituta za beton [4], potrebno je pristupiti zaštiti betona od zamrzavanja sve dok ne dostigne čvrstoću na pritisak od 3,5 MPa [5], što obično iznosi 24 h za smešu betona sa vodocementnim (VC) faktorom ispod 0,6, kada je beton izložen temperaturi t=20ºC. Ukoliko se beton izloži zamrzavanju pre nego što dostigne čvrstoću od 3,5M Pa, njegova konačna čvrstoća na pritisak biće značajno umanjena [6]. Shodno tome, od posebnog je interesa proučavanje otpornosti na mraz svežeg betona za vreme zimskih meseci, sa prosečnom dnevnom temperaturom ispod 0^0C i do 15 dana uzastopno, i sa minimalnim dnevnim temperaturama ispod -10ºC [7]. U takvim uslovima, zamrzavanje vode u svežem betonu može dovesti do trajnog oštećenja strukture novoformiranog cementnog matriksa.

I pored velikog broja prethodnih istraživanja o uticaju niskih temperatura na pritisnu čvrstoću betona [8-11], do sada nisu vršena istraživanja uticaja „oštrog'' mraza na svojstva svežeg betona, sa temperaturama i do -25ºC, uključujući i efekat brzih temperaturnih promena, sa amplitudom i do 45ºC za samo nekoliko dana. Uzimajući u obzir niske temperature zabeležene na području Beograda sa čestim slučajevima oštrog mraza, postoji realna potreba za jednom funkcionalnom antifriz smešom svežeg betona. Ovakvi oštri klimatski uslovi mogli su se očekivati i pri mašinskom iskopu hidrotehničkog tunela u Višnjici, što je moglo dovesti i do zaglavljivanja tunelske mašine.

Osnovni cilj istraživanja je razvoj pouzdanog aditiva, koji bi omogućio izvođenje tunelske obloge bez zaštite od mraza čak i u takvim surovim klimatskim uslovima. Shodno tome, u radu se analizira uticaj različite količine predloženog hemijskog aditiva (4% i 8%) na pritisnu čvrstoću svežeg betona pri različitim režimima mraza: jednodnevni mraz (-10ºC), trodnevni mraz (-10ºC, -5ºC i -15ºC), i sedmodnevni mraz (sa oscilacijama temperature između 0ºC i -25ºC).

TRAJANJE MRAZA U REALNIM USLOVIMA

U cilju potvrde realne potrebe za praktičnom primenom antifriz aditiva za prskani beton, najpre je izvršena analiza klimatskih karakteristika na području Beograda u periodu 1993-2012. g. na osnovu podataka Republičkog Hidrometeorološkog zavoda [7]. Analiza ekstremnih slučajeva iznenadnog otopljavanja za decembar, januar, februar i mart izvedena je sa ciljem definisanja prvog i drugog režima mraza. Na slici 1 prikazana je maksimalna zabeležena temperaturna amplituda samo za one dane sa prelazom iz negativnih u pozitivne temperature za dva uzastopna dana (maksimalna vrednost od 16,8ºC zabeležena je tokom februara 1996.g.).

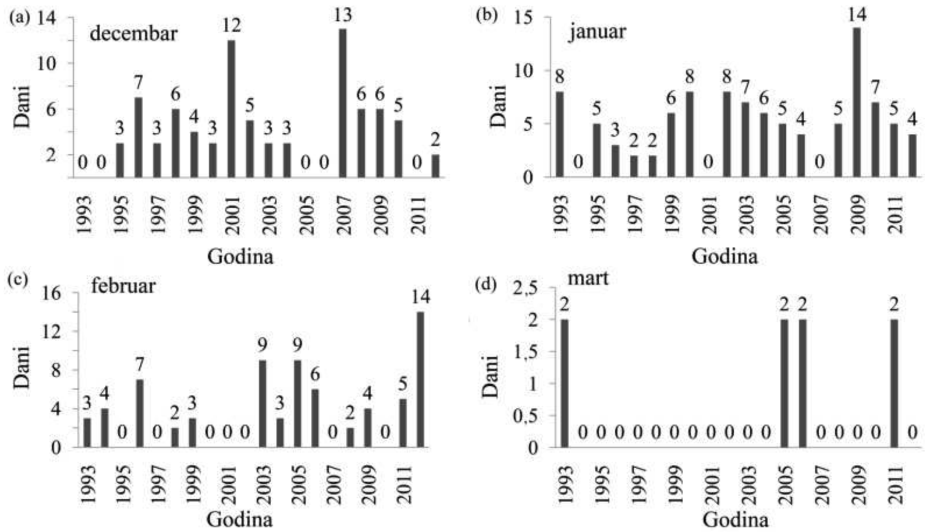


Sl. 1. *Maksimalne dnevne temperaturne amplitude sa iznenadnim prelazom od negativnih ka pozitivnim vrednostima za dva uzastopna dana u periodu 1993-2012.g. za: (a) decembar, (b) januar, (c) februar; (d) mart. Nulta vrednost se dodeljuje za mesece/godine u kojima nije zabeležen prelaz od negativnih ka pozitivnim temperaturama za dva uzastopna dana*

Treći režim mraza, kojem su izloženi uzorci betona, definisan je na osnovu maksimalnog broja uzastopnih dana sa mrazom za decembar, januar, februar i mart, prikazanih na slici 2 (14 dana tokom januara 2009. g. i februara 2012. g.).

EKSPERIMENTALNA PROCEDURA

U prvoj fazi istraživanja, pritisna čvrstoća betona određivana je na uzorcima sa i bez hemijskog aditiva nakon nege u vodi u izotermalnim uslovima (20°C). U drugoj fazi istraživanja, pristupa se analizi efekta 4% i 8% hemijskog aditiva na pritisnu čvrstoću uzoraka betona, nakon njihovog izlaganja različitim režimima mraza. Pri tome, osnovni sastavni elementi betona su (Tabela 1): cement (CEM I 42,5 R, Lafarge Cement, Beočin), agregat (drobljeni kamen, kamenolom Šumnik) i aditiv ("T-25ºC"). Uzorci betona oblika kocke (10x10 cm) pravljeni su u laboratorijskoj mešalici, sa periodom mešanja od 3 minuta za sve smeše. Livenje je obavljeno na vibracionom stolu dok nije postignuta potpuna konsolidacija.



Sl. 2. *Broj uzastopnih dana sa temperaturom ispod 0ºC u periodu 1993-2012.g. za: (a) decembar, (b) januar, (c) februar; (d) mart (samo dva i više dana je uzimano u obzir)*

Tabela 1. *Sastav smeša betona*

komponenta po 1m^3 betona	aditiv 0%	aditiv 4%	aditiv 8%
cement: CEM I 42,5 R	417 kg	411 kg	408 kg
agregat andezita 0 - 2 mm (30%)	574 kg	567 kg	563 kg
agregat andezita 2 - 4 mm (10%)	192 kg	189 kg	188 kg
agregat andezita 4 - 8 mm (10%)	192 kg	189 kg	188 kg
agregat andezita 8 -11 mm (20%)	383 kg	378 kg	375 kg
agregat andezita 11 -16 mm (30%)	575 kg	568 kg	563 kg
aditiv	-	16,4 kg	32,6 kg
voda	167 kg	148 kg	139 kg
V/C	0,40	0,36	0,34
zapreminska težina	2500 kg/m^3	2467 kg/m^3	2456 kg/m^3

Uzorci betona za prvu fazu testiranja (u izotermalnim uslovima nege) pripremljeni su prema prethodno opisanoj proceduri, i izliveni u čelične kalupe. Nakon 24 h, referentni uzorci su izvađeni iz kalupa i negovani pod istim uslovima u vodi na temperaturi od 20ºC. Čvrstoća na pritisak je određena nakon 3, 7 i 28 dana. U drugoj fazi istraživanja uzorci su pripremljeni na siti način kao zaprethodnu fazu. Temperatura smeša za vreme livenja iznosila je 20ºC. Odmah nakon livenja, metalni kalupi sa svežim betonom stavljeni su u aklimatizacionu komoru na temperature -10^{o}C, a potom su izlagani promeni temperature definisanoj sa tri različita režima mraza: (a) režim mraza 1 simulira jednodnevni mraz, pri čemu su uzorci betona izloženi temperaturi od -10ºC u toku jednog dana, a potom, drugog dana, uzorci su izloženi temepraturi od 20ºC; (b) režim mraza 2 simlira više-dnevni mraz, pri čemu se uzorci betona izlažu temperaturi od -10ºC tokom prvog dana, a potom blagom porastu temperature do -5ºC tokom drugog dana, potom temperaturi od -15ºC tokom trećeg dana, a tokom četvrtog dana uzorci se neguju u vodi na temperaturi od 20ºC; (c) režim mraza 3 simulira duži sedmodnevni mraz sa temperaturom prvog dana od -10ºC, drugog dana od -5ºC, trećeg dana od -15ºC, četvrtog dana od -25ºC, petog dana od -10ºC i šestog dana od -5ºC. U periodu od 8. do 28. dana uzorci betona se neguju u vodi na temperaturi od 20ºC.

EKSPERIMENTALNI REZULTATI

Rezultati prve faze istraživanja prikazani su u Tabeli 2. Jasno je da je pritisna čvrstoća betona sa aditivom nakon 3 dana veća od čvrstoće uzoraka bez aditiva. Međutim, nakon sedam dana, nešto veća pritisna čvrstoća zabeležena je za uzorak betona sa 4% aditiva, dok je značajno manja čvrstoća zabeležena za uzorak sa 8% aditiva. Sa druge strane, nakon 28 dana čvrstoća na pritisak za uzorak betona sa 4% aditiva se povećava, a sa 8% aditiva se nešto smanjuje, ali je i dalje veća u poređenju sa čvrstoćom uzoraka bez aditiva. Izvedeno istraživanje je pokazalo da aditiv ne utiče nepovoljno na očvšćavanje betona nakon 28 dana.

Tabela 2. *Svojstva uzoraka betona sa različitom količinom hemijskog aditiva, negovanih u vodi na temperaturi od 20ºC.**

uzorak broj	starost (dani)	0% aditiva		4% aditiva		8% aditiva	
		γ (kg/m^3)	σ_c (MPa)	γ (kg/m^3)	σ_c (MPa)	γ (kg/m^3)	σ_c (MPa)
1	3	2470	52,0	2405	57,5	2490	61,0
2		2460	52,0	2420	58,0	2480	62,0
3		2460	51,0	2490	54,5	2480	65,0
4	7	2470	77,4	2470	74,5	2420	66,2
5		2580	73,8	2450	78,0	2460	64,0
6		2450	72,0	2450	72,0	2440	68,5
7	28	2460	88,5	2450	93,0	2470	83,7
8		2470	70,6	2470	84,0	2470	96,5
9		2440	81,0	2450	90,0	2430	81,6

** γ označava zapreminsku težinu, a σ_c je čvrstoća na pritisak uzorka betona.*

U drugoj fazi istraživanja, pritisna čvrstoća betona određena je nakon izlaganja uzoraka različitim režimima mraza, sa temperaturom do -25ºC. Postupak ispitivanja se sastojao u sledećem. Najpre je ispitan efekat zamrzavanja na uzorke svežeg betona bez hemijskog aditiva (Tabela 3).

Tabela 3. *Zapreminska težina i čvrstoća na pritisak uzoraka betona bez hemijskog aditiva*

uzorak broj	režim mraza	starost (dani)		ekvivalentna starost (t_e)*	svojstva betona bez aditiva			
		< 0°C	= 20°C		γ (kg/m^3)	srednja vrednost	σ_c (MPa)	srednja vrednost
1	1	1	1	1	2455	2478	7,9	8,2
2	1	1	1	1	2500		8,5	
3	2	3	1	1	2430	2420	10,1	10,2
4	2	3	1	1	2410		10,4	
5	3	7	1	0,83	2410	2400	11,8	12,1
6	3	7	1	0,83	2390		12,4	
7	3	7	1	0,83	2355		16,7	
8	3	7	3	2,83	2530	2425	19,0	17,6
9	3	7	3	2,83	2390		17,1	
10	3	7	3	2,83	2390		21,0	
11	3	7	7	6,83	2410	2397	21,8	21,5
12	3	7	7	6,83	2390		21,8	
13	3	7	7	6,83	2525		31,0	
14	3	7	28	27,83	2410	2440	28,0	29,3
15	3	7	28	27,83	2385		29,0	

**ekvivalentno vreme (t_e) određeno je na osnovu Solovog modela [12]*

Rezultati eksperimentalne analize pritisne čvrstoće uzoraka betona sa 4% i 8% aditiva prikazani su u Tabelama 4 i 5. U oba slučaja, čvrstoća na pritisak uzoraka betona je mnogo veća, skoro i do tri puta (za režim mraza 1 od 8,2 MPa do 25,9 MPa sa 4% aditiva) u poređenju sa pritisnom čvrstoćom na uzorcima betona bez aditiva (Tabela 3).

Tabela 4. *Svojstva uzoraka betona sa 4% hemijskog aditiva*

uzorak broj	režim mraza	starost (dani)		ekvivalentna starost (t_e)	svojstva betona sa 4% aditiva			
		< 0°C	= 20°C		γ (kg/m^3)	srednja vrednost	σ_c (MPa)	srednja vrednost
1	1	1	1	1	2440	2445	25,8	25,9
2	1	1	1	1	2450		26,0	
3	2	3	1	1	2470	2460	15,2	15,6
4	2	3	1	1	2450		16,1	
5	3	7	1	0,83	2440	2445	26,0	25,2
6	3	7	1	0,83	2450		24,3	
7	3	7	1	0,83	2380		31,0	
8	3	7	3	2,83	2380	2390	31,5	31,5
9	3	7	3	2,83	2410		32,0	
10	3	7	3	2,83	2370		45,0	
11	3	7	7	6,83	2410	2390	39,5	43,1
12	3	7	7	6,83	2390		44,8	
13	3	7	7	6,83	2440		50,7	
14	3	7	28	27,83	2460	2453	53,8	53,6
15	3	7	28	27,83	2460		56,4	

Neophodno je naglasiti da je razlika u ponašanju uzoraka betona sa 4% i 8% aditiva vrlo mala, što ukazujena činjenicu da dalje dodavanje hemijskog aditiva ne bi doprinelo značajnijem povećanju čvrstoće na pritisak uzoraka betona. S druge strane, iako se zapaža značajno povećanje pritisne čvrstoće u poređenju sa uzorcima bez aditiva (Tabele 3, 4 i 5), registrovane vrednosti su i dalje niže u odnosu na pritisnu čvrstoću uzoraka betona negovanih u izotermalnim uslovima (Tabela 2).

Tabela 5. *Zapreminska težina i čvrstoća na pritisak uzoraka betona sa 8% hemijskog aditiva*

uzorak broj	režim mraza	starost (dani)		ekvivalentna starost (t_e)	svojstva betona sa 8% aditiva			
		< 0°C	= 20°C		γ (kg/m³)	srednja vrednost	σ_c (MPa)	srednja vrednost
1	1	1	1	1	2440	2440	17,0	17,6
2	1	1	1	1	2440		18,1	
3	2	3	1	1	2430	2445	24,0	23,8
4	2	3	1	1	2460		23,7	
5	3	7	1	0,83	2430	2435	38,7	39,4
6	3	7	1	0,83	2440		40,2	
7	3	7	1	0,83	2410		41,0	
8	3	7	3	2,83	2385	2402	40,0	40,5
9	3	7	3	2,83	2410		40,5	
10	3	7	3	2,83	2410		46,3	
11	3	7	7	6,83	2420	2403	46,5	47,9
12	3	7	7	6,83	2380		51,0	
13	3	7	7	6,83	2430		56,1	
14	3	7	28	27,83	2450	2443	69,4	61,0
15	7	7	28	27,83	2450		57,4	

U cilju poređenja čvrstoće na pritisak uzoraka betona nakon izlaganja različitim režimima mraza (sa i bez aditiva) i pritisne čvrstoće uzoraka negovanih u izotermalnim uslovima, procena pritisne čvrstoće uzoraka betona izvedena je za sledeće dane: 0,83; 1; 2,83; 6,83 i 27,83, što predstavlja ekvivalentnu starost za sve ispitivane slučajeve (četvrta kolona u tabelama 3, 4 i 5). Čvrstoća na pritisak uzoraka betona za navedene dana ocenjena je koristeći Ploumanov model (Slika 3), koji daje vezu između čvrstoće betona negovanog u izotermalnim uslovima i zrelosti betona po Solu:

$$S_p = a + b \times \log M_s$$

gde je:

- S_p - predviđena vrednost čvrstoće na osnovu Ploumanove jednačine [13],
- M_s - je zrelost betona na osnovu Solovog modela [12], a
- a i b su konsatnte.

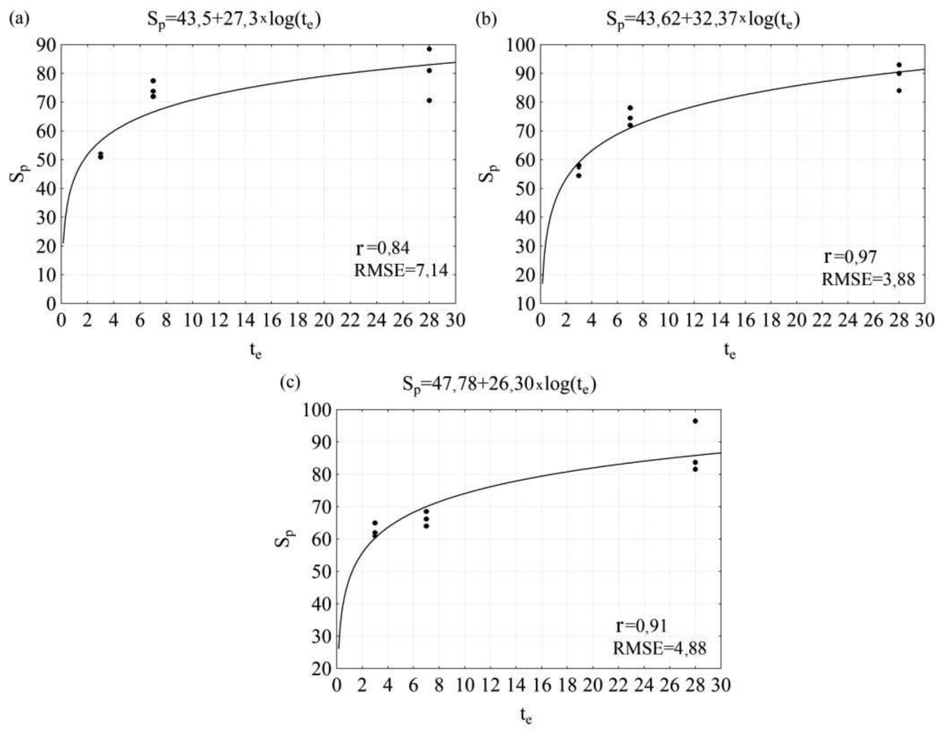
Zrelost betona M_s određena je na osnovu ekvivalentne starosti, uzimajući u obzir spregnuti uticaj proteklog vremena i temperature na razvoj čvrstoće [14]:

$$t_e = \left(\sum_{1}^{n} (T - T_0) \times \Delta t_i \right) / (T_r - T_0),$$

gde je:

- t_e - ekvivalentna starost,
- T - je temperatura očvršćavanja betona u vremenskom intervalu Δt_i,
- T_0 - označava referentnu temperaturu (–10ºC),
- T_{r} - je temperatura nege betona (20ºC), a
- Δt_i - je posmatrani vremenski interval.

Očigledno je, na osnovu slike 3, da Ploumanov model daje zadovoljavajuću procenu eksperimentalnih rezultata, sa visokim koeficijentom korelacije (*r*>0,8) i niskom vrednošću srednje kvadratne greške (*RMSE*≤7,14). Prema tome, vrednosti čvrstoće na pritisak za ekvivalentnu starost mogu da se očitaju sa ovih dijagrama sa zadovoljavajućom tačnošću (četvrta kolona u tabelama 3, 4 i 5).



Sl. 3. *Rezultati predviđanja čvrstoće na pritisak uzoraka betona pomoću Ploumanovog modela sa različitom količinom aditiva, negovanih u izotermalnim uslovima (u vodi na temperaturi 20°C): (a) 0% aditiva; (b) 4% aditiva; (c) 8% aditiva*

Poređenje čvrstoće na pritisak betona negovanog u izotermalnim uslovima i nakon izlaganja različitim režimima mraza prikazano je u Tabeli 6. Jasno je da uzorci betona sa 8% aditiva postižu 86,3% željene pritisne čvrstoće, za režim mraza 3 sa sedmodnevnim mrazom i samo jednim danom otkravljivanja.

Isti uzorci postižu 71,1% željene pritisne čvrstoće za režim mraza 3 sa sedmodnevnim mrazom i 21 danom otkravljivanja. U svim drugim slučajevima, uzorci betona postižu manje od 70% pritisne čvrstoće referentnih uzoraka negovanih pod izotermalnim uslovima u vodi na temperaturi od 20ºC.

Tabela 6. *Smanjenje čvrstoće na pritisak uzoraka betona sa i bez hemijskog aditiva, negovanih u izotermalnim uslovima, i pri delovanju različitih temperaturnih režima*

ekvivalentna starost (t_e)	σ_c (MPa) sa 0% aditiva			σ_c (MPa) sa 4% aditiva			σ_c (MPa) sa 8% aditiva		
	Izotermalni uslovi	Nakon različitih režima mraza	% postignute izotermalne čvrstoće σ_c	Izotermalni uslovi	Nakon različitih režima mraza	% postignute izotermalne čvrstoće σ_c	Izotermalni uslovi	Nakon različitih režima mraza	% postignute izotermalne čvrstoće σ_c
0,83	41,29	12,1	29,3	41,00	25,2	61,5	45,65	39,4	86,3
1	43,50	8,2-10,2	18,9-23,5	43,62	15,6-25,9	35,8-59,4	47,78	17,6-23,8	36,8-49,8
2,83	55,83	17,6	31,5	58,24	31,5	54,1	59,66	40,5	67,9
6,83	66,28	21,5	32,4	70,63	43,1	61,0	69,73	47,9	68,7
27,83	82,94	29,3	35,3	90,38	53,6	59,3	85,77	61,0	71,1

ZAKLJUČAK

U radu se analizira efekat hemijskog aditiva na čvrstoću na pritisak uzoraka betona nakon izlaganja različitim režimima mraza. U sva tri ispitana slučaja, uzorci betona sa hemijskim aditivom dostigli su znatno višu pritisnu čvrstoću (čak i do 200% veću) u odnosu na uzorke bez hemijskog aditiva. Rezultati analize potvrđuju da se primenom hemijskog aditiva može sprečiti lom svežeg prskanog betona čak i takvim oštrim zimskim uslovima.

Naglasimo da je poređenje pritisnih čvrstoća zabeleženih pri različitim temperaturnim uslovima (Tabela 6) izvedeno korišćenjem regresione analize (Ploumanov model), što može dovesti do nepouzdanih interpretacija. Međutim, relativno visoka vrednost koeficijenta korelacije (r>0.8) ukazuje na to da je moguća greška u proceni pritisne čvrstoće u intervalu greške merenja. S druge strane, izvedena analiza je u znatnoj meri ograničena malim brojem ispitanih uzoraka betona: u pojedinim slučajevima ispitivana su po tri uzorka, što je i uobičajeno u laboratorijskoj praksi, dok su, u drugim slučajevima, svojstva betona određivana na samo dva uzorka. Međutim, čak i sa većim brojem uzoraka, ne bi trebalo očekivati značajnije promene u pogledu dostignute pritisne čvrstoće sa dodatim hemijskim aditivom.

U pogledu pravca daljih istraživanja, izvedena analiza bi trebalo biti proširena dodatnim analizama efekta predloženog hemijskog aditiva, pre svega u odnosu na postizanje željene čvrstoće na pritisak betona. Naravno, buduća istraživanja bi morala uzeti u obzir i ekonomske efekte, sa ciljem određivanja najpovoljnijeg procenta aditiva, koji obezbeđuje najveću pritisnu čvrstoću betona. Ovi opiti bi morali da budu izvedeni u realnim uslovima, *in situ*, postavljanjem svežeg betona po konturi iskopa, čime bi se obuhvatio i uticaj pomeranja stenske mase ka tunelskom otvoru na razvoj čvrstoće mladog prskanog betona. Na taj način, bila bi izvršena još realnija procena efekta hemijskog aditiva na stabilnost i postojanost svežeg prskanog betona.

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