Građevinski materijali i konstrukcije
Building Materials and Structures

journal homepage: www.dimk.rs

https://doi.org/10.5937/GRMK2300013B

Original scientific paper

Effect of aggregate origin on freeze/thaw resistance of self-compacting concrete with and without a de-icing agent

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Article history

Received: 08 November 2023
Received in revised form: 06 December 2023
Accepted: 11 December 2023
Available online: 20 December 2023

Keywords

self-compacting concrete,
natural aggregate,
recycled concrete aggregate,
water absorption,
freeze/thaw resistance,
freeze-thaw resistance with de-icing agent

ABSTRACT

Freezing and thawing cycles, with or without de-icing agents, are the principal causes of concrete structure degradation during the winter. This paper explores the effects of aggregate type on the level of degradation of self-compacting concrete (SCC) due to freeze-thaw (f/t) action. Natural river (NRA) and/or natural crushed (NCA) aggregate, as well as the recycled aggregate of known (RCA-N) and unknown provenance (RCA-A), were employed to produce six different SCC mixtures. The temperature, density, air content, and consistency were determined for fresh concrete, while compressive strength, water absorption by gradual immersion and vacuuming, and frost resistance with and without de-icing salts were tested for hardened concrete. Even though all tested concretes have met the criteria for frost resistance with and without the de-icing salts, it was found that the type of aggregate has a noticeable influence on it. The type of natural aggregate has little effect on SCC frost resistance, but it does influence its behavior when frost and salt are present at the same time. In f/t conditions, RCA-N can be used the same way as natural aggregate, while RCA-A causes the biggest frost resistance reduction. However, both RCAs are not recommended for application in conditions of simultaneous frost and salt impacts.

1 Introduction

The durability of concrete is a very current issue, given that it is regarded as the core material of modern buildings and that the problem of its degradation owing to the aggressive effects of numerous environmental conditions is obvious. One of the most prominent deteriorating mechanisms in regions with cold winter conditions is the action of frost [1], [2]. The destructive force of this impact is amplified in the presence of salt, which is commonly used in the winter regime to accelerate the process of thawing snow and ice [2], [3], and [4]. As a result, it is crucial to conduct any research that can help reduce the level of degradation this mechanism causes. In this regard, it is especially vital to define criteria for the selection of component materials for self-compacting concrete (SCC). Given the issue of overuse of natural resources, it is critical to use the potential of waste materials as a way to produce valuable but greener components for new environmentally friendly concrete [3].

The selection of the appropriate type of aggregate is one of the possibilities for modeling the durability properties of concrete in terms of resistance to frost effects with and without the presence of salt. Several studies revealed that increasing the presence of RCA increases the value of water absorption in concrete [5], [6], [7], [8], [9], [10], [11], [12], and [13]. Some examples are Modani et al. [6], who found that adding 20, 40, 60, 80, or 100% RCA to coarse natural aggregate in SCC increases absorption by 21, 28, 31, 36, and 41%, respectively (absorptions of fine and coarse NA and coarse RCA were 0.84, 1.31, and 5.64%, respectively).

M. Gesoglu et al. [9] investigated the durability performance of concrete produced by varying two types of aggregate blended with silica fume. The concrete with the lowest permeability (measured by gas permeability, water impermeability, and capillary absorption) was made with NRA as the coarse aggregate. The concrete with the highest permeability was made with RCA. The combination of coarse RCA and fine NRA proved to be even more advantageous than the combination of coarse NRA and fine RCA.

Oliveira et al. [14] varied the participation of the coarse RCA in SCC, manufactured with limestone filler, in proportions of 20, 40, and 100%. It was discovered that using

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RCA has no effect on the gas permeability, water permeability, or water impermeability of SCC. When evaluating the water permeability results, it was discovered that permeability coefficients of insignificant value were achieved for all types of SCC, compared to the usual level of such values for conventional concrete. The coefficient of capillary absorption also goes down as the amount of RCA goes up, by about 5 to 13 percent, when coarse NA is completely replaced by RCA. This is due to the beneficial influence of limestone filler, but it is also considered that RCA disrupts the concrete structure, favorably affecting the creation of barriers or voids that interrupt the capillary pore system.

Despotović [15] conducted research on the effect of RCA application on the level of absorption of SCC as assessed by the gradual immersion method. Higher absorptions of concrete with NRA were recorded by substituting the coarse aggregate fraction (8/16mm) in amounts of 0, 50, and 100% with RCA. Tuyan et al.'s research [16] also indicates the usefulness of using RCA with regard to capillary absorption of SCC. The amount of water to powder (w/p) was changed from 0.43 to 0.48 to 0.53, and the coarse part of the crushed aggregate (NCA) was switched out for RCA in increments of 0, 20, 40, and 60%. The amounts of fine and coarse NCA and RCA that were absorbed were 0.67, 0.21, and 4.80%, respectively. It was discovered that the participation of RCA impairs chloride absorption and penetration. At the same time, the higher w/p had an even stronger influence on the growth in the values of the aforesaid tests' results. Nonetheless, RCA participation improves the capillary pore system, particularly in concrete with higher w/p (0.48 and 0.53). Concretes with 20% RCA have the lowest coefficients of capillary absorption, but as the proportion of RCA increases, the sorption power of the concrete rises as well (it should be noted that, regardless of the stated increase in sorption, the coefficients of capillary absorption of concrete with RCA are lower than the same coefficients of concrete with NA). Finally, a considerable number of studies have established that permeability, as seen primarily through water permeability, is dependent on the capillary porosity of the cement stone of new concrete and the capillary porosity of the cement stone of recycled concrete. If RCA was obtained by crushing low-porosity concrete, the level of water permeability of the new concrete will be primarily determined by the granulometric composition and the achieved structure of the new cement stone. Hence, RCA can be successfully used to produce concrete with a high level of water impermeability.

According to research conducted by M. S. Hameed et al. [17], replacing the fine fraction of river aggregate in SCC with waste material – marble powder (more than 60% of grains smaller than 0.125 mm) and finely crushed rubble (D_{max}=4.75mm for both materials), lowers concrete permeability, as measured by absorption, waterimpermeability, and chloride diffusion tests, while having no influence on compressive strength. Similarly to the preceding, substituting the fine fraction of river aggregate with waste material – granite powder enhances compressive and flexural strength by up to 40% and reduces the absorption of SCC by up to 60%, according to the research by Jain et al. [18].

Although permeability is one of the good indirect indicators of resistance to the effect of frost and the simultaneous effect of frost and salt, the direct measurements of concrete resistance according to the mentioned durability aspects are also extremely important due to the cold climatic conditions of the winter period in the Balkans. Tuyan et al. [16] found that increasing w/p and the amount of coarse RCA in SCC makes it less resistant to frost after 300 cycles (tested according to ASTM C666). However, it turned out that w/p had a greater influence on the property in question. In addition, this research showed that there is a strong link between mass loss after full f/t cycles and absorption using the gradual immersion method. Using the same standard, Öznur et al. [19] investigated the impact of pumice stone application in coarse aggregate fractions by varying its involvement in quantities of 10, 20, 25, and 30%. It was demonstrated that the use of pumice reduces compressive strength, but that the lowest strength drop after 300 cycles is obtained for concretes containing 10, 15, and 20% pumice, respectively. According to the authors, this is a result of the porous nature of the pumice and its propensity to absorb water, which migrates from the cement stone's capillary system into the pumice 's pore space during the freezing process. However, the use of pumice in the proportion of 30% coarse aggregate provides additional "space," which reduces frost resistance. The mass loss measurement findings revealed that increasing the number of cycles caused the samples' mass loss to increase. In this regard, tests of concrete containing 10% pumice yielded the best results, whereas those containing 30% pumice yielded the worst. Finally, the subject research concluded that SCC with a 10% pumice involvement has the best resistance to the effect of frost after 300 cycles of freezing and thawing, both in non-destructive and destructive ways. This lightweight aggregate can be used up to 20% of the volume of the coarse aggregate. However, as its percentage increases, SCC resistance decreases according to this breakdown process.

Huda et al. [20] demonstrated that all designed concrete mixtures, blended with fly ash, met the frost resistance criterion after 300 f/t cycles when the coarse NA aggregate was substituted by RCA in amounts of 0, 30, 40, and 50% in SCC (in accordance with ASTM C666). Regardless of the foregoing, it was shown that RCA participation reduces frost resistance, with 40% RCA participation offering the least resistance. The resistance to 200 frost cycles of SCC was evaluated in line with GB/T50082 in the study of Hao Yan et al. [21], in which the involvement of aeolian sand in the amounts of 0, 20, 40, and 60% and the coarse RCA in the amounts of 0, 25, and 50% were varied. It was discovered that increasing the proportion of aeolian sand increases the loss in frost resistance, but increasing the proportion of RCA inhibits this tendency. In this regard, the most effective shares of sand and RCA were determined to be 20 to 40% and 25 to 50%, respectively.

Resistance to the simultaneous action of frost and salt as a function of aggregate application is a less explored topic for newer forms of concrete composites, such as SCC. I.F. Bosque et al. [22] investigated the influence of RCA in the amounts of 0, 25, and 50% on frost resistance of SCC, with and without the addition of deicing agents, in line with the provisions of CEN/TS 12390-9 and ASTM C666.

All RCA concretes met the resistance criteria for exposure classes XF1 and XF3, with a durability factor of over 90% and scaled materials weighing under 0.1 kg/m^2 after 56 cycles. However, the same concrete mixtures are not resistant to freeze–thaw (f/t) in the presence of de-icing salts – exposure classes XF2 and XF4, generating scaled material weighing over 1.00 kg/m^2 and grade 5 visual deterioration.

Although the use of SCC in Bosnia and Herzegovina is extremely limited, a portion of the professional public has recognized the benefit of using this concrete technology to

produce prefabricated buffers on roads, which are among the most vulnerable to the aggressive simultaneous effects of frost and salt.

Figure 1 illustrates the progressive deterioration of traditional concrete safety barriers, raising concerns about safety and necessitating expensive replacement costs. The first series of barriers built by SCC were constructed in Banjaluka in the city parking area and on sections of the Banjaluka-Gradiška highway (Figure 2). It turns out that the first-placed blocks made using the SCC-NCA recipe (given in the experimental section of this study) have not been affected by any degradation mechanisms after 12 years of use.

Figure 1. Safety barrier built of traditional concrete with NRA

Figure 2. Safety barrier built of SCC-NCA, highway Banja Luka –Gradiška, after 12 years of exploitation

This research investigated the effects of various natural aggregates (NA) and their combinations, as well as recycled aggregates (RCA) generated by crushing waste concrete, on the resistance of SCC to frost effects with and without the presence of de-icing agents. Water absorption tests via gradual immersion and vacuuming were chosen as an indirect method.

2 Experimental study

As part of the experiment, six different types of concrete mixes were tested to see how the type of aggregate affected the resistance of SCC to frost, with and without de-icing salt. Natural aggregates (river – NRA and/or crushed – NCA) and recycled aggregates (known – RCA-N and unknown origin – RCA-A) were utilized. All aggregate mixes are designed with three fractions, with a nominal grain size of 16 mm.

The concrete mixtures labels and aggregate types utilized are listed below:

- SCC-NRA–self-compacting concrete produced with natural river aggregate,
- SCC-NCA–self-compacting concrete produced with natural crushed aggregate,
- SCC-NMA-I–self-compacting concrete produced with a mixture of natural river and natural crushed aggregate (water to cement ratio = 0.40),
- SCC-NMA-II–self-compacting concrete produced with a mixture of natural river and natural crushed aggregate (water to cement ratio = 0.43),
- SCC-RCA-N–self-compacting concrete is produced with a mixture of fine river aggregate and coarse recycled concrete aggregate of known origin and
- SCC-RCA-A–self-compacting concrete is produced with a mixture of fine river aggregate and coarse recycled concrete aggregate of unknown origin.

The following properties were tested on fresh concrete:

- temperature, according to EN 12350-1 [23] and SRPS U.M1.032 [24],
- density, according to EN 12350-6 [25],
- entrapped air content, according to EN 12350-7 [26] and
- consistency, according to EN 12350-8 [27].

The following properties were tested on hardened concrete:

- compressive strength at the age of 28 days, according to EN 12390-3 [28],
- water absorption by the test of gradual immersion at atmospheric pressure, according to EN 13755 [29],
- water absorption by vacuuming, according to EN 1936 [30],
- freeze/thaw resistance, according to SRPS U.M1.016 [31] and
- freeze/thaw resistance with a de-icing agent, according to SRPS U.M1.055 [32].

2.1 Component materials

The following materials were utilized for concrete production:

- Cement CEM II/B-M (S-LL) 42,5 N, "Dalmatia-cement", "St. Juraj" Split, (Kaštel Sućurac), specific gravity of 3140 kg/m^3,
- Addition type I –limestone filler, "Japra" Ltd. Novi Grad, specific gravity of 2780 kg/m^3,
- Aggregates:
  - NRA – river aggregate "Petroševci", "Road Structures" Laktaši, Bosnia and Herzegovina, were washed and separated into fractions of 0/4, 4/8, and 8/16 mm (the results of the tested properties are listed in Table 1);
  - NCA – crushed aggregate "Dobrnja", "Binis", Banja Luka, Bosnia and Herzegovina, separated into fractions of 0/4, 4/8, and 8/16 mm (the results of the tested properties are listed in Table 2);

- RCA-N – recycled aggregate of known origin, obtained by crushing waste concrete classes C25/30 and C35/45, fractions of 4/8 and 8/16 mm (the results of the tested properties are listed in Table 3);
- RCA-A – recycled aggregateof unknown origin, obtained by crushing waste concrete taken from the construction debris landfill, fractions of 4/8 and 8/16 mm (the results of the tested properties are listed in Table 4);
- Admixture–superplasticizer "Cementol®Zeta Super S", "TKK", Srpenica, Slovenia, and
- Tap water.

Table 1. Physical, mechanical and chemical properties of NRA

Property	Standard	Units of measurement and category, according to EN 12620		Fraction		
				0/4 mm	4/8 mm	8/16 mm
Loose bulk density	EN 1097-3 [33]	[kg/m^3]		1606	1554	1582
Particle density	EN 1097-6[34]	[kg/m^3]		2740	2696	2683
Water absorption	EN 1097-6	[%]		0.6	0.8	0.4
Resistance to weathering	EN 1367-2 [35]	[%]	MS_{18}	0.6	0.6	1.3
Total sulphur content (SO_3)	EN 1744-1 [36]	[%]	S_1	0	0	0
Water-soluble chloride ion content (Cl^-)	EN 1744-1	[%]	-	0.007	0.007	0.007
Resistance to fragmentation (LA)	EN 1097-2 [37]	[%]	LA_{30}		27.4	

Table 2. Physical, mechanical and chemical properties of NCA

Property	Standard	Units of measurement and category, according to EN 12620		Fraction		
				0/4 mm	4/8 mm	8/16 mm
Loose bulk density	EN 1097-3	[kg/m^3]		1546	1354	1318
Particle density	EN 1097-6	[kg/m^3]		2709	2746	2718
Water absorption	EN 1097-6	[%]		1.64	1.22	0.71
Resistance to weathering	EN 1367-2	[%]	MS_{18}	0.2	0.2	0.1
Total sulphur content (SO_3)	EN 1744-1	[%]	S_1	0	0	0
Water-soluble chloride ion content (Cl^-)	EN 1744-1	[%]	-	0.014	0.014	0.014
Resistance to fragmentation (LA)	EN 1097-2	[%]	LA_{30}		28.6	

Table 3. Physical, mechanical and chemical properties of RCA-N

Property	Standard	Units of measurement and category, according to EN 12620		Fraction	
				4/8 mm	8/16 mm
Loose bulk density	EN 1097-3	[kg/m^3]		1278	1231
Particle density	EN 1097-6	[kg/m^3]		2350	2350
Water absorption*	EN 1097-6	[%]		2.4	2.2
Resistance to weathering	EN 1367-2	[%]	MS_{18}	1.0	0.5
Total sulphur content (SO_3)	EN 1744-1	[%]	S_1	0.04	0.04
Water-soluble chloride ion content (Cl^-)	EN 1744-1	[%]	-	0.007	0.007
Resistance to fragmentation (LA)	EN 1097-2	[%]	LA_{25}	23.1	

*Note: after 30 min in accordance with [5], [38].

Table 4. Physical, mechanical and chemical properties of RCA-A

Property	Standard	Units of measurement and category, according to EN 12620		Fraction	
				4/8 mm	8/16 mm
Loose bulk density	EN 1097-3	[kg/m^3]		1267	1221
Particle density	EN 1097-6	[kg/m^3]		2330	2330
Water absorption*	EN 1097-6	[%]		3.6	3.1
Resistance to weathering	EN 1367-2	[%]	MS_{18}	1.0	0.5
Total sulphur content (SO_3)	EN 1744-1	[%]	S_1	0.04	0.04
Water-soluble chloride ion content (Cl^-)	EN 1744-1	[%]	-	0.007	0.007
Resistance to fragmentation (LA)	EN 1097-2	[%]	LA_{25}	21.8	

*Note: after 30 min in accordance with[5], [38].

2.2 Mix proportion

The mixtures were designed to meet the SF2 consistency class criteria (according to The European Guidelines for Self-Compacting Concrete, Specification, Production, and Use, 2005), i.e., to provide the requisite slump-flow range of 660 to 750 mm.

Table 5 displays the component material quantities in 1 m^3 of the designed concrete mixtures, as well as the water-to-cement ratio and computed densities of concrete in the fresh state.

2.3 Experimental program

Mixing was performed in a laboratory mixer manufactured by "CONTROLS", model "TTM 140V". The temperature of the fresh concrete was measured using digital thermometers manufactured by "CONTROLS", model "82-D1226/A" and manufactured by "HANNA", according to EN 12350-1. The consistency assessment was conducted by using the slump-flow test, according to EN 12350-8, at the normal position of the cone during the test. Tests were performed using an Abrams cone, manufactured by "CONTROLS", model "C150/A" and a baseplate, manufactured by the same manufacturer, model "54 C0149/20". The entrapped air content was measured by the pressure gauge method, according to EN 12350-7. As all the utilized aggregates belong to the group of normal-weight aggregates, the value of G is negligible and was consequently set to zero in accordance with the standard. According to EN 12350-6, the density of fresh concrete was derived as a mean value measured on three cube-shaped samples with a 15cm edge.

The compressive strength was obtained as a mean value measured on three cube-shaped samples, with an edge of 15 cm, at the age of 28 days, according to EN 12390-3.

Table 5. Mixture compositions, water-to-cement ratio and density of designed SCC

Mix identity				SCC-NRA	SCC-NCA	SCC-NMA-I	SCC-NMA-II	SCC-RCA-N	SCC-RCA-A
Cement			[kg/m^3]	453	448	460	442	450	450
Limestone filler			[kg/m^3]	181	153	169	162	196	193
Aggregate	NRA	0/4 mm	[kg/m^3]	909	–	337	332	832	860
Aggregate	NRA	4/8 mm	[kg/m^3]	185	–	–	–	–	–
Aggregate	NRA	8/16 mm	[kg/m^3]	460	–	–	–	–	–
Aggregate	NCA	0/4 mm	[kg/m^3]	–	827	481	474	–	–
Aggregate	NCA	4/8 mm	[kg/m^3]	–	239	237	233	–	–
Aggregate	NCA	8/16 mm	[kg/m^3]	–	539	534	526	–	–
Aggregate	RCA	4/8 mm	[kg/m^3]	–	–	–	–	234	262
Aggregate	RCA	8/16 mm	[kg/m^3]	–	–	–	–	394	335
Admixture – HRWRA			[kg/m^3]	6.74	6.73	6.61	6.58	6.75	6.75
Effective water			[kg/m^3]	202.4	188.7	183.6	190.4	189.0	189.0
Additional water*			[kg/m^3]	–	–	–	–	14.3	19.9
Water-cement ratio			[–]	0.45	0.42	0.40	0.43	0.42	0.42
Density			[kg/m^3]	2397	2401	2408	2366	2316	2316

*Note: Aiming to reach the required consistency, an additional amount of water, which the recycled aggregate absorbs in 30 minutes, was added (in accordance with the guidelines [39], [40]).

In the absence of a suitable standard for testing SCC water absorption, stone material water absorption regulations were used, including the progressive immersion at air pressure method – EN 13755 [29] and the vacuum method – EN 1936 [30]. The collected data were used to calculate the saturation coefficient, determined as the ratio of water absorption obtained by the gradual immersion method to absorption obtained by vacuuming. Based on practical experience, this value may be utilized as an indirect measure of frost resistance in concrete [41]. The number of specimens required for testing one concrete mixture is nine for the gradual immersion method (Figure 3), and three for testing by vacuuming (Figure 4).

The destructive approach was used to test the frost resistance of concrete in accordance with the national standard SRPS U.M1.016 [31]. Each concrete mixture contains fifteen specimens, separated into the following groups:

- E_0 - reference specimens, whose compressive strength is determined on the day the test starts,
- E_I - reference specimens that were not exposed to freezing, whose compressive strength is determined on the day of equivalent age, compared to specimens that were exposed to 150 f/t cycles,
- E_{II} - reference specimens that were not exposed to freezing, whose compressive strength is determined on the day of equivalent age, compared to specimens that were exposed to 200 f/t cycles,
- M_{150} - specimens exposed to 150 f/t cycles and
- M_{200} - specimens exposed to 200f/t cycles.

The concrete surface's resistance to frost and de-icing salt was tested in accordance with SRPS U.M1.055 [32], which included 25 f/t cycles. Four prism specimens with dimensions of 15x7.5x7.5 cm were tested for the SCC-NRA, SCC-NCA, SCC-NMA-I, and SCC-NMA-II concretes, while three cube specimens with edge lengths of 15 cm were tested for the SCC-RCA-N and SCC-RCA-A concretes.

The freezing-thawing procedure was carried out for both test methods in the cooling chamber of the manufacturer "CONTROLS", model – 65-D1409, with a capacity of 50 kg and the ability to maintain a constant air temperature from -20^0C to +65^0C with an accuracy of $0,1^0$C and automatic air temperature registration.

3 The results

Table 6 shows the findings of testing concrete in its fresh form – temperature (T), density (D), entrapped air content (Ac), and the slump-flow (SF)

Figure 3. Water absorption by the test of gradual immersion at atmospheric pressure

Figure 4. Water absorption by vacuuming

Table 6. Test results of fresh concrete properties

Mix identity	T [^oC]	D [kg/m^3]	A_c [%]	SF [mm]
SCC-NRA	26	2396	1.1	760
SCC-NCA	25	2400	1.8	700
SCC-NMA-I	27	2408	2.0	650
SCC-NMA-II	27	2366	3.0	630
SCC-RCA-N	29	2316	4.2	660
SCC-RCA-A	29	2317	4.2	710

Table 7 illustrates the results of the compressive strength at the 28 days of age ($f_{c,cube,28}$), absorption by the gradual immersion method (A_b), absorption by vacuuming (A_p), and the calculated saturation coefficient (k_p).

Table 8 displays the mean compressive strengths of the reference specimens, tested on the first day of f/t cycles, fc, cyl(E0), specimens subjected to 150 and 200 f/t cycles, fc,cyl (M150) and fc,cyl (M200), and reference specimens of equivalent age, fc,cyl (EI) and fc,cyl (EII).

Table 9 displays the results of testing f/t resistance with de-icing salt as the least favorable values of the cumulative results of mass loss (L) and depth of damage (H_{FTR-S}) measurements, visual assessment, and damage degree. Figures 5-14 also illustrate the photographed surfaces of the specimens before and after the first and 25th test cycles, as well as after the NaCl solution was removed from the samples.

Table 7. Test results of compressive strength, water absorption and concrete saturation indicators

Mix identity	$f_{c,cube,28}$ [MPa]	A_b [%]	A_p [%]	k_p [-]
SCC-NRA	59.1	3.332	5.164	0.645
SCC-NCA	63.1	3.219	3.845	0.814
SCC-NMA-I	54.1	3.229	3.982	0.811
SCC-NMA-II	47.1	3.398	4.753	0.715
SCC-RCA-N	65.1	3.612	6.414	0.563
SCC-RCA-A	60.9	3.822	6.507	0.587

Table 8. Test results of freeze/thaw resistance

Mix identity	$f_{c,cyl}(E_0)$	$f_{c,cyl}(E_I)$*	$f_{c,cyl}(M_{150})$ [MPa]	$f_{c,cyl}(E_{II})$*	$f_{c,cyl}(M_{200})$
SCC-NRA	56.3	62.7	61.8	66.1	57.4
SCC-NCA	63.0	70.7	64.8	74.4	65.0
SCC-NMA-I	55.3	69.8	69.0	72.6	65.1
SCC-NMA-II	57.3	64.4	63.5	65.6	62.9
SCC-RCA-N	65.9	66.0	65.8	66.1	60.7
SCC-RCA-A	60.1	60.3	59.3	60.3	47.5

*Note: The equivalent age is lower than the calendar age and is determined according to the standard due to the slow increase in compressive strength during the freezing period.

Table 9. Test results of freeze/thaw resistance with de-icing salt

Sample mark	Number of f/t cycles	L [mg/mm²]	H_{FTR-S} [mm]	Visual assessment	Damage degree*
SCC-NRA	5	0.01	0.00	without surface changes	0 – without scaling
	10	0.02	0.00	without surface changes	0 – without scaling
	15	0.04	0.03	without surface changes	0 – without scaling
	20	0.07	0.05	local damage of cement mortar	0 – without scaling
	25	0.10	0.08	damage of cement mortar	1 – a little scaling
SCC-NCA	5	0.00	0.00	without surface changes	0 – without scaling
	10	0.00	0.00	without surface changes	0 – without scaling
	15	0.00	0.00	without surface changes	0 – without scaling
	20	0.01	0.00	without surface changes	0 – without scaling
	25	0.02	0.01	without surface changes	0 – without scaling
SCC-NMA-I	5	0.00	0.00	without surface changes	0 – without scaling
	10	0.00	0.00	without surface changes	0 – without scaling
	15	0.00	0.00	without surface changes	0 – without scaling
	20	0.01	0.01	without surface changes	0 – without scaling
	25	0.03	0.02	without surface changes	0 – without scaling

Sample mark	Number of f/t cycles	L [mg/mm^2]	H_{FTR-S} [mm]	Visual assessment	Damage degree*
SCC-NMA-II	5	0.00	0.00	without surface changes	0 – without scaling
	10	0.00	0.00	without surface changes	0 – without scaling
	15	0.00	0.00	without surface changes	0 – without scaling
	20	0.01	0.01	without surface changes	0 – without scaling
	25	0.03	0.02	without surface changes	0 – without scaling
SCC-RCA-N	5	0.00	0.00	without surface changes	0 – without scaling
	10	0.03	0.04	without surface changes	0 – without scaling
	15	0.08	0.10	local damage of cement mortar	0 – without scaling
	20	0.10	0.15	damage of cement mortar	1 – a little scaling
	25	0.12	0.20	damage of cement mortar	1 – a little scaling
SCC-RCA-A	5	0.01	0.00	without surface changes	0 – without scaling
	10	0.05	0.06	without surface changes	0 – without scaling
	15	0.06	0.12	local damage of cement mortar	0 – without scaling
	20	0.09	0.18	damage of cement mortar	1 – a little scaling
	25	0.12	0.25	damage of cement mortar	1 – a little scaling

*Note:0 – without scaling (L≈0mg/mm^2, H_{FTR-S}≈0 mm),1 – a little scaling (L≈0.2 mg/mm^2, H_{FTR-S}≈1.0 mm), 2 – medium scaling (L≈0.5 mg/mm^2, H_{FTR-S}≈4.0 mm),3 – severe scaling (L≈1.0 mg/mm^2, H_{FTR-S}≈10.0 mm).

Figure 5. SCC-NRA surface appearance before testing

Figure 6. SCC-NRA surfaceappearance after 25 f/t cycles with de-icing salt

Figure 7. SCC-NCA surface appearance before testing

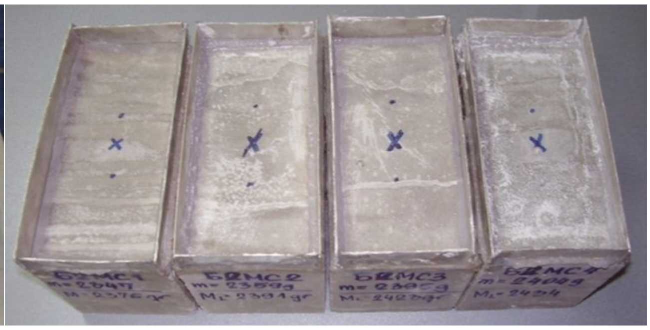

Figure 8. SCC-NCA surface appearance after 25 f/t cycles with de-icing salt

Figure 9. SCC-NMA-I surface appearance before testing

Figure 10. SCC-NMA-I surface appearance after 25 f/t cycles with de-icing salt

Figure 11. SCC-NMA-II surface appearance before testing

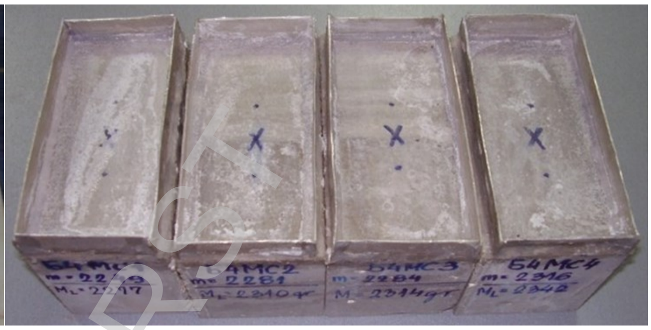

Figure 12. SCC-NMA-II surface appearance after 25 f/t cycles with de-icing salt

Figure 13. SCC-RCA-N and SCC-RCA-Asurfaces appearance before testing

Figure 14. SCC-RCA-N and SCC-RCA-Asurfaces appearanceafter 25 f/t cycles with de-icing salt

4 The results analysis and discussion

4.1 Freeze-thaw resistance

The frost resistance coefficient, calculated as the ratio of the mean value of the compressive strength of the specimens subjected to f/t cycles and the mean value of the compressive strength of the reference samples tested at the equivalent age, was used to assess freeze-thaw resistance. The results of testing the frost resistance revealed that for all of the concretes tested, the frost resistance coefficient is not below 75% (150 and 200 cycles) (Figure 15). According to the criterion [31], all tested types of concrete meet the quality requirements after 150 and 200 f/t cycles.

A more comprehensive analysis of the acquired results revealed that the type of aggregate used, the achieved compressive strength, and porosity all have an effect on the resistance of concrete to frost effects.

Frost resistance is the lowest in SCC-RCA-A. This concrete has great resistance up to 150 cycles, and after only 50 additional cycles, the indicator of its resistance has dropped by 24.1% (which is much higher than the 8.3% average decline of all other concrete types). Furthermore, after 200 cycles of frost exposure, the SCC-RCA-A specimens were physically destroyed, evaluated visually, and documented by mass loss (5%), implying that this concrete would not exceed the more severe frost resistance requirements. Results of water absorption support these findings. Regardless of the exceptionally beneficial value of

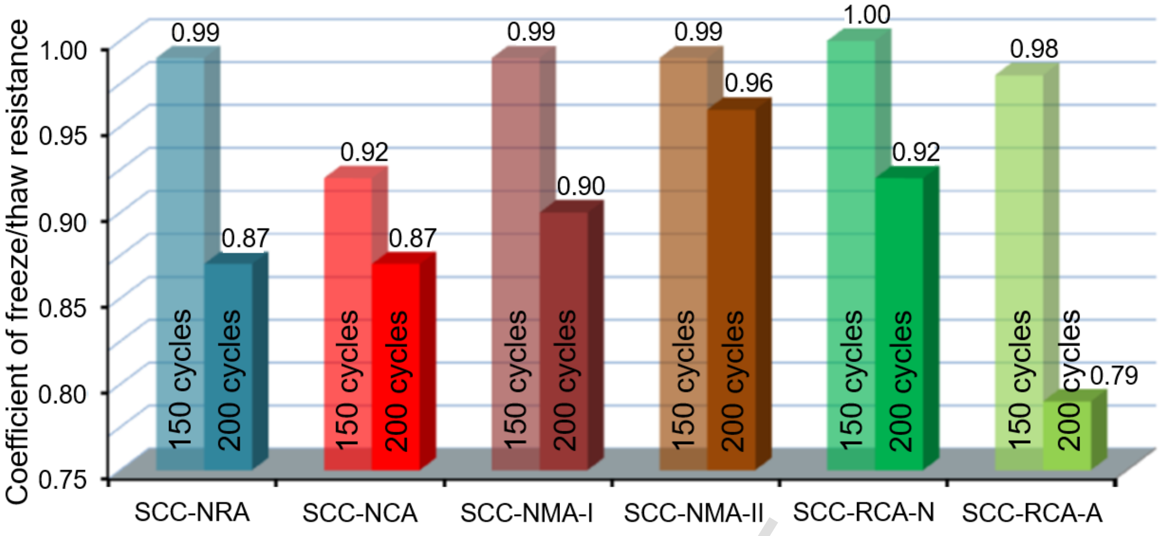

Figure15. The frost resistance coefficient (r_{FTR})

k_p, the largest values of water absorption (by both methods used) also contribute to the least desirable frost result after 200 cycles.

SCC-RCA-N exhibits a completely different behavior due to the effects of frost. This concrete has a high degree of resistance for both series of f/t cycles (150 and 200), with a decline in frost resistance coefficient (r_{FTR}) of about 8.3% between the 200 and 150 cycles. Except for SCC-RCA-A, this is close to the average abovementioned value. When compared to the SCC-NRA concrete, the SCC-RCA-N concrete is found to be more frost-resistant. SCC-NRA and SCC-RCA-N concretes were chosen for comparison as the original RCA-N grains employed are of river origin (the aggregates differ in the presence of old cement stone). This implies that, based on the investigated attributes, the presence of old cement stone in RCA is not a disadvantage of this aggregate. Furthermore, the pores of the old cement stone in RCA enabled the migration of water from the new transition zone and, therefore, the expansion of ice during freezing. Similarly, Öznur et al. [19] reported that the strength reductions after 300 f/t cycles for the application of 10, 20, and 30% pumice in the coarse aggregate are lower compared to reference concrete (due to the porous structure of pumice, a comparison with RCA can be made to some extent). In the case of SCC-RCA-N concrete, a higher porosity of the cement stone was obtained, implying a greater pore space (large pores and capillaries) for ice expansion and water migration during freezing (a lower k_p value). As a result, porosity also has an impact on concrete's resistance to frost. When comparing the concrete SCC-NCA, SCC-NMA-I, and SCC-NMA-II, the same rule applies.

In addition to the frost resistance coefficient of concrete after 200 cycles (r_{FTR}), the values of the 28-day compressive strength of concrete ($f_{c,cube,28}$), entrapped air content (A_c), and saturation coefficient (k_p) are illustrated in Figure 16 for easier comparison and calculation of mutual dependency. A following correlation for concretes produced with crushed aggregate and dominantly crushed aggregate (SCC-NCA, SCC-NMA-I and SCC-NMA-II) may be detected: greater frost

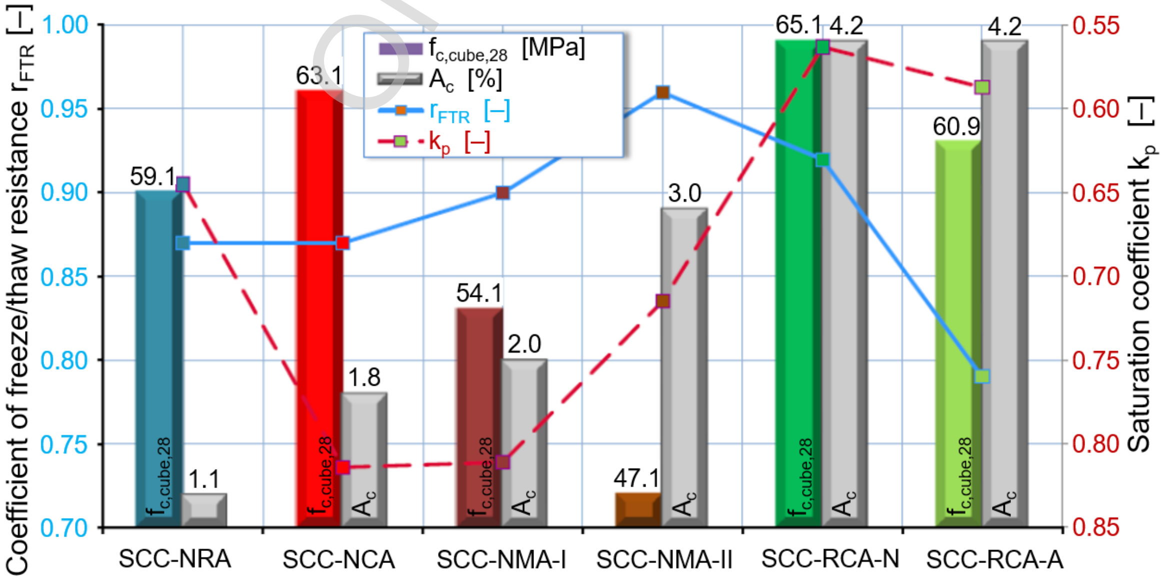

Figure16. Frost resistance coefficient as a function of influencing parameters

resistance – lower compressive strength – higher air content– lower saturation coefficient. Based on these observations, the effect of replacing a portion of the fine fraction of crushed aggregate with river aggregate in the tested concretes can be ignored.

When comparing concrete with river and crushed aggregate, it is clear that there is no substantial difference in frost resistance.

According to the preceding, due to the distinctive behavior of RCA during frost action,natural aggregates are the only ones that have a reliable one-parameter functional dependence on one of the influential properties of concrete. With the inclusion of RCA, such a strong correlation in functional dependence could not be achieved, as when only NA is addressed. The obtained compressive strength, in particular, has less of an impact on the frost resistance of RCA concrete than it does on NA concrete. Figure 17 displays the relationship between the frost resistance coefficient and the compressive strength of concrete made with natural aggregates, which can be explained by the following formula:

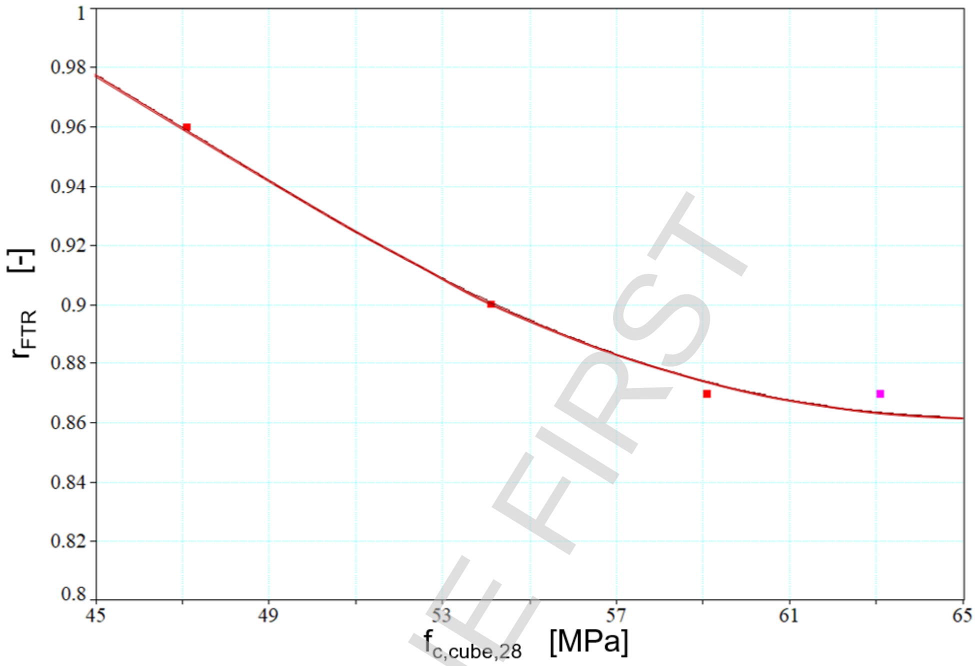

Figure 17. Frost resistance coefficient of concrete produced with NA as a function of compressive strength

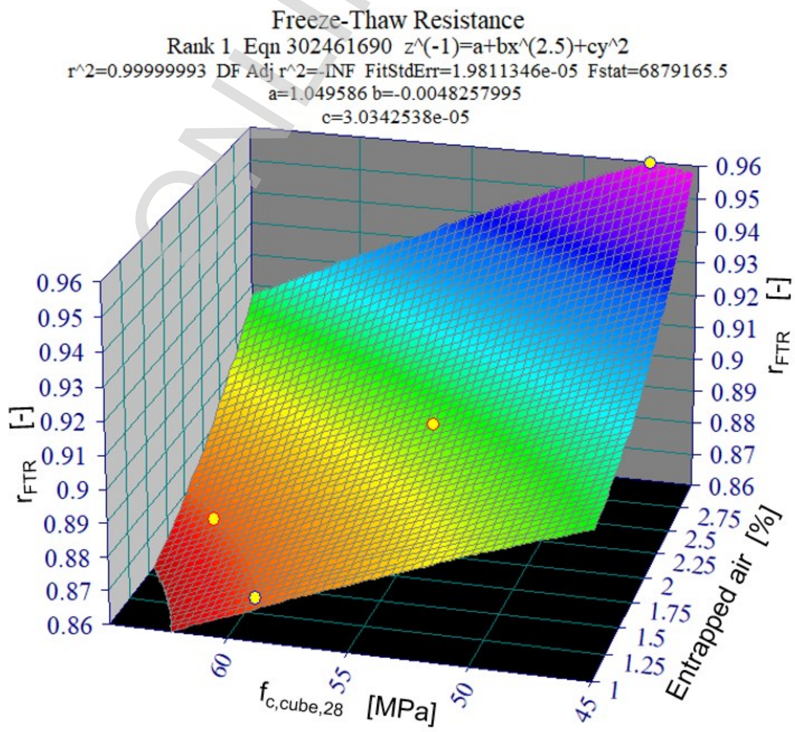

Figure18. Frost resistance coefficient of concrete produced with NA as a function of compressive strength and entrapped air content

$$r_{FTR} = -1.5827 \cdot 10^{-6} - 1.6796 \cdot 10^{-2} \cdot f_{c,cube,28} + 6.5056 \cdot 10^{-3} \cdot f_{c,cube,28}^{2} - 2.7345 \cdot 10^{-4} \cdot f_{c,cube,28}^{3} + 4.\dot{7} \cdot 10^{-6} \cdot f_{c,cube,28}^{4} - 3.8404 \cdot 10^{-8} \cdot f_{c,cube,28}^{5} + 1.1719 \cdot 10^{-10} \cdot f_{c,cube,28}^{6} \quad [–] \qquad (1)$$

R^2 = 0,9949326674

where:

r_{FTR}	–	frost resistance coefficient after 200 f/t cycles,
$f_{c,cube,28}$	–	compressive strength at the age of 28 days, MPa and
R	–	correlation coefficient.

Using the TableCurve 3D v4.0 software, which allows for the establishment of a two-parameter dependence of the analyzed property, a correlation between frost resistance, compressive strength, and percentage of entrapped air in fresh concrete produced with natural aggregates was obtained. Figure 18 depicts the aforementioned function, denoted by the expression:

$$r_{FTR} = \frac{1}{1.049586 - 0.004826 \cdot A_c^{2.5} + 3.03425 \cdot 10^{-5} \cdot f_{c,cube,28}^{2}} \quad [–] \qquad (2)$$

R^2 = 0,9999999273

where:

r_{FTR}	–	frost resistance coefficient after 200 f/t cycles,
A_c	–	entrapped air content, %,
$f_{c,cube,28}$	–	compressive strength at the age of 28 days, MPa and
R	–	correlation coefficient.

4.2 Resistance to the simultaneous action of frost and de-icing salt

All of the tested concretes met the requirements for the grade "frost resistant" after 25 f/t cycles in the presence of a 3% salt solution, according to SRPS U.M1.055.

A deeper review of the test findings revealed that the aggregate type influences the mass of scaled material and the depth of concrete surface damage caused by the simultaneous action of frost and de-icing salts. Crushed aggregate (concrete SCC-NCA) application yields the best test results – the so-called zero degree of damage, with no sign of surface alterations during visual inspection. A zero degree of damage was also noted by replacing part of the fine fraction of the crushed aggregate with river aggregate (concretes SCC-NMA-I and SCC-NMA-I), with no clear indications of changes in the surface during the visual evaluation. Only sporadic changes in shade and the "smoothness" of the concrete surface are observed under a microscope.

Furthermore, according to the analyzed effect, still good resistance is obtained by employing river aggregate (SCC-NRA), rated with the degree of damage "1" –localized damage to the cement stone is detected. Finally, although meeting the criteria for the grade "resistant" with the degree of damage "1", the SCC-RCA-N and SCC-RCA-A concretes have evident surface damages to the cement stone.

Given that these damages are distributed across the entire exposed surface of the concrete, SCC-RCA-N and SCC-RCA-A are unlikely to achieve the higher requirements for resistance to the simultaneous actions of frost and salt. At the same time, the type of RCA based on their origin is irrelevant, RCA-A delivered negligibly less favorable results. The aforementioned result is supported by the work of Bosque et al. [22], who employed a blend of RCA-N and RCA-A as RCA. Those concretes, like in the subject experiment, demonstrated greater resistance to the action of frost in the absence of de-icing salt than in the presence of salt.

Bosque et al. [22] employed a greater number of f/t cycles with de-icing agents (56 cycles) in their study. The concretes were found to be non-resistant for exposure classes XF2 and XF4.

5 Conclusion and recommendation

This paper aimed to explore the effects of aggregate type on the level of degradation of self-compacting concrete due to freeze-thaw action. The key conclusions that arise from the study are given below:

- The frost resistance of concrete is determined by the type of aggregate used. This mostly concerns the decision between recycled concrete aggregate of unknown origin and other, more often used types of aggregate (river, crushed, blend of river and crushed, and recycled concrete aggregate of known origin). The use of recycled concrete aggregate of unknown origin reduces frost resistance compared to the resistance of concrete to some of the other aggregate types. The frost resistance reduction occurs only after 200 f/t cycles, which was undoubtedly aided by the fact that this concrete is characterized by: 1) a greater amount of cement stone; 2) the greatest amount of absorbed water; and 3) the highest possibility that ingredients that reduce the quality of the aggregate remain to a lesser extent (it should be noted that the raw material used to produce this aggregate was recycled concrete). As a result, it cannot be envisaged that the use of recycled aggregate of unknown origin will meet the more demanding requirements for frost resistance. However, using all of the listed materials and the technology for producing self-compacting powder-type concrete, it was discovered that it was possible to produce concrete resistant to 200 f/t cycles.

- The choice of river and/or crushed or recycled material of known origin has no major effect on frost resistance. It has been demonstrated that the lower the compressive strength of the concrete, the higher the air content, and the lower the saturation coefficient, the better the resistance to frost impacts. It should be emphasized that these findings are specific to SCC and may not entirely apply to other types of concrete, such as typical normal-weight concrete.
- Very reliable functional correlations between frost resistance coefficient and compressive strength, as well as two-parameter functions between frost resistance coefficient, compressive strength, and entrapped air percentage, were established for concrete produced with natural aggregates.
- In terms of resistance to the simultaneous impacts of frost and deicing salt, all tested types of SCC meet the standard's requirements. However, the quality of the concrete surfaces differs once the test cycles are completed. It was discovered that the type of aggregate has the greatest impact. In comparison to the other concrete parameters studied in the experiment, it was established that the type of aggregate used had the largest influence on the degree of damage to the concrete surface.
- The following aggregate grades may be established in terms of favorability to frost resistance with and without de-icing salt: crushed natural aggregate, mixture of natural crushed and river aggregate, natural river aggregate, recycled concrete aggregate of known origin, and recycled concrete aggregate of unknown origin.
- Although it meets the prescribed requirements for frost resistance with and without de-icing salt, recycled concrete aggregate should be used sparingly. It is especially not recommended for the production of concrete used for structural repair, bridge structures, concrete pavements, elements that will be exposed to a direct sprinkling of deicing salt solutions during exploitation, hydrotechnical concrete in highly aggressive environments, and generally hydrotechnical concrete that is exposed to changing water levels in climates with cold climatic conditions in the winter period.

Acknowledgement

The paper presents the part of research realized within the project "Development of new binders based on agricultural and industrial waste from the area of Vojvodina for the production of eco-friendly mortars" financed by the Provincial Secretariat for Higher Education and Scientific Research in Vojvodina.

The authors gratefully acknowledge the resources and expertise provided within the experimental program by "The Institute for testing, assessment, and repair of structures doo" in Novi Sad, Serbia.

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