

Article

The Structural Use of Recycled Aggregate Concrete for Renovation of Massive External Walls of Czech Fortification

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Abstract: The use of recycled aggregate concrete is mainly negatively affected by its poorer mechanical and long-term properties. However, there are few structural applications for which recycled aggregates can be used. In this case study, the possibility of use as massive external reinforcement wall is verified. For this structural application, the most important characteristics are freeze–thaw resistance, and carbonation resistance and then the mechanical properties such as compressive strength. Durability characteristics of the materials have been tested and improved in the study. The mechanical properties and durability of recycled aggregated concrete have been verified and crystalline mixture has been used to improve durability. The specific structural application of the massive external reinforcement wall is for the renovation of the Czech WW2 concrete fortification, which is one of the most important cultural heritages of the Czech Republic of the 20th century. However, these buildings have not yet been professionally rebuilt, but this research project aims to change this trend. The thickness of the bunker wall is between 0.5 and 3.5 m (depending on the type of bunker) which leads to a huge amount of concrete and primary resources consumption; however, the security function is not necessary today, so the reconstruction could be provided by recycled aggregate concrete. The results showed a positive effect of the crystalline mixture on the essential properties of recycled aggregate concrete. Recycled aggregate concrete with a complete replacement of aggregate by recycled concrete or masonry aggregate is possible to use for the reconstruction of the Czech WW2 concrete fortification and save natural aggregate as a primary resource.

Keywords: recycled aggregate concrete; recycled concrete aggregate; recycled masonry aggregate; durability of recycled aggregate concrete; crystalline admixture; Czech WW2 concrete fortification



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1. Introduction

The main strengths and weaknesses of recycled aggregate concrete (RAC) are well known and have been described several times. The use of RAC for structural applications contributes to reducing primary consumption. However, RAC has mainly poorer and low quality properties compared to conventional concrete made of natural aggregate (NA). It is mainly about its mechanical properties, especially modulus of elasticity and its durability, which is related to water absorption. Consequently, RAC has limited structural applications around the world. In addition, there are three commonly known RAC types depending on the recycled aggregate used from construction and demolition waste (CDW).

The types of aggregate are recycled concrete aggregate (RCA) originating from waste concrete, recycled masonry aggregate (RMA) originating from waste masonry including red and clay bricks, mortars, plasters, etc., and mixed recycled aggregate (MRA) containing mixed demolition waste containing waste concrete, red and clay bricks, mortar, plaster, etc. Quality, composition, and properties, which depend on the demolition and recycling process [1–8], influence the possible use of RA [5,9]. The weak properties of the RAC are

mostly caused by the adhered mortar attached to the particles in the case of RCA, which influences the mechanical properties by the interfacial transition zone (ITZ—zone between new cement paste, old cement paste attached on aggregate surface, and aggregate) and high porosity. In the case of RMA, the weak properties are caused by porous and low strength materials such as red clay bricks, ceramic masonry blocks, aerated concrete, and natural aggregate with adhered mortar. The utilization limits depend on the type of aggregate and its specifications. Typically, one of the main problems of RA, in general is higher water absorption, mostly related to its porosity, whose properties negatively influence the durability of RAC. Generally, it could be said that the properties of RAC linearly depend on the replacement rate.

According to Czech standards [10], the coarse fraction (particle size greater than 4 mm) RCA with a concrete residue content greater than 90% can be used as aggregate for concrete in some specific environment. The maximum gravel replacement rate is 50% or 30%, respectively. On the contrary, it is not possible to use RMA efficiently, with its adverse impact on mechanical properties and durability, as an aggregate for concrete according to the standard. The durability characteristics of RAC, such as freeze–thaw and carbonation resistance, are usually weaker than conventional concrete due to the higher porosity and higher water absorption [11–13]. These facts apply to all three types of RA. However, RMA and MRA have not found satisfactory use yet.

Several physical and mechanical properties are examined before and after a certain number of freeze and thawing cycles. Subsequently, these properties are compared and the freeze–thaw resistance of concrete is estimated due to the results [4,14]. Generally, it was found that the freeze–thaw resistance decreases with the increasing replacement ratio [15] and is linearly correlated with the porosity and water absorption capacity [16]. As an example, in study [15], freeze–thaw resistance of two concrete classes were evaluated. The compressive strength of concrete class C35 decreases after 150 freeze–thaw cycles by between 7.1% and 10% and by 15.3% to 21.2% after 300 cycles; and for concrete class C60 the decrease in compressive strength ranges from 3.4% to 6.3% after 150 freeze–thaw cycles and from 11.9% to 15.9% after 300 cycles, respectively. Expectedly, the freezing process causes the pressure inside the pores of concrete to increase with an increase in the volume of water, which can lead to local cracks. The RAC freeze–thaw resistance is closely related to water absorption and very often influences the future use of concrete structural elements in environments. For internal utilization, the worse freeze–thaw resistance does not lead to more complication. However, for external structures which are in contact with the ground, the worse freeze–thaw resistance could cause an essential complication with the future use.

Concrete carbonation can be described as a physical–chemical process taking place on the surface of the concrete in reaction to atmospheric CO₂. The permeability, moisture content, cement content and water/cement ratio, mineral additions, aggregate type, and porosity of concrete are responsible for the resistance to carbonation of concrete. Furthermore, concrete carbonation is influenced by CO₂ content, relative humidity, and ambient temperature of the environment [13,17]. The resistance to concrete carbonation is an essential knowledge for the future use of reinforced concrete because it is necessary to protect reinforcement bars against corrosion. Concrete provides the passive coating of steel bars and can be destroyed by carbonation and chloride ingress. The corrosion of steel bars is negatively influenced by the RA in the concrete, depending on the level of RA, which decreases with an increasing amount of RA in the concrete. Furthermore, carbonation starts earlier in RAC compared to NAC [9,17–27]. The majority of world standard defines that the maximal replacement rate of coarse fraction in concrete is 30%, which correlates with general global findings that there are no significant changes for a concrete with the replacement rate of up to 30% [20,26]. Furthermore, the masonry content in RA worsens the resistance to carbonation resistance of concrete, leading to the an increase in the carbonation depth with increasing replacement rate of RMA [13]. On the contrary, the worse resistance to carbonation of RAC can bring environmental benefits due to the larger amount of atmospheric CO₂ in concrete [28,29].

In general, there are a few methods to improve the characteristics of fresh and hardened RAC. First, RAC characteristics can be positively influenced by the mixing process, for example, to compensate the absorbability of RA with additional water, added during mixing of concrete [30] or before mixing by presoaking the RA for 24 h [31]. Presoaking of RCA to compensate its absorbability (determined according to the water absorption test) using the two-stage mixing approach [32] positively influences the concrete mix which achieves greater compressive strength and durability [33–35]. The reason for this is that the water in the porous RA affects the internal healing effect. In this way, water is gradually released to further hydrate cement [35–37]. Furthermore, the possibilities for treating RA rather than pre-water treatment are carbonation, lime carbonation and immersion of acetic acid [38], bio-deposition treatment [39] or impregnation by cement paste, limewater or diluted water glass [40]. Additionally, carbon treatment could be used to separate the attached mortars and reduce the ITZ zone [41–43]. In previous studies, the possibilities to improve durability have been confirmed. First, the durability of the RAC could be improved by adding mineral admixtures [4] such as the optimal amount of fly ash, metakaolin, silica fume, or ground-granulated blast furnace slag [44–50] which are able to fill pores and therefore improve the microstructure [51]. Furthermore, the density and strength of the concrete could be enhanced by the ability of mineral admixtures to react with $\text{Ca}(\text{OH})_2$ to form an additional C–S–H gel. However, when the cement is partially replaced by mineral additives, the pH of concrete is reduced, which leads to worsening of carbonation resistance [13]. However, low calcium bentonite has been confirmed as a potential partial replacement for Portland cement with a positive influence on the mechanical properties and durability of RAC [52]. Another possibility is the use of superplasticizers leading to crystal growth, which causes a denser concrete structure, which may reduce the depth of RAC carbonation at an early age, as described [53], but fortunately this effect weakens over time. Third, the other way to reduce the carbonation depth is by lowering the w/c ratio [13]. In addition, the durability of the RAC could be improved by adding fibers, such as Nano- SiO_2 or Basalt fibers [47,54]. Finally, the freeze–thaw resistance and carbonation resistance, which are the essential characteristics of RAC used for external reinforcement wall, decrease as a result of the higher porosity and water absorption capacity of RA. Therefore, in this investigation, the crystalline admixture, whose ability to improve freezing–thawing and carbonation resistances was verified in a previous study [55], was used.

The use of RAC has also been tested in structural applications. RCA is mostly tested and used as a backing layer in road structures [7]. However, the application for building construction has also been evaluated. RA was proven to be a possible replacement for NAs in structural concrete. The decrease in mechanical properties has been found to be marginal compared to conventional solutions [56]. For the precast concrete beams [57], paving with precast concrete paving [58], masonry blocks for low-rise houses [59] and paving blocks or hollow tiles [60], the partial or complete replacement of aggregate by RMA was verified. In general, it has been found that the most affected property of RAC, which is essential for structural utilization of RAC, is the elastic modulus [61], while the compression and tensile strengths were maintained to acceptable values also for mixtures with full substitution of NA. The maximal acceptable replacement rate for RCA and RMA has been stated as up to 35% of the coarse fraction in the concrete mixture, which corresponds to the standards for some environmental and strength classes. On the contrary, the RA in a concrete mixture could have a positive influence in the case of external wall which is the increase of thermal resistance of the material [59,62,63].

The concrete fortifications of the Czech Republic were built before the Second World War along the defense line of the former Czechoslovak border to protect it against Hitler's army. Today, a few bunkers are registered as a national cultural heritage, which must meet the requirements of historical authenticity. The protection and preservation of historical monuments is an important approach for future generations. The Czech concrete fortifications contain thousands of small (light) and hundreds of large (heavy) concrete fortifications (bunkers) which were built in the highest class of resistance (of that time)—the ceiling

thickness of heavy bunkers is mostly: 2.6 m, front wall: 2.75 m, back wall: 1.25 m, and the compressive strength of the concrete was around 45–50 MPa. Some of these bunkers are listed as Czech national technical monuments, which ensures their protection [64].

One of the typical elements of the reinforced concrete fortifications built in Europe in the 1930s and 1940s was the cloches, the steel structural element, which was used for light or heavy machine guns. After the occupation of Czechoslovakia by Hitler's troops, most of them were removed mostly by using explosives and the steel was used for war production of Nazi Germany. During the explosion, part of the fortresses was damaged—part of the concrete structure was completely destroyed (Figure 1). The cloches used for the reconstruction of the fortifications are newly made of reinforced concrete [65].



Figure 1. Damaged heavy bunker N-S 84 "Voda" in the town of Náchod.

The damaged part of the bunker will be necessary to build again for the completion of construction. Thickness of the structures must be preserved for authenticity. For these reasons, the recycled aggregate concrete (RAC) mixtures were designed and tested for this specific use, because it is not necessary to use concrete with natural aggregate, provided that the fortifications no longer serve to defend the borders. Recycled concrete aggregate (RCA) and recycled masonry aggregate (RMA) from construction and demolition waste (CDW) could be used as aggregate for concrete used for this application. However, the properties of recycled concrete aggregate concrete (RCAC) and recycled masonry aggregate concrete (RMAC) must be verified for suitability of use for this application. For this reason, the possibility of improving the crystalline admixture for the better properties of concrete in connection with the further use for massive external reinforced concrete walls was verified.

The main objective of this study is to find optimal RAC mixture for the massive reinforced concrete external walls. This type of construction is possible to use as retaining wall, basement wall, acoustic barrier wall, or for reconstruction of Czech historical fortification as in this case. As was written before, for the massive concreting of the destroyed parts of heavy bunkers it is not necessary to use conventional concrete with primary raw materials due to the non-safe function. There are a few requirements for the concrete used: Sufficient load-bearing capacity to transfer loads from the cloche; water absorption and sufficient

freeze-thaw resistance due to the outdoor environment of the utilization; knowledge of the carbonation depth because of the steel reinforcement of the bunker walls. This study builds on the previous study [55] in which the durability of RMAC was improved by crystalline admixture. In this study, the RCAC mixtures improved by crystalline admixture was also tested, due to the possibility of the use of waste concrete from damaged parts of the bunkers. The main goal was to find the optimal solution for massive concrete external walls reinforced with steel bars, in this case for concrete fortification. The improvement of the RAC physical, mechanical properties, freeze-thaw resistance, and carbonation resistance by crystalline admixture was proven by laboratory measurements. The practical verification in situ follows. The novelty of this approach is given by the possible considered use of RAC mixture improved by the crystalline admixture for the future specific solution of the massive reinforced concrete external walls.

2. Materials and Methods

In total, six RAC mixtures were studied to optimize the concrete mixture for massive external reinforced concrete wall used to reconstruct damaged parts of bunkers. The NAC mixture with NA was also prepared for comparison. Crystalline admixtures (X) are inherently hydrophilic because they are easily able to react with water and have been added to four different mixtures in different amounts. The crystalline admixtures react with cement and water, which leads to resistance to water penetration through an increased density of calcium silicate hydrate. It is necessary to achieve the reaction of various chemical components to perform the correct function of the waterproofing effect of the crystalline material in the porous concrete system [66]. In previous experimental measurements [55,67–71], the possibility of improvement and its positive influence on the durability were verified. For example, in some cases, penetration depths can be reduced by nearly 50% [72].

The examined concrete mixtures were manufactured from RMA and RCA and three crystalline admixture (X) contents 0%, 1.5%, and 3% (to the weight of cement). These mixture were compared with the reference mixture with a natural aggregate and without crystalline admixture. The physical, mechanical, and durability properties were tested. Compressive and flexural strengths, modulus of elasticity, capillary water absorption, freeze–thaw resistance, and carbonation resistance were examined at age 28 days.

2.1. Recycled Aggregate

Generally, the density of RA (coarse and fine) is lower compared to NA (gravel and sand), and ranges from 1900 to 2400 kg/m³ [73] for RCA and 1800 to 2300 kg/m³ for RMA [74–76], respectively. The previously measured water absorption of RMA has been up to 20% and RCA up to 15% for all tested fractions, respectively.

In this study, three fractions (0/4, 4/8, and 8/16 mm) NA, RCA, and RMA from separated construction and demolition waste by a Czech recycling center were used for concrete manufacturing. The RCA contained more than 90% of waste concrete and the red clay bricks and RMA contained more than 70% of the waste masonry, waste concrete, and unbound aggregates (see Figure 2).

The examined properties of both types of aggregate differed from those of NA and between each other. The water absorption capacity of RCA was up to 6%, which is maximum five times higher than NA. However, the water absorption of RMA was up to 10 times higher than that of NA. The dry density of RA was lower compared to NA, with a decline up to 15% for RCA and up to 25% for RMA. In comparison, the verification of both physical properties shows similar results published in previous studies. As a result of the fact that RA contains more fine particles, the water absorbability of RA is higher, and consequently the granulometry of RA differs in comparison with NA. However, the granulometry of both types of aggregate meets the requirements in standard for all fractions examined [77] (see Figure 3). Therefore, the basic properties of the aggregates (see Table 1),

with the high importance of the design of the mixture, are presented to show the differences in the materials used for the preparation of the concrete mixtures.

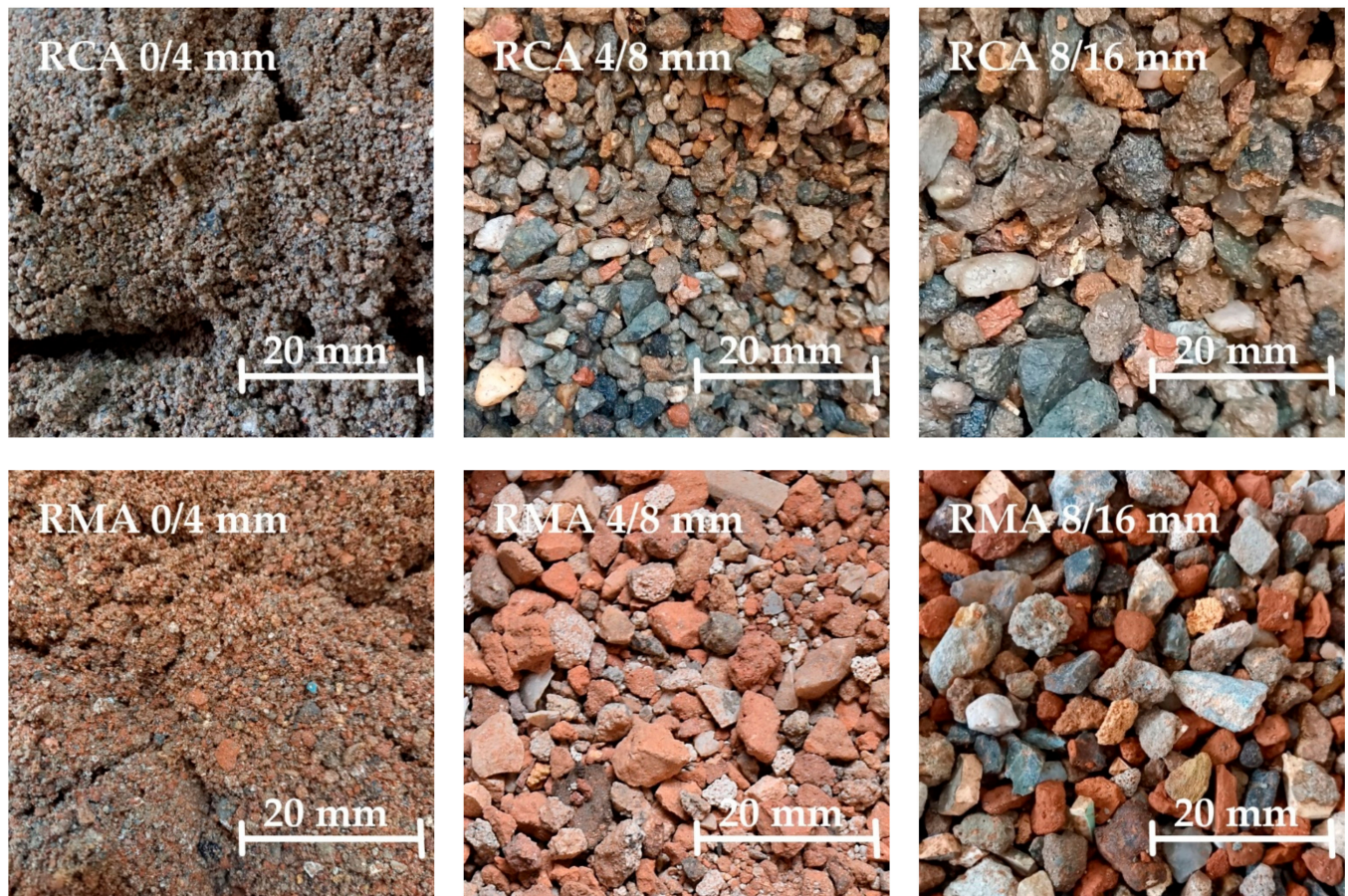


Figure 2. Recycled concrete aggregate (RCA) and recycled masonry aggregate (RMA) of fraction 0–4, 4–8 and 8–16 mm.

Table 1. Physical properties of particular fractions of used aggregates.

Types of Recycled Aggregate	Grading (mm)	Content of Finest Particles	Oven-Dried Particle Density		Water Absorption Capacity (%)	
		f (%)	ρ_{RD} (kg/m^3)	σ	WA ₂₄ (%)	σ
Natural aggregate (NA)	0–4	2.0	2570	81	1.0	0.0
	4–8	0.1	2530	12	1.7	0.3
	8–16	0.2	2540	12	1.9	0.2
Recycled concrete aggregate (RCA)	0–4	1.2	2240	21	4.6	0.3
	4–8	0.2	2330	97	6.1	1.1
	8–16	0.2	2340	46	5.0	0.3
Recycled masonry aggregate (RMA)	0–4	1.0	2320	132	6.6	0.8
	4–8	1.2	1910	87	15.6	2.2
	8–16	0.2	2050	33	10.7	1.4

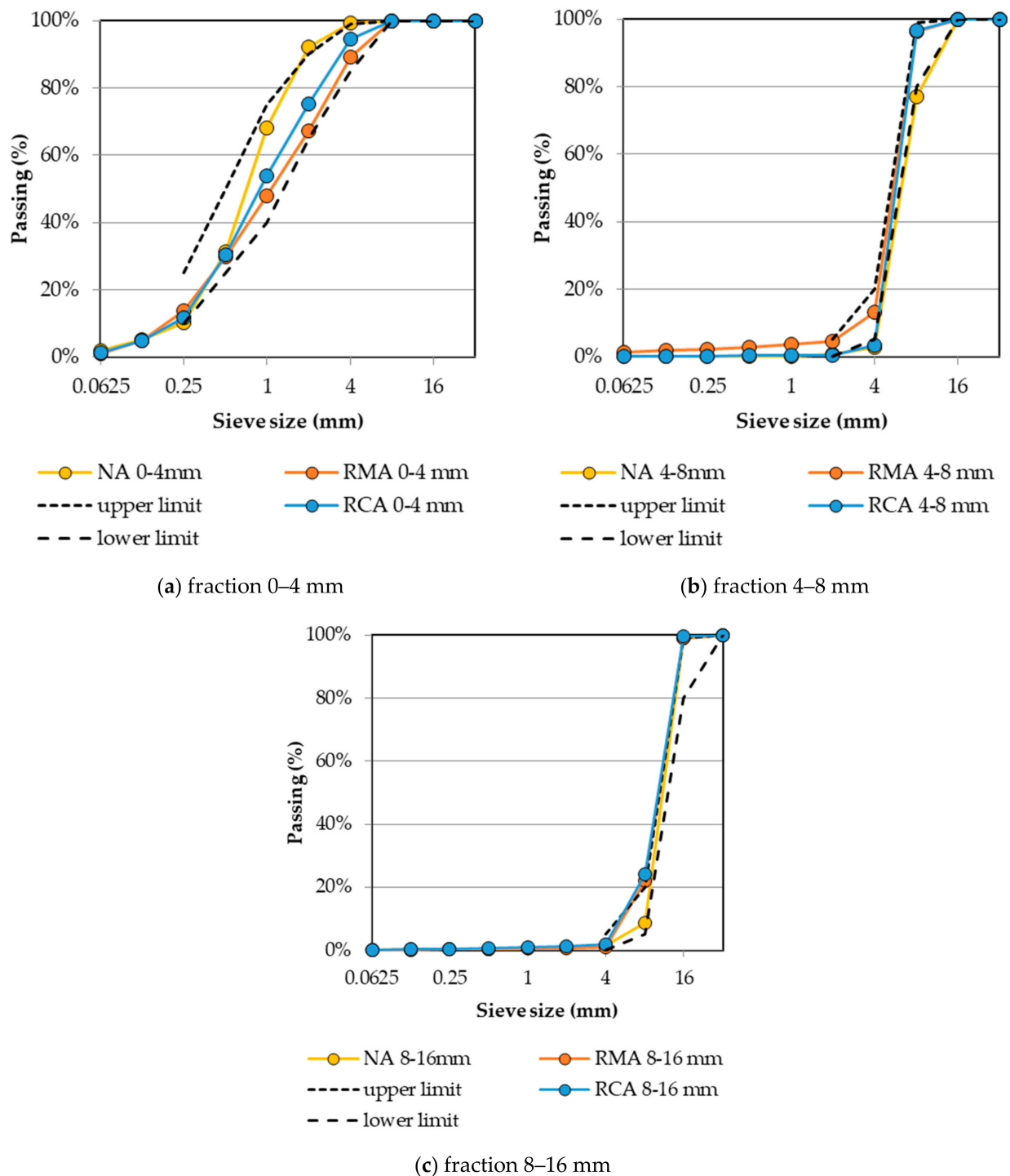


Figure 3. Sieving curves for natural aggregate, recycled masonry aggregate with limits defined in the standard [77] used in concrete mixtures.

2.2. Recycled Aggregate Concrete Mixtures

The verification of the possibility of the use RAC for the massive external reinforced concrete wall was carried out by the laboratory measurements on seven concrete mixtures. The mixtures had the same amount of cement CEM I 42.5 R 260 kg/m³ and same effective w/c ratio 0.65, which is calculated without additional water used for compensation of the water absorption of RA. All types of aggregate have same particle size which was till 16 mm. The granulometry of the aggregate was used to optimize the skeleton of the mixture according to the particle size distribution curve developed by Bolomey. The additional

water for RAC mixtures was calculated as a difference of RA water absorption after 10 min and current water content in aggregate particles. In a previous investigation [55], the positive effect of a higher effective w/c ratio of 0.65 on the influence of the crystalline admixture was found. Seven mixtures were manufactured in total (see Table 2): (i) Two mixtures RCAC X0 and RMAC X0 with two different types of RA were prepared without the crystalline admixture; (ii) four mixtures RCAC and RMAC X1 contained 1.5% (of cement weight) of crystalline admixture and mixtures RCAC X3 and RMAC X3 contain 3% (of cement weight) of crystalline admixture; (iii) the reference mixture with only NA without crystalline admixture was prepared for comparison.

Table 2. Concrete mix proportion, per cubic meter.

Designation	NAC—REF	RCAC X0	RCAC X1	RCAC X3	RMAC X0	RMAC X1	RMAC X3
Cement (kg/m)	260	260	260	260	260	260	260
Water (kg/m ³)	169	190	190	190	219	219	219
Sand (kg/m ³)	710	0	0	0	0	0	0
NA 4/8 (kg/m ³)	520	0	0	0	0	0	0
NA 8/16 (kg/m ³)	609	0	0	0	0	0	0
RMA 0/4 (kg/m ³)	0	805	805	805	807	807	807
RMA 4/8 (kg/m ³)	0	67	67	67	54	54	54
RMA 8/16 (kg/m ³)	0	775	775	775	653	653	653
Crystalline admixture (kg/m ³)	0	0	5	9	0	5	10
w/c eff (-)	0.65	0.65	0.65	0.65	0.65	0.65	0.65
w/c (-)	0.65	0.73	0.73	0.73	0.84	0.84	0.84

Physical, mechanical, and durability properties were tested on samples $100 \times 100 \times 400 \text{ mm}^3$, $150 \times 150 \times 150 \text{ mm}^3$, and $100 \times 100 \times 100 \text{ mm}^3$ at age 28 according to valid Czech standards.

The content of crystalline admixture is shown in Table 3, and compared with cement and silica fume (see Table 3).

Table 3. Composition of crystalline admixture compared with cement and silica fume.

Designation	CaO	SiO ₂	Fe ₂ O ₃	Na ₂ O	Al ₂ O ₃	MgO
Cement (%)	61.9	20.2	3.0	0.2	4.7	2.6
Silica fume (%)	0.4	94.5	0.1	0.1	0.9	1.6
Crystalline admixture (%)	85.3	9.7	1.9	1.5	0.6	-

2.3. Evaluation Methodology

The evaluation methodology corresponded with the previous investigation for the possibility of comparison [55]. Five samples were tested for each mixture for each evaluated property in this investigation. Control samples were tested at age 28 days for all properties determined. The curing environment of the samples differs depending on the evaluation methods. The determination of mechanical properties was carried out by Controls MCC8 50-C8422/M (Controls Group, Milan, Italy) according to the relevant standards. The freeze–thaw resistance was tested by cyclic loading by freezing and thawing cycles using KD 20 testing equipment developed by the Ecofrost company (Olomouc, Czech Republic) to test the frost resistance according to the Czech standard CSN 73 1322 (1969). After a defined number of freezing–thawing cycles, the samples were tested to determine their dimensions, weight, bulk density, and dynamic modulus of elasticity and flexural strength. Carbonation resistance was tested in a laboratory incubator with air circulation with CO₂ atmosphere CO2CELL (MMM group, Munich, Germany). The samples were placed in an environment with a concentration of $3.0 \pm 0.2\%$ CO₂ for 28 days.

3. Results and Discussion

3.1. Physical Properties

As was found in previous studies [2,78], the water absorption of concrete fundamentally affects its durability. For this reason, the capillary water absorption was determined to determine its impact. The results of the density and capillary water absorption evaluation of all tested concretes are shown in Table 4. The RAC density was lower than the NAC and the maximum decline was 15%. The density evaluations did not show any significant correlations between the amount of crystalline admixture in the RAC. The measured densities for all RAC mixtures are slightly the same, the densities of RCAC mixtures are slightly higher compared to RMAC, the maximal decline was 6%. RAC capillary water absorption examinations showed higher values than NAC (see Figure 4). In addition, the capillary absorption of RCAC was higher than that of the RMAC mixture. The results show the positive influence of crystalline admixture on capillary water absorption for concrete with both types of RA. However, the increase in capillary water absorption of concretes with RA is once to twice higher compared to ordinary concrete (NAC-REF) which is without crystalline admixture. The measured values showed the lower capillary water absorption for the RMA mixture and 1.5% of crystalline admixture (to the cement content) corresponding to the measured density which was the highest for the RMAC X1. The results of the water absorption and density tests of the RAC and NAC confirmed the results of previous studies [2,78–81].

Table 4. Average values of results of physical properties of concrete, including standard deviation.

Recycled Concrete Mixture Designation	Dry Density		Capillary Water Absorption	
	(kg/m ³)	σ	(kg/m ²)	σ
NAC—REF	2280	18	3.34	0.8
RCAC X0	1940	10	14.45	0.8
RCAC X1	2040	11	13.39	0.7
RCAC X3	1970	15	11.40	0.3
RMAC X0	1935	17	10.13	0.5
RMAC X1	1935	9	8.56	0.6
RMAC X3	1930	9	9.65	0.2

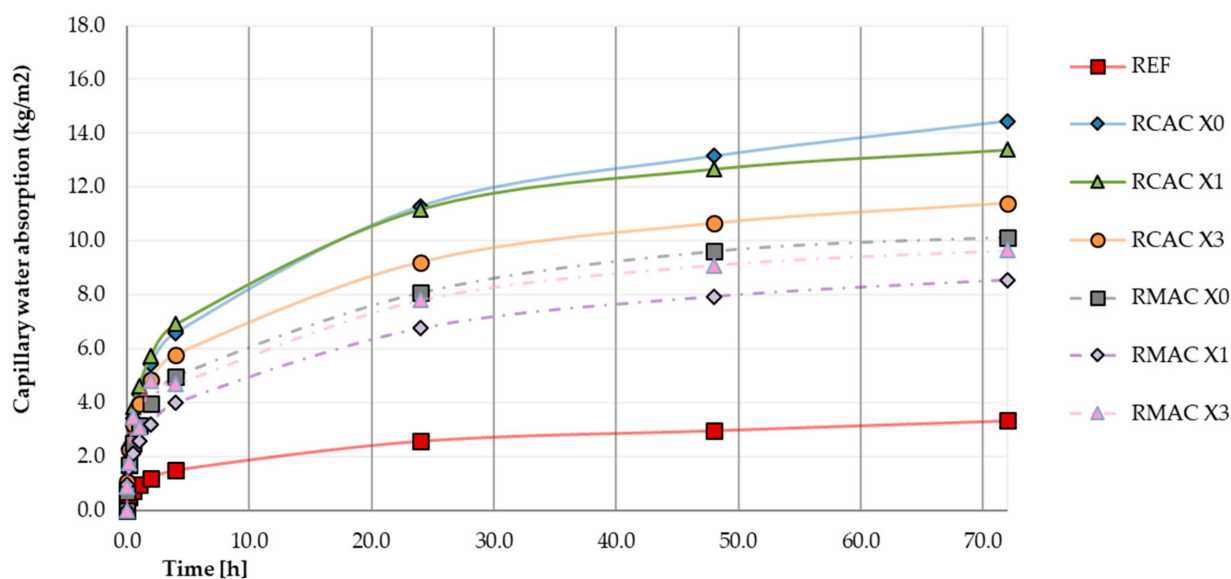


Figure 4. Comparison and progression of capillary water absorption of NAC, RCAC, and RMAC.

3.2. Mechanical Properties

The mechanical properties of concrete influence its possible utilization in the construction industry. As an essential mechanical property for the massive reinforced concrete wall, compressive strength was established. Strengths (compressive and flexural) and modulus of elasticity (static and dynamic) of all concretes were tested before the durability test due to the knowledge of basic material properties (see Table 5). The compressive strength, mostly negatively influenced by the recycled aggregate content [1,30,31,57,79,82–102], is one of the determining properties of concrete for its structural use. The compressive strength, evaluated at age 28 days on the cubic samples, showed lower values for all tested compared to NAC and furthermore, the lower measured values for RCAC mixtures in comparison with RMACs. The maximal decrease in the compressive strength was 55% (see Figure 5). The test results showed an increase of compressive strength with the crystalline admixture, especially for both mixtures with 1.5% (to cement content), with increase 30% for the RCAC mixtures and 20% for RMAC mixture, respectively. The highest compressive strength was measured for the RMAC X1 with a decline only up to 20%.

Table 5. Average values of results of mechanical properties of concrete, including standard deviation.

Recycled Concrete Mixture	Compressive Strength		Flexural Strength		Static Modulus of Elasticity		Dynamic Modulus of Elasticity	
	28 days							
Designation	(MPa)	σ	(MPa)	σ	(GPa)	σ	(GPa)	σ
NAC—REF	33.3	2.5	6.2	0.2	36.7	1.4	37.6	1.3
RCAC X0	14.9	0.2	2.8	0.1	13.2	0.3	18.6	0.6
RCAC X1	19.5	1.0	3.6	0.6	15.5	2.3	23.0	1.2
RCAC X3	16.8	0.4	3.0	0.3	14.0	0.5	19.5	1.0
RMAC X0	22.5	2.7	5.1	0.2	14.9	0.4	17.7	2.0
RMAC X1	27.3	0.6	4.9	0.2	15.2	0.0	21.1	1.5
RMAC X3	24.2	0.2	4.8	0.4	15.6	0.9	19.9	1.2

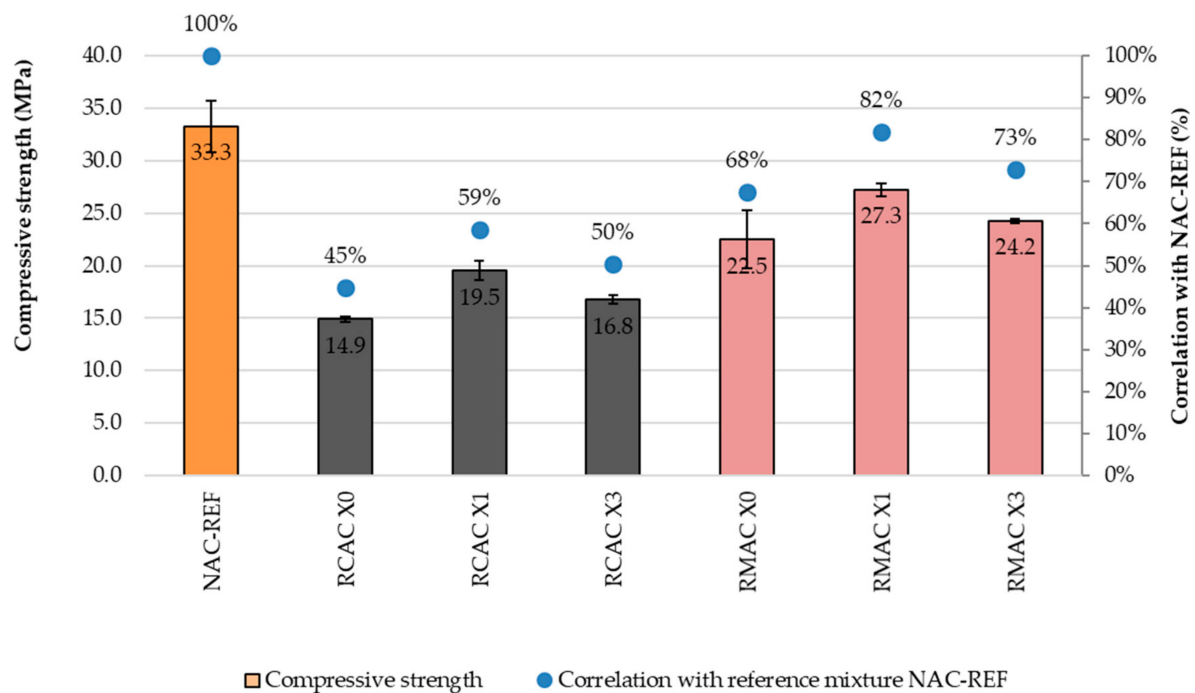


Figure 5. Comparison of compressive strength of NAC, RCAC, and RMAC at age 28.

The flexural strength of RCAC mixtures was also lower in comparison with NAC and RMAC. The maximal decline was measured for the RCAC X0 mixture which was more than 50%, while the lowest decline of RMAC X0 mixture was 18%. The addition of the crystalline admixture positively influences the flexural strength of RCACs; however, it is not the same for the RMACs.

As reported in previous studies [61,103,104], the static modulus of elasticity is the most negatively influenced mechanical property while replacing RA in concrete mixture. It was found that the decline is mostly more than 50%, for full replacement rates that was applied in this case too. The decrease in static modulus of elasticity ranges between 68% and 74%. This finding fundamentally limits the structural usage of RAC; however, it is not so essential for massive reinforcement walls. There is no significant impact of crystalline admixture on the static modulus of elasticity.

The second most affected property of concrete was found to be the dynamic modulus of elasticity which shows a decline between 40% and 50%. However, in this case, the positive impact of crystalline admixture was shown on the dynamic modulus of elasticity. As the most efficient addition was found, 1.5% of the crystalline admixture (to cement content) corresponds with the results of compressive strength and density; however, the density directly influences the dynamic modulus of elasticity measured by ultrasonic.

In conclusion, the results of the mechanical properties of RACs, especially the compressive strength, which is essential for planned structural application, show their suitability to be used for the massive external reinforced concrete wall specifically for the bunkers in this case.

3.3. Durability Properties

Generally, the use of RAC is influenced by its durability as an essential assumption to maintain the performance of concrete throughout the useful life of a structure. It was found that, due to the poor durability of RAC, it is useful to use it in internal or stable environments such as internal walls or foundation structures, respectively. This study deals with two durability properties that are essential for planned structural use, with the prediction of the positive influence by adding the crystalline admixture. Freeze–thaw resistance was evaluated due to the external use of the planned structure, which will not be treated. Additionally, resistance to carbonation was determined considering the knowledge of carbonation depth to design the reinforcement.

3.3.1. Freeze–Thaw Resistance

Frost resistance is the essential index of the durability of external concrete structures. As written before, the freeze–thaw resistance is usually negatively influenced when NA is replaced by RA, which is caused by porosity, water content, and aggregate types [4] and moreover the environmental conditions. The resistance to frost is evaluated by the freezing and thawing cycles where concrete properties such as dynamic modulus of elasticity, weight loss rate, and flexural strength loss rate are measured after exposure to defined number of freeze–thaw cycles.

In this case, the dynamic modulus of elasticity and flexural strength was evaluated for samples exposed to freezing and thawing cycles. The dynamic modulus of elasticity was measured by the ultrasonic method after 0, 25, 50, 75, and 100 cycles (see Table 6), where 0 cycles were measured at age 28 days before placing samples in the freezing–thawing chamber. A flexural strength examination of 0 to 100 cycles was also carried out. The frost resistance coefficient was determined as the ratio of two values measured before and after a defined number of freeze–thaw cycles (see Table 7). Concrete is determined as frost resistant when the frost resistance coefficient does not decrease below the value 0.75. The frost resistance coefficient determined from the dynamic modulus of elasticity and flexural strength and its linear development trend are shown in Figure 6.

The results of the dynamic modulus of elasticity tested during the freezing and thawing cycles by the ultrasonic method show stable results of all concretes tested during the whole evaluation except for RCAC X1. Therefore, the positive influence of the crystalline admixture is not clearly visible. On the contrary, the slightly positive impact of the crystalline admixture on the RMAC mixtures is shown by the evaluation of the flexural strength after the freeze–thaw cycles. In general, the results showed similar or slightly increasing properties after the freeze–thaw cycles as before freeze–thaw cycles for almost all mixtures (except for RCAC X1). This could be possibly caused by the additional hydration of cement due to the water contained in RA, the so-called self-healing. Furthermore, the crystals of frozen water could grow into the RA with high porosity. The capillary water absorption, which is affected by the addition of crystalline admixture, shows a slight correlation for the RMAC mixture, where the similar trend is visible between the frost resistance coefficient and the capillary water absorption (see Figure 7). However, this was not verified for the RCAC mixture, where the mixture with 1.5% crystalline admixture was not frost resistant and therefore does not follow the trend. However, this could be caused by the unknown aspect, whose finding will be necessary to answer in the following study. In conclusion, the results of the frost resistance of RACs showed their suitability for use for the massive external reinforced concrete wall specifically for the bunkers in this case.

Table 6. Dynamic modulus of elasticity measured by ultrasonic method and frost resistance coefficient determined from the dynamic modulus of elasticity after freezing and thawing cycles.

Recycled Concrete Mixture	Dynamic Modulus of Elasticity (GPa) + Frost Resistance Coefficient (-)										Freeze–Thaw Resistance Cycles
	0 Cycles	25 Cycles		50 Cycles		75 Cycles		100 Cycles			
Designation											
NAC—REF	37.6	36.5	0.97	36.6	0.97	35.9	0.95	37.0	0.98	100	
RCAC X0	24.2	19.9	0.82	22.3	0.92	23.1	0.95	21.5	0.89	100	
RCAC X1	27.6	21.1	0.76	11.5	0.42	8.5	0.31	3.1	0.11	25	
RCAC X3	24.6	23.4	0.95	22.9	0.93	23.7	0.96	23.0	0.93	100	
RMAC X0	23.6	20.8	0.88	19.1	0.81	21.0	0.89	21.4	0.91	100	
RMAC X1	23.0	19.2	0.84	16.8	0.73	18.9	0.82	20.4	0.89	100	
RMAC X3	23.1	19.0	0.82	18.6	0.81	18.3	0.79	20.1	0.87	100	

Table 7. Flexural strength and frost resistance coefficient determined from flexural strength after freezing and thawing cycles.

Recycled Concrete Mixture	Flexural Strength				Frost Resistance Coefficient (-)
	(MPa)		σ		
	0	100	0	100	
NAC—REF	6.2	6.9	0.2	0.1	1.13
RCAC X0	2.8	4.2	0.1	0.3	1.48
RCAC X1	3.6	1.0	0.6	0.6	0.29
RCAC X3	3.0	4.0	0.3	0.1	1.37
RMAC X0	5.1	4.3	0.2	0.5	0.85
RMAC X1	4.9	4.9	0.2	0.4	1.00
RMAC X3	4.8	5.0	0.4	0.3	1.06

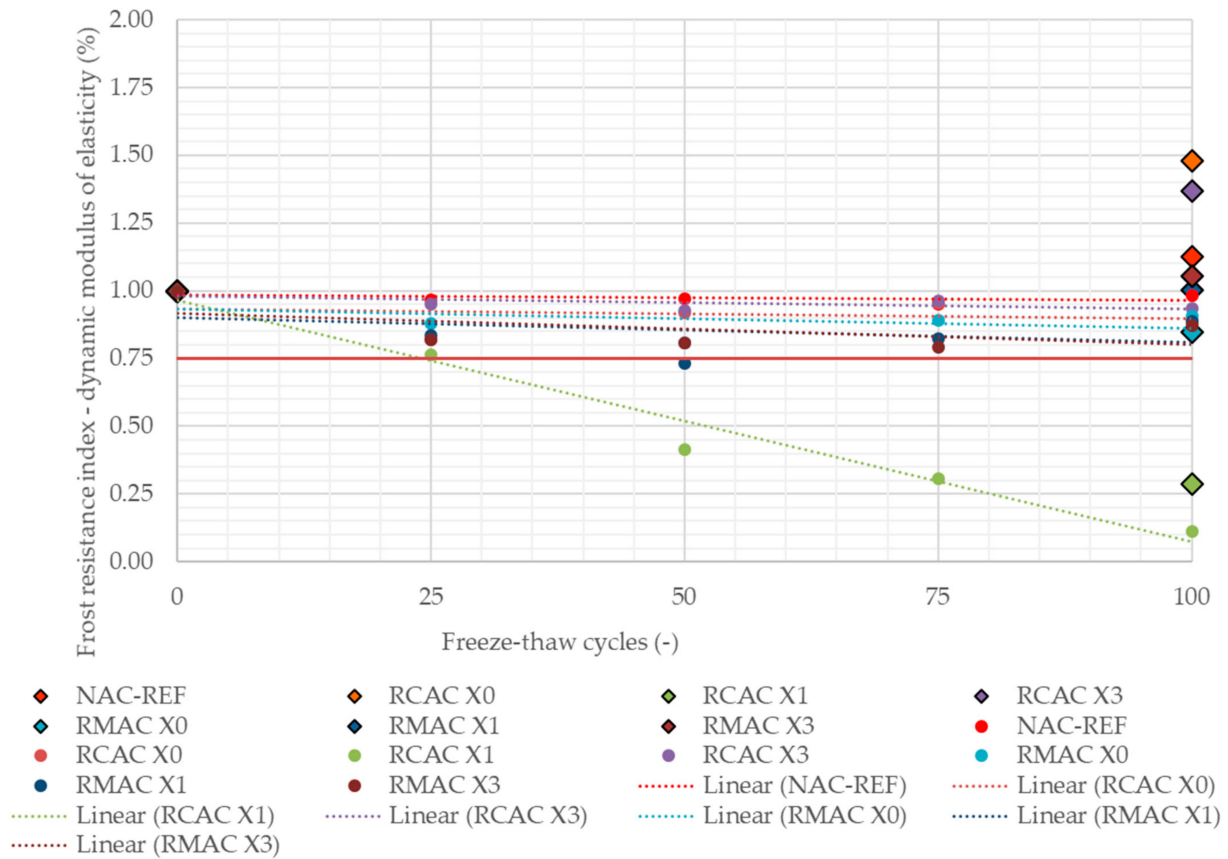


Figure 6. Frost resistance coefficient determined from the dynamic modulus of elasticity and flexural strength.

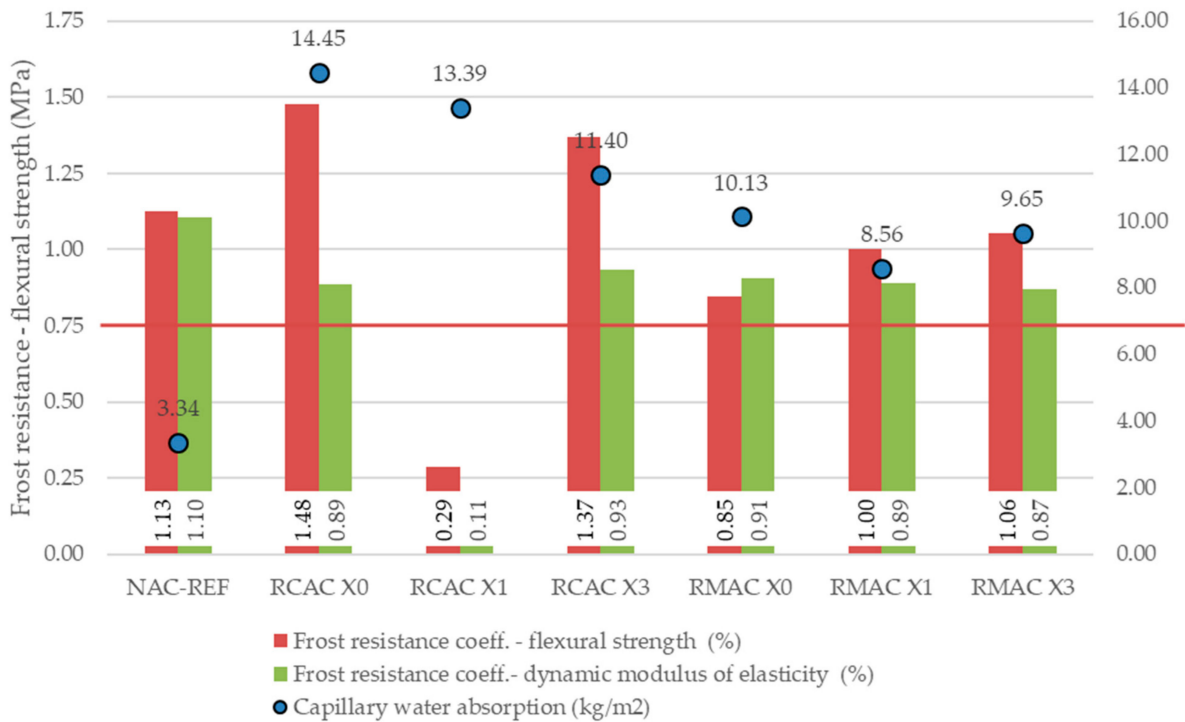


Figure 7. Frost resistance coefficient and capillary water absorption.

3.3.2. Carbonation Resistance

Carbonation resistance is the essential index of durability of reinforced concrete structures negatively influenced by the RA contained in concrete mixture due to its relation with the porosity of the aggregate. The presence of carbon dioxide (CO_2) causes physicochemical process with several chemical reactions promoting the reduction of pH in concrete. Concrete with a lower pH loses the ability to protect the reinforcement, which could more easily corrode. The microstructure and properties of concrete have been negatively influenced by CO_2 , as has been described in the previous studies. However, in some cases, CO_2 penetrating the concrete mainly through a diffusion mechanism can form calcium carbonate (CaCO_3) with calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the presence of moisture. They can slightly increase strength and reduce permeability due to CaCO_3 deposits in the pores of the cement matrix. [13,105]. Prismatic samples $100 \times 100 \times 400 \text{ mm}^3$ in which the depth of reduction of the concrete pH was measured by the phenolphthalein method are shown in Figure 8. The results are also compared with NAC by the indicator of increasing the depth of carbonation (see Table 8).

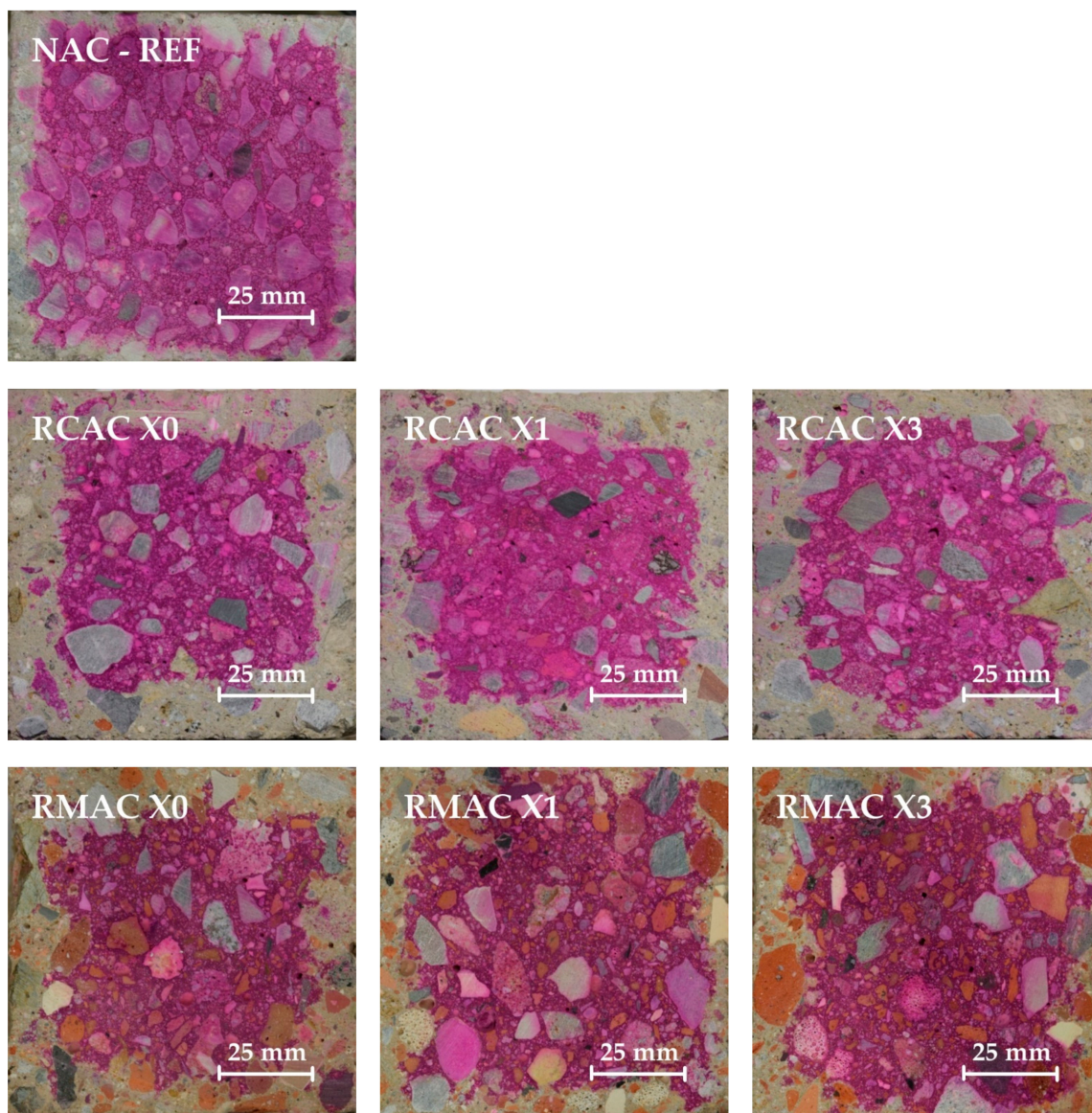
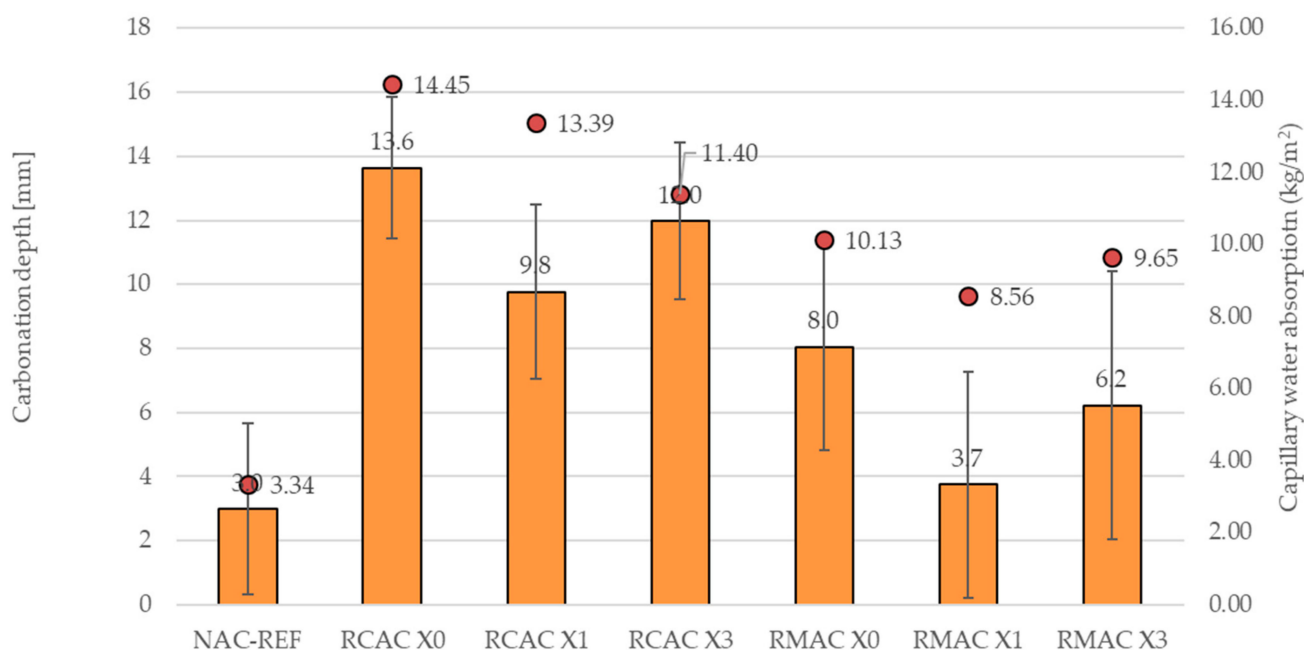


Figure 8. Carbonation depth of NAC, RCAC, and RMAC.

Table 8. Carbonation depth and indicator of increase of carbonation depth compared to NAC after 28 days in laboratory incubator with air circulation with CO₂ atmosphere.

Recycled Concrete Mixture	Carbonation Depth + Standard Deviation		Indicator of Increase of Carbonation Depth Compared to NAC
Designation	(mm)		(-)
NAC—REF	3.0	2.7	1.0
RCAC X0	13.6	2.2	4.6
RCAC X1	9.8	2.7	3.3
RCAC X3	12.0	2.4	4.0
RMAC X0	8.0	3.2	2.7
RMAC X1	3.7	3.5	1.3
RMAC X3	6.2	4.2	2.1

In general, the carbonation results show the deep effect of CO₂ on all RAC mixtures results in a significant improvement in the carbonation resistance of RAC with the addition of crystalline admixture. This carbonation depth of RMAC X0 without crystalline admixture is almost 2.7 times higher corresponding to the results presented in the previous study [13], where for the mixture in which only the coarse aggregate is replaced, the carbonation depth is 2.5 times higher in comparison to NAC. However, in this study, also the fine fraction of RMA was used for concrete. The most positive influence of the crystalline admixture was found in the case of RMAC mixtures at 1.5%. However, the measured values of RMAC with 3% of crystalline admixture also show lower carbonation depth in comparison with RMAC X0. Furthermore, the indicator of increase in carbonation depth of RMAC X1 is only about 25% deeper compared to the reference mixture. Additionally, the indicator of increase of carbonation depth of RMAC X3 is shown to be more than two times deeper than the carbonation depth compared to the reference mixture. Furthermore, the RMAC results of the carbonation resistance show the correlation between capillary water absorption and carbonation depth (see Figure 9).

**Figure 9.** Carbonation resistance—the measured carbonation depth, the indicator increases of measured carbonation depth compared to NAC and correlation with the capillary water absorption.

The carbonation resistance of RCAC mixtures is worse compared to those of NAC and RMAC mixtures. The carbonation depth of the mixture without crystalline admixture was 4.5 times higher compared to the NAC reference mixture and 1.7 times higher than that of the RMAC mixture without crystalline admixture. Similarly, with the RMAC mixtures, the lowest carbonation depth was measured for the RCAC mixture with 1.5% crystalline admixture. However, it was still 3.3 times higher than NAC and 2.6 times higher than RMAC, respectively.

In conclusion, the results of the carbonation resistance of RACs with 1.5% of crystalline admixture show their suitability to be used for the massive external reinforced concrete wall, specifically for the bunkers in this case.

4. Conclusions

In this study, the possibilities of using recycled aggregate concrete for structural usage as massive external reinforced concrete wall were evaluated, especially for the renovation of fortification in Czechia. The evaluation was carried out by experimental verification of the physical, mechanical, and durability properties of concrete containing recycled aggregate. As a result of the assumption of worse durability properties of recycled aggregate concrete, the improvement by crystalline admixture was examined and discussed. The aspects of the decrease in the mechanical properties and durability of concrete with the partial or full replacement of natural aggregate, with recycled aggregate such as higher porosity and water absorption, are generally known. For this reason, methods to fill the pores by adding suitable admixture and reducing the porosity have been verified in previous studies. In this case, due to future structural application of the massive external reinforced concrete wall future, improvement of durability with two types of RA by crystalline admixture was investigated. The final conclusions that have been reached can be summarized in the following points.

- The crystalline admixture reduces the capillary water absorption of RAC mixtures; however, it was still more than three times higher for most concretes. The results of capillary water absorption confirmed the results of the mechanical properties in terms of better suitability of recycled masonry aggregate concretes.
- The results of frost resistance showed the suitability of using recycled aggregate concretes for external application. The majority of RAC mixtures meet the requirement of frost resistance according to the Czech standard. The use of crystalline admixture slightly improves the frost resistance of recycled aggregate concrete; however, it is not necessary to use it in this case.
- The carbonation depth of the recycled concrete aggregate concrete without crystalline admixture was 2.7 times higher and the recycled concrete aggregate concrete, 4.6 times higher compared to conventional concrete. The recycled masonry aggregate concrete where crystalline admixture was used, the carbonation depth of the mixture with 1.5% was only approximately 25% higher compared to ordinary concrete. Recycled concrete aggregate mixtures with crystalline admixture also show lower carbonation depth in comparison with the mixture without it. Thus, the positive influence of the crystalline admixture on the carbonation resistance was shown.
- It was found that the addition of crystalline admixture, especially 1.5% (of the cement content), significantly improves the evaluated mechanical properties; for example, improvement in RAC mixtures by mineral admixture. Furthermore, better mechanical properties were found for recycled masonry aggregate concrete.

The novelty of this study was the utilization of recycled aggregate concrete for new type of structural application, which is the external massive reinforced concrete wall where a large volume of concrete is used, but practically without load (only by its own weight). For attaining sufficient durability for the application, crystalline admixture was added to improve the durability of concrete and its influence was verified. It was assumed that this admixture could fill the pores as a result of its reaction with water, which is contained in recycled aggregate, subsequently improving the durability. The positive impact of

crystalline admixture is shown for capillary water absorption, which is slightly lower for mixtures containing crystalline admixture. Moreover, clear benefits of crystalline admixture utilization on durability were found, especially on carbonation resistance.

In conclusion, according to the experimental results, the recycled masonry aggregate concrete mixture with 1.5% crystalline admixture (RMAC X1) was chosen as the best one for future structural application. This mixture has the best frost resistance, and the carbonation depth was similar to ordinary concrete which means that reinforcement can be placed in the same position as when using conventional concrete with natural aggregate. Furthermore, mechanical properties, especially compressive strength, are essential for this specific application. Finally, in this case, the optimal solution for the bunker wall has been found; however, the other application could be the retaining wall, barrier walls, or foundation wall structures.

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