Influence of additives on properties of concrete with recycled aggregate and fly ash

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Abstract. It is possible to considerably enhance the environmental friendliness of concrete production by increasing the usage of recycled concrete aggregate (RCA) and supplementary cementitious materials (SCM) in concrete industry [1, 2]. The idea of concrete with recycled concrete aggregate (RCA), additives such as microsilica, metakaolin, fluidized fly ash and superplasticizers might be controversial - it assumes usage of waste material and expensive additives - it is popular though. The aim of this paper was to determine, what the frost resistance of such concrete is. Additionally tests of other properties (sorptivity, absorbability and air void parameters) were performed.

1 Introduction

Recycling of waste materials became necessary to reduce greenhouse gas emission. It is possible to considerably enhance the environmental friendliness of concrete production by increasing the usage of recycled concrete aggregate (RCA) and supplementary cementitious materials (SCM) in concrete industry [1, 2]. The availability of natural sources of aggregates, which make up about 60–70% of concrete volume, is becoming more limited due to restrictions on quarrying operations and longer hauling distances.

Studies on the application of RCA in concrete mixtures have mainly concerned mix design [3, 4], mechanical properties [5, 6], structural performance [7, 8] and the final purpose [9, 10]. Until now many of the durability parameters have been investigated, technological recommendation and detailed requirements based on the quality of RCA were drawn [11].

The idea of concrete with recycled concrete aggregate (RCA), additives such as microsilica, metakaolin, fluidized fly ash and superplasticizers might be controversial - it assumes usage of waste material and expensive additives - it is popular though. Motivation for further investigation was confirmed possibility of preparing concrete with compressive strength higher than 60 MPa from waste materials.

The aim of this paper was to determine, what the frost resistance of such concrete was. Additionally examination of other properties (sorptivity, absorbability and air void analysis) was performed. Correlations between frost resistance and other parameters were determined.

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Water cumulated in air voids can increase its volume (up to 9%) during the frost process and cause micro damages of concrete. This is why structure of pores – their cumulated content, size and distribution - has strong influence on frost resistance. There were performed many analysis, which aims were to determine correlations between porosity parameters and frost resistance [12-14]. Intentional aeration of concrete, in which the structure of pores are controlled, can increase frost resistance. There are set some regulations for these kinds of concrete. Requirements for frost resistant concrete in various European countries are shown in Table 1. They are related to air content in both: concrete mixture and hardened concrete.

Table 1. Requirements for frost resistance of concrete in various European countries [15]

Standard	Requirements	Class of frost exposure			
		XF1	XF2	XF3	XF4
EN 206-1 (Poland)	min. content of air in concrete mixture, [%]	-	4	4	4
PN-B-06265 (Poland)	min. content of air in concrete mixture, [%]	-	4	4	4
ÖNORM B 4710-1 (Austria)	min. content of air in concrete mixture, [%]	-	2.5	2.5	4
	min content of micro air voids <300 μm, [%]	-	1	1	1.8
	max. spacing factor L, [mm]	-	-	-	1.8
DS 2426 (Denmark)	min. content of air in concrete mixture, [%]	-	4.5	4.5	4.5
	min content of micro air voids <300 μm, [%]	-	3.5	3.5	3.5
	max. spacing factor L, [mm]	-	0.2	0.2	0.2
	surface damage resistance of concrete	-	good	good	good

2 Materials and methods

2.1 Materials

CEM III/A 42.5 N-LH/HSR/NA cement from Gorażdże Cement Plant was used. The main component of CEM III as per PN-EN 197 is blast furnace slag. Class F fly ash from coal combustion in Kozienice Power Plant, which complies with the requirements of PN-EN 450-1:2012, was used. As natural aggregate (NA), river sand of 0-2 mm and 2-4 mm fractions were used. recycled concrete aggregate (RCA) was obtained by crushing concrete pieces of compressive strength between 35-50 MPa. RCA was sieved into fractions of: 4-8 mm and 8-16 mm. NA was used at air-dry condition. The RCA was weighted and saturated with water, in an amount of 3.5% of its air-dry weight. The absorbed water was not taken into account when calculating W/C and (W+SP)/(C+P) ratios. High-range water reducer Muraplast FK 88 manufactured by MC-Bauchemie was used. Regular tap water was used as mixing water.

Four concrete mixtures were prepared – one without additives and three with different additive each. Mix proportions are presented in Table 2.

Microsilica and metakaolin were delivered by company Rominco Polska and fluidized fly ash from Czech Republic was used.

Table 2. Mixture proportions for 1 m^3 of concrete [kg].

Component/mixture	**REC1**	**REC2**	**REC3**	**REC4**
CEM III/A 42.5N	290.58	291.09	291.08	294.06
Fly ash	193.72	194.06	194.05	196.04
Microsilica	0.00	48.52	0.00	0.00
Metakaolin	0.00	0.00	48.51	0.00
Fluidized fly ash	0.00	0.00	0.00	49.01
Natural sand 0-2	483.51	454.47	457.86	452.48
Natural sand 2-4	227.49	213.99	215.29	212.99
RCA 4-8	787.18	740.06	745.27	736.47
RCA 8-16	0.00	0.00	0.00	0.00
SP FK-88	7.75	8.73	8.73	8.82
Water	197.65	210.06	209.52	209.29
(W+SP)/(C+P)*	0.42	0.45	0.45	0.45
W/C*	0.68	0.72	0.72	0.71

*Previous to mixing RCA has been saturated, the saturation water is NOT incorporated in the ratio.

2.2 Compressive strength test

Specimens were prepared and cured as per PN-EN 12390-3:2011 and tests were carried out according to instructions included in PN-EN 12390-3:2011. 2 days after concreting the specimens were demoulded and water-cured in the laboratory till the age of 28 days and 90 days. ToniTechnic, ToniPACT II having 3000 kN loading capacity was used. The rate of loading was maintained at 0.5 MPa/s.

2.3 Frost resistance test

Frost resistance test was carried out in accordance with PN-B-06250:1988. For each mixture 12 cubic specimens with the edge of 100 mm were tested. They were subjected to cyclic frosting (for 4 hours) and defrosting (for 4 hours). Additionally reference samples were stored in water with temperature of +18±2°C during the whole test. After last cycle of frosting compressive strength of specimens and reference specimens were examined. Medium loss of compressive strength were determined as:

$$\Delta R = \frac{(R_1 - R_2)}{R_1} \cdot 100\% \tag{1}$$

where:
R_1 – medium compressive strength of reference specimens [MPa];
R_2 – medium compressive strength of specimens subjected to cyclic frosting and defrosting [MPa].

2.4 Sorptivity test

The halves of 150 mm cubic specimens were dried out and placed in the containers with water maintained at the level of 5 mm. The samples were weighted after set periods of time: after 15, 30, 60, 120, 180, 240 and 360 minutes from the beginning of test.

Fig. 1. Sorptivity test

Sorptivity was determined as direction coefficient of the linear function, which expressed correlation between mass of absorbed water divided by specimen surface in contact with water and time raised to the power of 0.5:

$$\Delta m/F = S \cdot t^{0.5} \tag{2}$$

where:
Δm – mass of absorbed water;
S – sorptivity;
F – specimen surface in contact with water;
t – time of penetration.

2.5 Absorbability test

Absorbability tests were performed according to PN-B-06250:1988. Absorbability was determined as water uptake relative to dry mass. The 6 halves of 150mm cubes were used for each mixture type. 28 days after concreting samples were placed in container in the way the specimen was no higher than 200 mm. Then the water was poured to the container so its level was at half of samples height. Temperature of water was 18±2°C. After 24 hours water was poured again. The level of water was 10 mm above specimens height and this level was maintained till the end of the test.

Every 24 hours samples were taken out of water and weighted. Tests ended, when two measures in a row did not show growth. Fully soaked specimens were then dried out in the temperature of 105-110°C till the mass was stable.

Absorbability was determined as:

$$n_w = \frac{(G_2 - G_1)}{G_1} \cdot 100\% \tag{3}$$

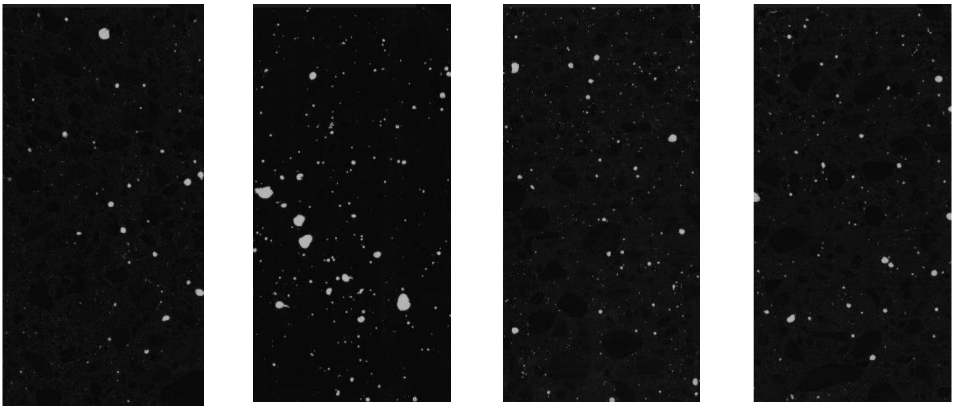
where:

n_w – absorbability of concrete [%],
G_1 – mass of dried out samples [kg];
G_2 – mass of soaked samples [kg].

According to PN-B-06250:1988 absorbability should be no higher than:
- 5 % for concrete elements directly exposed to weather conditions;
- 9 % for concrete elements protected from direct exposure to weather conditions.

2.6 Air void analysis

Air void analysis in hardened concrete was performed in compliance with PN-EN 480-11:2008. Specimens were cut out of 150 mm concrete cubes. Their dimensions were 2 cm/10 cm/15 cm. The length of each traverse line was 1200 mm. The samples were firstly polished in order to achieve smooth surface of the specimen. During the polishing it was important not to crush edges of the pores. Then the necessary contrast was achieved with the usage of zink paste and ink. The RapidAir 457 were used to perform microscopy analysis and calculate necessary values: summary air void content, spacing factor and micro air void content.



a) b) c) d)

Fig. 2. Image of the specimen surface after applying contrast – a) REC1; b) REC2; c) REC3; d) REC4

3 Research results

3.1 Compressive strength of concrete

As it was also shown in article [2] specifying only the strength after 28 days for concretes mixtures with CEM III cements does not fully reflect the real strength properties. Significant gain in compressive strength after 90 days was observed (about 30%).

Table 3. Results of compressive strength tests

	Compressive strength after 28 days			Compressive strength after 90 days			Relative increase of compressive strength from day 28th to 90th after concreting [%]
	Medium value [MPa]	Standard deviation [MPa]	Relative standard deviation [%]	Medium value [MPa]	Standard deviation [MPa]	Relative standard deviation [%]	
REC1	46.30	1.05	2.27	61.43	1.66	2.70	32.7
REC2	41.65	0.43	1.04	53.38	0.83	1.56	28.2
REC3	40.85	0.83	2.02	54.43	0.40	0.73	33.2
REC4	46.13	1.38	2.99	60.10	2.65	4.41	30.3

3.2 Frost resistance

Compressive strength of specimens were tested after 50, 100 and 130 cycles of frosting and defrosting. After 130 cycles almost every samples were in such bad conditions that tests were impossible. Concrete cubes damaged after 130 cycles were shown in Figure 3. Some specimens after 50 and 100 cycles also were too damaged to perform compressive strength tests. They were marked with * in the Table 4, where relative decrease of compressive strength after 50, 100 and 130 cycles of frosting are shown.

Fig. 3. Damaged specimens after 130 cycles

Table 4. Results of frost resistant tests – relative decrease of compressive strength

	Compressive strength [MPa]				Decrease of compressive strength (related to the day 28) [%]		
	after 28 days	after 50 cycles of frosting	after 100 cycles of frosting	after 130 cycles of frosting	after 50 cycles of frosting	after 100 cycles of frosting	after 130 cycles of frosting
REC1	46.3	35.93	16.21*	-*	22.4	65.0*	-*
REC2	41.65	32.41	29.50*	21.82*	22.2	29.2*	47.6*
REC3	40.85	35.85	26.14	-*	12.2	36.0	-*
REC4	46.13	37.75	26.35*	21.75*	18.2	42.9*	52.9*
*In that case some specimens were too damaged to perform compressive strength test							

3.3 Sorptivity and absorbability

In Table 5 there are presented results of absorbability and sorptivity tests.

Table 5. Results of sorptivity and absorbability tests

	Absorbability		Sorptivity	
	Medium value [%]	**Standard deviation [%]**	**Medium value [g/(cm^{2}h$^{0.5}$)]**	**Standard deviation [%]**
REC1	7.33	0.16	0.1057	0.0042
REC2	8.29	0.25	0.1148	0.0035
REC3	7.46	0.14	0.1031	0.0030
REC4	7.40	0.16	0.0969	0.0034

3.4 Air void analysis

There were calculated air content, micro air voids content (concerning pores with diameters smaller than 300 μm) and spacing factor as per PN-EN 480-11:2008. The results for each mixture are shown in Table 6.

Table 6. Parameters of air void analysis

Parameters	REC1	REC2	REC3	REC4
Air content - A [%]	1.17	1.45	1.22	1.21
Micro air voids content - A300 [%]	0.363	0.147	0.347	0.267
Spacing factor - L [mm]	0.267	0.761	0.283	0.389

4 Summary

Absorbability did not fulfil requirement of PN-B-06250:1988 for concretes directly exposed to weather conditions and it hardly fulfilled requirements for concretes protected from weather conditions. Due to high absorbability low frost resistance was expected.

Sorptivity was relatively low, but it appeared that predicting high level of frost resistance depending only on the level of sorptivity might not be true in such concretes.

Parameters of air void analysis also lead to low frost resistance prediction. For further investigations there should be carried out analysis, how the air voids in RCA differs from the pores in newly created cement paste concerning their influence on calculating air void parameters and assuming frost resistance.

After 50 cycles of frosting the lowest decrease of compressive strength had mixture with the addition of metakaolin (REC3). It was also only mixture type, for which every four specimens after 100 cycles of frosting were in condition good enough to carry out compressive strength tests. Though, REC2 (with additive of microsilica) achieved lower decrease of compressive strength after 100 cycles.

To sum up, frost resistance of concrete with recycled aggregate and fly ash presented in this paper is low. Additives (such as microsilica, metakaolin, fluidized fly ash) and superplasticizers increases this parameter. Although this increase can be noticed, the frost resistance is still too low to recommend this type of concrete for wide usage in Poland.

Applicability might be limited due to climatic conditions, even though mechanical properties are satisfying.

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