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Ecological Concrete Based on Blast-Furnace Cement with Incorporated Coarse Recycled Concrete Aggregate and Fly Ash Addition

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Received November 13, 2016; Accepted December 06, 2016

ABSTRACT: This article deals with an experimental study concerning the development of concrete mixtures with significant ecological benefits. The studied concrete mixtures were based on blast-furnace cement, with an additional application of supplementary cementitious materials—fly ash, metakaolin, and silica fume and fluidized fly ash. Coarse aggregate in the form of crushed concrete was applied for all studied concrete mixtures. The experimental program was primarily focused on the assessment of the durability properties of the studied mixtures in terms of mechanical tests, absorption tests, chloride migration coefficient tests, water penetration tests, and accelerated carbonation depth tests. The results obtained showed good potential for waste materials in durable concrete production. The studied mixtures, with incorporated supplementary cementitious materials, exceeded the level of high performance concrete (HPC) in terms of mechanical properties. Such modification of the binding system also significantly contributed to an increase in durability properties; however, mixtures with the fluidized fly ash application exhibited reduced resistance to carbonation.

KEYWORDS: Ecological concrete, durability, recycled aggregate, waste utilization, supplementary cementing materials, blast-furnace cement

1 INTRODUCTION

Reducing greenhouse gas emissions, frugal management of natural resources, and recycling of waste materials have become necessary due to the significant negative effects caused by climate change. This necessity has led to a number of investigators discovering new technologies focused on the transition to an energy-efficient, low-carbon economy, and the reuse and recycling of existing materials [1–3].

Increasing the use of recycled concrete aggregate (RCA) and supplementary cementing materials (SCM) in the concrete industry can considerably enhance the environmental friendliness of concrete production. 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. Additionally, the disposal of old concrete produced by the demolition of existing structures is still a problem, and such waste is frequently placed in landfills [4]. As a result, an important and predictable trend in the future of concrete has appeared. It assumes the growing utilization of waste and recycled materials as ingredients of concrete mixtures [5, 6]. Concrete made utilizing these materials will also fulfill all requirements concerning its properties and durability. Some researchers [7–9] indicate the possibility of obtaining high quality, durable, green concrete by utilizing a high amount (over 50% wt) of fly ash as a binder component—such concrete is referred to as "high volume fly ash concrete" (HVFAC). They also claim that the utilization of high amounts of fly ash not only has a positive ecological effect (reducing cement utilization and, consequently,

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DOI: 10.7569/JRM.2017.634103

carbon dioxide emission), but is also beneficial to the durability of concrete. It should be noted, however, that so-called "green concrete," despite utilizing waste materials, may be more expensive than concrete made from currently used components [8, 10]. However, the general use of RCA as a substitute for the natural aggregates, and SCM as a partial cement replacement in concrete mixture, is a means to potentially address economic and environmental concerns.

Waste materials and RCA used as SCM are often considered to be low quality components, which, while slightly lowering the cost of concrete, also deteriorate most of its vital properties. Some authors claim that RCA is not a suitable component for manufacturing concretes with designed compressive strength higher than 25 MPa [11]. Attempts to obtain high performance concrete using RCA and high SCM content are rare, and they are usually based on RCA of a very high quality acquired from demolition of structures made from concrete of very high compressive strength (even more than 100 MPa) [12–14]. However, RCA of such a high quality is a rarity, and it cannot be assumed that it will be widely available.

Utilization of coarse RCA in concrete manufacturing has been thoroughly researched. Quality requirements for aggregate are defined [15], as are recommendations for the use of coarse RCA in concrete manufacturing [15–17]. Many of the durability parameters have been investigated as well, and technological recommendations with detailed requirements based on the quality of RCA have been drawn [15]. It has been stated that it is possible to design and produce durable concretes with an adequate good quality of RCA. The aggregate characteristics of density, porosity, and water absorption are primary factors in determining the proper concrete mix and required concrete properties.

Most of the research concerning RCA quality and the durability of concrete made with RCA has been performed in countries where the technical culture has achieved a high level. As a consequence, the quality of RCA is also high. In some countries, however, certain parts of existing concrete structures (mainly of minor importance: pavements, salvage system elements, and also some industrial structures) have been made using poor quality concrete [18]. Obtaining RCA of suitable quality from these structures, which would meet the vital requirements, can present a major problem.

Some research concerning the application of low quality RCA in concrete technology has been conducted. It has been primarily concentrated on the various techniques and methods that can enhance the physical properties of low quality RCA [19–22]. Tsujino *et al.* [23] tested the possible applicability of low quality recycled aggregate finished with an oil-type surface improvement agent. A surface improvement agent reduced the water absorption of low and middle quality recycled aggregate. Jaskulski and Mękal [24] tested the possibility of improving the quality of RCA with water glass impregnation, but the results were ambiguous. The polymer-based treatment techniques were also applied to improve the water permeability of concrete with RCA. They showed a positive effect in the water absorption capacity of RCA [25]. On the other hand, Mukharjee and Barai [26] investigated the effect of the incorporation of colloidal nanosilica on the behavior of concrete containing 100% recycled coarse aggregate. The results of the investigation determined that compressive strength and tensile strength, as well as nondestructively tested parameters, were enhanced due to the nanosilica addition. The studies presented in this article partially support the trend in the technology of concrete aimed at manufacturing good quality material using low-quality RCA, thus enabling the development of more environmentally friendly, good performing, concrete.

In their paper, Kubissa *et al.* [27] presented the possibility of manufacturing high quality concretes with coarse RCA and significant amounts of Class F fly ash. The authors also drew attention to the possibility of reducing the environmental impact of concrete production through the use of cements with major amounts of waste additions [28]. One of the most frequently mentioned cements of this type is blast-furnace cement (CEM III according to EN 197-1 [29] and PN-B-19707:2013-10 [30]) [28, 31–33]. The use of CEM III cement, beside its ecological effects, provides increased durability of concrete. The lower content of Portland clinker in the blast-furnace cement composition results in lower greenhouse gas emissions, mainly CO_2, and the protection of nonrenewable natural resources [31, 32, 34].

The main objective of the research was to evaluate the possibility of using both RCA as a replacement for natural coarse aggregate, and SCM as a binder component in manufacturing concrete of mechanical properties higher than average and low permeability. The presence of various SCMs in concrete mix can positively influence the durability of concrete [35, 36]. The addition of fly ash can significantly reduce the permeability and diffusivity of concrete [36] and, therefore, positively affects both quality and durability. Based on previous studies [9, 27], concrete composition containing 300 kg/m^3 of cement and 200 kg/m^3 of Class F fly ash was chosen. This formulated binding system was additionally modified by other types of SCMs.

The fundamental criteria were set to the studied mixtures: concrete flow value about 400 mm after 60 minutes from adding water to the mixture (to assure good workability), an average of 28 days compressive strength of about 55 MPa, and durability parameters greater than for ordinary concrete made with utilizing traditional components. To meet these requirements, a high range water reducer (HRWR) was used, together with the addition of silica fume, metakaolin, fluidized fly ash, and Centrilit NC Powder additive. The amount of added water was not in fixed relation with cement content because the goal was to obtain a similar flow values.

2 MATERIALS AND TESTS

2.1 Materials

Blast-furnace cement CEM III/A 42.5N LH/HSR/NA from the Górażdże Cement Plant (as per EN 197-1) was used for the performed experimental program. Basic physical and chemical properties presented by the cement manufacturer are shown in Table 1.

The binder was modified by the addition of fly ash from coal combustion in the Kozienice Power Plant-Class F for all of the studied mixtures. Individual mixtures were additionally modified by other types of active additives—silica fume, metakaolin, Centrilit NC (amorphous aluminosilicate), and fluidized fly ash. Detailed chemical and physical properties of used binding components are shown in Table 2. Chemical composition of Centrilit NC is confidential and that is why it is not introduced.

The RCA was manufactured by crushing hardened concrete, of which compressive strength was 35–50 MPa. The originated aggregate could be classified as RCAC II according to Rilem [16], or type II according to DIN 4226-100 [36], respectively type A according to PN-EN 206 [37]. RCA was sorted using a standard EN sieve set to particular fraction: 0–2 mm, 2–4 mm, 4–8 mm and 8–16 mm, of which only the last two (4–8 and 8–16 mm) were used. The crushing resistance of used aggregates was 14.19 for 4–8 mm and 17.41 for 8–16 mm. Natural siliceous sand of fractions 0–2 mm and 2–4 mm was used to complete a suitable gradation curve of designed aggregate mix. The final granularity of the combination of the above introduced aggregate types is shown in Figure 1.

Superplasticizer Muraplast FK 88, based on polycarboxylates, was selected to reduce the total dosage of water, as well as to ensure suitable workability. Tap water, which greatly exceeds all common requirements for the mixing water, was used for the mixture production.

Seven concrete mixtures with constant content of binder consisting of blast-furnace cement and fly ash were prepared. The blast-furnace cement formed 60%

Table 1 Basic physical and chemical properties of the cement.

	Setting time		Compr. strength [MPa]	Specific surface area (Blaine) [cm^2/g]	Specific gravity [g/cm^3]	SO_3 [%]	Cl [%]	Na_2O_{eq} [%]
	Start [min]	End [min]						
CEM III/A 42.5N - LH/HSR/NA	237	314	56.9	5452	2.91	2.23	0.083	0.32

Table 2 Chemical composition and properties of binding components.

	Cement CEM III/A	Fly ash		Metakaolin	Silica fume
		Class F	Fluidized		
SiO_2	30.16	51.67	35.64	53.1	95.4
Al_2O_3	6.16	31.32	32.19	41.7	0.4
Fe_2O_3	1.87	5.26	6.06	1.08	0.3
CaO	53.86	1.46	12.71	0.13	0.3
MgO	3.39	1.73	0.60	0.18	0.5
Na_2O	0.32	0.52	0.46	–	0.2
SO_3	2.23	0.40	4.87	0.71	0.8
K_2O	0.63	2.64	0.41	–	1.6
TiO_2	–	1.38	6.53	1.80	–
Loss on ignition [%]	1.24	2.79	6.28	3.8	2.5
Specific gravity [g/cm^3]	2.91	1.95	1.81	2.45	2.5
Specific surface area (Blaine) [cm^2/g]	5452	3150	3120	3455	245000

of the fundamental binder system, respectively 300 kg per cubic meter. Additionally, various active additives—silica fume, metakaolin, Centrilit NC and fluidized fly ash—were dosed in the amount of 10% of complete binder (cement and fly ash) weight. Centrilit NC was dosed in the mixture REC5 due to its high effectiveness in reduced amount, which presented 10% of cement dosage by weight. The dosage of selected plasticizer was gradually increased due to increased application of active powder additives to keep a suitable consistency of fresh mixture after 60 minutes. All types of aggregate used were kept under dry laboratory conditions; however, RCA were preconditioned by adding 3.5 mass% of water due to its increased absorbability. The absorbed water was not taken into consideration when calculating w/c or w/b ratios. Detailed composition of the studied concrete mixture is shown in Table 3.

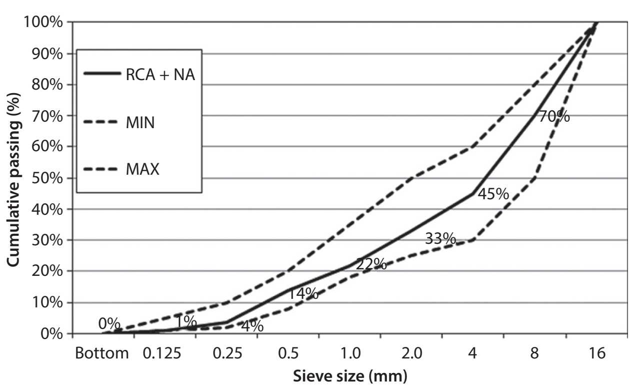

Figure 1

Concrete mixtures were produced in the laboratory horizontal mixer. Fresh concrete was casted into the steel molds and compacted by the double vibration. The method of compacting was prescribed by the obtained consistency, and a flow test according to PN-EN 12350-5 [38] was performed. Manufactured specimens were demolded after two days, and then cured under wet conditions according to PN-EN 12390-2 [39]. Wet curing was changed after 28 days to standard laboratory conditions (20 °C and 50% RH) up to the age of 90 days.

2.2 Compressive and Tensile Strength Test

Compressive strength and split strength were determined using cubic specimens of edge 150 mm after 28 and 90 days of curing. The specimens tested after 90 days were put into water for 5 days before the test. The setting of both tests was organized according to PN-EN 12390-3 [40] and PN-EN 12390-6 [41], respectively. A universal loading machine, ToniTechnic ToniPACT II, was used for the mechanical testing because it allows for test control according to an optional force rate. The loading rate for compressive strength determination was 0.5 MPa/s for all the studied mixtures; for split strength determination a measurement of 0.05 MPa/s was used.

2.3 Sorptivity Test

The measurement of sorption was organized as free water intake, using cubic specimens of edge 150 mm dried at 105 °C. Samples were partially wetted (up to

Table 3 Proportions of concrete mixtures [kg/m^3].

Component/mixture	REC1	REC2	REC3	REC4	REC5	REC6	REC7
CEM III/A 42.5	300	300	300	300	300	300	300
fly ash	200	200	200	200	200	200	125
silica fume	0	50	0	0	0	0	0
metakaolin	0	0	50	0	0	0	0
Centrilit NC	0	0	0	50	30	0	0
fluidized fly ash	0	0	0	0	0	50	125
natural sand 0–2	538	505	509	498	517	507	493
natural sand 2–4	196	184	185	181	188	184	179
RCA 4-8	369	347	349	342	355	348	338
RCA 8-16	443	416	419	410	426	417	406
SP FK-88	8	9	9	9	9	9	10
water	172	186	185	183	175	183	201
W+SP/(C+P)	0.359	0.354	0.353	0.349	0.346	0.349	0.384
W/C	0.572	0.620	0.618	0.611	0.583	0.610	0.671

Table 4 Concrete durability classification based on the value of sorptivity [42].

Sorptivity [cm/h$^{0.5}$]	Concrete durability class				
	Very low	Low	Middle	High	Very high
	>0.37	0.37–0.20	0.20–0.12	0.12–0.05	<0.05

Table 5 Concrete durability classification based on the value of chloride migration coefficient [45].

Chloride migration coefficient [m^2/s]	Resistance to chloride penetration			
	Unacceptable	Acceptable	Good	Very good
	$>16 \cdot 10^{-12}$	$8–16 \cdot 10^{-12}$	$2–8 \cdot 10^{-12}$	$<2 \cdot 10^{-12}$

3 mm) in water vessels, and the growth of water mass absorbed into the concrete was recorded in selected time intervals. Subsequent measurement was carried out for 6 hours. The consecutive results of mass gain were approximated with linear function. The slope of the function was calculated, and this determined the value of sorptivity. Sorptivity of the concrete can serve as a durability indicator because it expresses the ability to adsorb various media from the environment very well. Based on the previous long-term research of Kubissa presented in [42], aimed at sorptivity and durability aspects, concrete could be classified according to that property, as shown in Table 4.

2.4 Depth of Penetration of Water under Pressure Test

A water penetration test was carried out according to PN-EN 12390-8 [43] using cubic specimens of edge 150 mm. The applied water pressure during the test was 0.5 MPa for 72 hours. The results of this test showed the maximal visible depth of penetration after splitting. The subject test was performed after 28 days of prescribed curing for all studied mixtures.

2.5 Chloride Migration Coefficient Test

The Nordtest method (NT Build 492 [44]) was used for the determination of the migration coefficient of chloride ions in a non-steady state. The test was conducted on the cylindrical specimens with a diameter of 150 mm and a height of 50 mm after 90 days of curing. The upper surface of the specimen was equipped with a rubber sleeve before testing, which served as a reservoir for the anolyte (0.3 M solution of sodium hydroxide). It was necessary to reach the full saturated state of the specimen, which is why vacuum preconditioning of the specimen is prescribed. The prepared specimen was placed into the basin with the catholyte (10% solution of sodium chloride). The gradient was caused by two electrodes placed on both fundaments of the specimen. The test's duration was dependent on the initial response of the sample applying the potential difference of 30 V. Then, according to NT Build 492 recommendations, the test duration was assumed and the voltage was alternatively changed. The depth of chloride penetration was measured using a 0.1 M solution of silver nitrate, and the chloride penetration coefficient D_{nssm} was calculated according to formulas in the NT Build 492 manual. The particular criteria were published by Tang in [45] and are shown in Table 5.

2.6 Carbonation Depth Test

An accelerated test for the determination of the carbonation depth was carried out on the prismatic specimens (100 × 100 × 500 mm). The process of carbonation is highly dependent on the actual moisture content, which explains why prior curing of the specimens is necessary. Following this, the specimens were placed vertically into the climatic chamber, with prescribed internal conditions (40 °C and 60% RH) and a 10% concentration of carbon dioxide, for the next 28 days. During the test, specimens were taken out on the 7th, 14th and 28th days of the test to measure the depth of carbonation using phenolphthalein, which determines interface corresponding to pH of 9.

3 RESEARCH RESULTS

Research results are presented in Table 6 and Table 7. Each value is an average of six measurements; however, the results of the flow table test are an average of only three measurements. In Table 6, values of dry density of concrete series are also presented. It is worth mentioning that the values of density are about 15% lower than for typical ordinary concrete.

Table 6 Test results – mechanical and physical properties.

	REC1	REC2	REC3	REC4	REC5	REC6	REC7
flow 60 min [mm]	405	400	395	405	415	415	390
density dry [kg/m^3]	2050	2032	2074	2062	2094	2099	2055
compr. strength f_c 28d [MPa]	48.4	54.6	53.3	53.4	55.2	49.9	48.7
compr. strength f_c 90d [MPa]	58.1	66.2	60.8	62.5	66.2	61.4	55.7
tensile strength f_{ct} 28d [MPa]	2.83	3.18	3.63	3.56	3.61	3.25	3.53
tensile strength f_{ct} 90d [MPa]	2.97	3.26	3.81	3.78	3.81	3.45	3.67

Table 7 Test results – properties assuring durability.

	REC1	REC2	REC3	REC4	REC5	REC6	REC7
water penetration depth [mm]	29.0	30.7	22.8	25.8	14.7	23.3	17.7
sorptivity S 28d [cm/h$^{0.5}$]	0.095	0.109	0.078	0.068	0.049	0.088	0.127
sorptivity S 90d [cm/h$^{0.5}$]	0.113	0.120	0.104	0.110	0.092	0.122	0.152
chloride migr. coef. [$\cdot 10^{-12}$m^2/s]	1.19	0.55	1.42	1.51	0.98	0.12	0.15
carbonation depth 7d [mm]	4.6	5.4	5.3	6.3	4.3	6.8	9.3
carbonation depth 14d [mm]	6.5	7.7	6.7	6.8	6.7	10.9	11.8
carbonation depth 28d [mm]	8.8	9.0	9.4	10.4	9.7	14.8	16.8

3.1 Workability of Concrete

Flow values of concrete after 60 minutes are presented in Table 6. The flow values for all concrete mixtures were almost equal, and situated around an assumed value of 400 mm. The difference between the highest and the lowest value was 25 mm, which comprised about 6.3% of the assumed flow. The lowest value of 390 mm was reached for the REC7 mixture, despite using the highest amount of superplasticizer (10 kg/m^3) and a significantly higher amount of water compared with the other concrete series. This was the only mixture which contained a lower amount of fly ash (125 kg/m^3) and the same amount of fluidized fly ash which caused very high water demand. The results show that it is possible to obtain the assumed workability, measured after one hour, even while using RCA as 100% of the coarse aggregate replacement. Nevertheless, an increased dose of an efficient plasticizer is necessary to simultaneously maintain a low water/binder ratio and suitable workability.

3.2 Compressive Strength of Concrete

Results of the compressive strength test are presented in Table 6. The highest value of the strength after 28 days (55.2 MPa) was reached for REC5 concrete series with 30 kg/m^3 of Centrilit NC, which represents a 14% increase compared with the control mixture REC1 (48.4 MPa). A similar gain was obtained for the REC2 concrete mixture with 50 kg/m^3 of silica fume, which is the expected result because of the high quality and reactiveness of these additives. The addition of metakaolin also positively contributed to the values of compressive strength. Mixtures with the fluidized fly ash addition (REC6 and REC7) exhibited results similar to those of the control mixture.

The process of hydration significantly influenced the evolution of compressive strength. After 90 days, the same highest value of strength (66.2 MPa) was obtained for two concrete series: REC5 and REC2. The lowest value (55.7 MPa) was obtained for REC7 concrete series, and it was 4% lower than for the control series. The maximum strength gain between 28 and 90 days (11.6 MPa; 17.5%) was recorded in the case of the REC2 concrete series, which was only a little lower in absolute values (11.5 MPa), but a relatively higher (18.7%) value was recorded for REC6 concrete with the addition of 50 kg/m^3 of fluidized fly ash. The lowest absolute strength gain (7 MPa) appeared in the case of the REC7 concrete series, and the relatively lowest gain (12.3%) was recorded in the case of the REC3 series. All of the concrete series achieved the assumed minimal value of 55 MPa after 90 days. The results support the opinion presented by Batog [46] that specify only the strength value after 28 days for concrete made with CEM III cement does not fully reflect their properties. With respect to the 90 day values of compressive strength, a slightly negative impact of the fluidized fly ash addition can be observed. This is probably the result of the increased water dosage required to assure proper workability of the fresh concrete.

3.3 Tensile Strength of Concrete

Results of the tensile splitting strength test are presented in Table 6. The highest value of tensile splitting strength after 28 days (3.63 MPa) was obtained for the REC3 series with an addition of metakaolin. After 90 days, the maximum value of 3.81 MPa was reached, which was also obtained for both the REC3 series and the REC5 series with 30 kg/m^3 of Centrilit NC.

The lowest values of the strength exhibited by the REC1 reference series after both 28 and 90 days were 2.83 and 2.97 MPa, respectively. All of the tested concrete series with SCMs added achieved at least 10% higher tensile strength than the reference REC1 concrete. These results lead to the conclusion that the addition of SCM enhances the aggregate-matrix contact zone. The highest absolute increase of strength between 28 and 90 days (0.22 MPa) was observed for the REC4 concrete series with 50 kg/m^3 of Centrilit NC, and the relative result was the highest (6.2%) in the case of REC4 and REC6 concrete series with 50 kg/m^3 of fluidized fly ash. The lowest absolute (0.08 MPa) and relative (2.5%) difference of the strength between 28 and 90 days was recorded for the REC2 series with the addition of silica fume.

3.4 Depth of Penetration of Water under Pressure

Results of the water penetration test are presented in Table 7. All tested concretes showed high levels of watertightness. Concrete is commonly considered "impermeable" if the average depth of penetration does not exceed 30 mm according to DIN 1048 [47] or 50 mm according to EN 12390-8, respectively. However, specific types of environments could require a lower maximal depth of water penetration, especially for the chemically aggressive exposure—XA. Only the REC2 mixture slightly exceeded the depth of 30 mm, but the result (30.7 mm) was only about 2% higher than required, according to DIN 1048. It was the highest recorded value. The lowest value (14.7 mm) was observed for concrete REC5. Despite the increased porosity and permeability of RCA, the incorporation of active additives allowed the samples to achieve the highest level of watertightness of all concrete mixtures studied.

3.5 Sorptivity of Concrete

The lowest value of sorptivity after 28 days was reached in the case of concrete REC5, 0.049 cm/h$^{0.5}$, which indicates the classification "very high" in terms of concrete durability. The highest value was obtained for the REC7, 0.127 cm/h$^{0.5}$. It was the only series classified as "middle" class after 28 days.

After 90 days, the sorptivity values were increased in all studied series. The highest increases (0.043 cm/h$^{0.5}$ and 87.8%) were recorded for REC5 mixture, but it was still within the "high" durability class. The lowest increase (0.011 cm/h$^{0.5}$ and 10.1%) was observed in the case of the REC2 series. The series with the highest (0.152 cm/h$^{0.5}$) and lowest (0.092 cm/h$^{0.5}$) value of sorptivity after 90 days were the same as after 28 days, but now two series—REC6 and REC7—were classified as "middle" durability. All the others fulfilled the requirement for the "high" durability class. If a comparison with reference REC1 series is made, it can be observed that after 28 days only two of the concrete series, REC2 and REC7, demonstrated a higher value of sorptivity. Additionally, after 90 days the REC6 series joined this set. The unsatisfactory result for the REC7 series can easily be explained by the highest water content in the fresh mixture.

The increase of the adsorption after 90 days is likely caused by the slower progress of hydration and pore structure formation in the blended binder system. Capillary pores with higher diameters result in subsequently reduced capillary suction. However, additional research would be necessary to confirm this hypothesis.

3.6 Chloride Migration Coefficient of Concrete

The highest value of chloride migration coefficient ($1.51 \cdot 10^{-12} m^2/s$) was observed for the REC4 concrete series, with a slightly lower value ($1.42 \cdot 10^{-12} m^2/s$) for the REC3 concrete series. The values for these specific concrete mixtures were higher than the value measured for the REC1 control series ($1.19 \cdot 10^{-12} m^2/s$). The lowest values were recorded in the cases of the REC6 ($0.12 \cdot 10^{-12} m^2/s$) and the REC7 ($0.15 \cdot 10^{-12} m^2/s$) concrete series. The positive influence of fluidized fly ash on chloride migration coefficient of concrete was also published in [48]. However, all of the studied mixtures met the requirements for the range designated "very good," which presents the highest class of resistance.

3.7 Carbonation Depth of Concrete

Carbonation depth measured after 28 days of exposure is within the limits of 8.8 mm (REC1) to 10.4 mm (REC4) for all five concrete series, REC1 to REC5, and they can be considered similar to each other. In the cases of the two other series, with the fluidized fly ash, the depth of carbonation is significantly higher—14.8 mm (REC6) and 16.8 mm (REC7). After comparing the results obtained after 7, 14, and 28 days, it can be stated that, in the cases of REC7 and REC4 series, the rate of carbonation is clearly increased, in the cases of REC3 and REC5, the increase of carbonation rate is slight, and in the case of REC2 some decrease of the rate was noted. Both REC1 and REC6 concrete series exhibited an almost linear carbonation rate. The lowest value after 14 days (6.5 mm) and 28 days (8.8 mm) was measured in the case of the REC1 reference series. The result for REC5 concrete was slightly lower (4.3 mm) than for REC1 series (4.6 mm) only after the 7-day result.

4 SUMMARY AND CONCLUSIONS

Concrete mixtures with environmentally beneficial composition were studied in this experimental program to assess their durability properties as a crucial factor for their further utilization. Coarse natural aggregate was fully replaced by the RCA of lower quality, which was compensated by the introduction of various active additives. After analyzing the obtained results, it can be concluded that this approach to concrete mixture design allows suitable mechanical and durability properties of the subject mixtures to be achieved. Proper concrete composition with incorporated RCA and mineral additives ensures suitable workability of fresh mixtures; however, that required an additional slight increase of efficient plasticizer dosage. The results obtained correspond with other similar research focused on the compatibility of advanced binder systems and modern types of admixtures [49].

In terms of mechanical properties after 90 days of aging, the parameters meeting the requirements for HPC mixtures were achieved for all utilized additives in comparison to the control mixture, except the fluidized fly ash addition. Its application demands a significant increase of water dosage, which subsequently leads to a significant reduction of mechanical properties.

The finalized tests related to concrete durability actually corresponded with the mechanical test results. Nevertheless, differences were noticeable in the single mixtures, especially in the case of fluidized fly ash, the application of which negatively affected the results of carbonation depth. The results of the durability tests of all studied mixtures reached the level of the "outstanding" classification according to applied criteria. However, the application of fluidized fly ash seems to be inappropriate, due to the considerable reduction of the durability parameters.

Generally, the completed experimental program confirmed good practical potential for RCA and blended binding systems for the production of concrete, along with both significant environmental benefits and the importance of including the roles of durability in the complex assessment.

ACKNOWLEDGMENT

The research described in this article was carried out in the Laboratory of Innovative Technologies and Materials in Plock, co-financed by the European Union through the European Regional Development Fund under the Regional Operational Programme for Mazowieckie Voivodeship 2007-2013, and partially supported by the Czech Science Foundation under project No. GA15-11753S, both of which are gratefully acknowledged.

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