Properties of high-performance concrete with coarse recycled concrete aggregate for precast industry

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Abstract. Nowadays, industrially produced high-quality coarse recycled concrete aggregate (RCA) complying with NEN B 15-001 Type A+ are available in Belgium. The Flemish precast concrete industry is interested in incorporating such RCA in concrete products to enhance competitive advantages. This paper provides a feasibility study of using the commercial RCA to develop high-performance concrete (HPC) for structural precast concrete elements. The coarse natural aggregate was partially or fully replaced by RCA with a similar particle size distribution, and the replacement percentage were 0%, 30%, 50% and 100% in volume. The physical and mechanical properties and durability of concrete were tested. The results indicated that the incorporation of RCA had different effects on the various properties of concrete. It is feasible to produce HPC with RCA when concrete is appropriately designed and produced.

Keywords: High-performance concrete, Recycled concrete aggregate, Early-age strength, Carbonation resistance, Freeze-thaw resistance with de-icing salts

1 Introduction

High-performance concrete (HPC) is defined as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices [1]. These requirements for HPC typically involve qualified mechanical properties, high workability, high durability and high volume stability [2]. Carefully selecting, controlling, and proportioning all of the ingredients will achieve effective production of high-strength concrete [3], but this will not, by itself, ensure durable concrete. Appropriate placement practices and workmanship are essential to the production of durable concrete [4].

Recycled concrete aggregate (RCA) is defined as aggregate resulting from the processing of inorganic material previously used in construction, comprising a minimum of 90% crushed concrete [5]. Compared with natural aggregates, RCA generally has lower purity, higher porosity and lower resistance to fragmentation, and therefore, it is questionable whether RCA can be used to develop HPC.

A few experimental investigations [6-12] have shown some feasibilities of producing HPC with RCA, and the following general conclusions have been drawn: a) the mix design of concrete with RCA is very similar to natural aggregate concrete (NAC) [6]; b) properties of concrete with RCA may be significantly improved by using mineral additions and chemical admixtures, similarly to cases of NAC [6,11]; c) the quality of RCA has significant influence on the mechanical properties of concrete [6-10], and concrete containing RCA derived from high-strength concrete (approximately 80-100 MPa) may achieve performance similar to NAC [8]; d) the replacement percentage of natural aggregate significantly affects concrete properties [7,10-12]; e) an extra amount of water is required to compensate for the high water absorption of RCA [6]; f) utilizing RCA in concrete has satisfactory workability, but the concrete with RCA will have slump-loss higher than NAC due to the absorption process of RCA [8]; g) the compressive strength at an early age (24h) is more dependent on the free water content during mixing rather than the use of RCA [7]. In addition to those findings, knowledge about the effect of high-quality RCA on structural precast concrete elements is rather limited. In other words, it is not clear whether the existing conclusions still apply to HPC with a strength class greater than C50/60.

This study aims to evaluate the feasibility of incorporating commercial high-quality coarse RCA in HPC for precast industry. Taking the findings above into account, the following approaches were adopted, such as using conventional HPC mix design, adding superplasticizer and compensation water, considering appropriate replacement percentage, and following proper mixing, placing and curing practices. For the HPC, structural precast concrete elements commonly require high early compressive strength for hosting, reaching 40 MPa in cubic specimens at the age of 14 hours for example. When concrete is exposed to significant attack by freeze-thaw cycles whilst wet, such as precast concrete pavements and bridge decks in cold climates, high freeze-thaw resistance with de-icing salts (scaling) is required. In this work, a total of eight HPC mixes were produced and tested.

2 Experimental program

2.1 Materials

Portland cement, CEM I 52.5 R conforming to NBN EN 197-1 [13], was used to obtain high early strength. The specific surface of the cement was 5270 cm^2/g. Superplasticizer, Sika ViscoCrete-4035M, was used to obtain a high workability. The used RCA was derived from demolished concrete pavement, produced using a jaw crusher followed by an impact crusher at a local recycling plant, and conformed to the Type A+ category according to the Belgian standard NBN B 15-001 [14]. **Fig. 1** shows a photo of the RCA and **Fig. 2** presents the particle size distributions of RCA and limestone. **Table 1** summarizes the basic properties of the aggregates.

Fig. 1. Photo of 6.3/14 mm recycled concrete aggregate

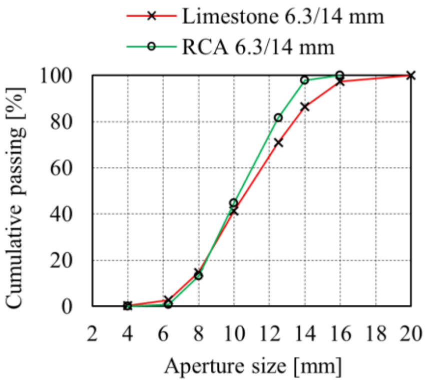

Fig. 2. Particle size distributions of recycled concrete aggregate (RCA) and limestone

Table 1. Physical and mechanical properties of the aggregates

Property	Sand	Limestone	Limestone	RCA	Standard
d/*D* [mm]	0/4	2/6.3	6.3/14	6.3/14	NBN EN 933-1 [15]
FM	2.3	-	-	-	NBN EN 12620 [16]
FI [%]	-	-	14	10	NBN EN 933-3 [17]
Rc [%]	-	-	-	Rc_{90}	NBN EN 933-11 [18]
M_{DE} [%]	-	-	16	17	NBN EN 1097-1 [19]
LA [%]	-	-	17	24	NBN EN 1097-2 [20]
ρ_a [kg/m^3]	2600	2710	2680	2660	NBN EN 1097-6 [21]
ρ_{rd} [kg/m^3]	2580	2680	2630	2380	
ρ_{ssd} [kg/m^3]	2590	2690	2650	2470	
WA_{24} [%]	0.4	0.5	0.8	4.8	

d/*D*: Particle size; *FM*: Fineness modulus; *FI*: Flakiness index; *Rc*: Mass content of crushed concrete and crushed mortar in coarse recycled aggregates; M_{DE}: Micro-Deval coefficient; *LA*: Los Angeles coefficient; ρ_a: Apparent particle density; ρ_{rd}: Oven-dried particle density; ρ_{ssd}: Saturated and surface-dried particle density; WA_{24}: Water absorption.

2.2 Concrete mixes and specimen preparations

According to ACI 211.4R [3] and NBN B 15-001 [14], eight concrete mixes were designed, as shown in **Table 2**. The moisture content of RCA was between 2.2% and 3.2%. This value is a function of the aggregate storage locations and the weather conditions on site [22]. A two-stage mixing approach [23] was adopted in the production of concrete. Cylindrical specimens Ø150 mm × 300 mm were used to determine the density, ultrasonic pulse velocity, compressive strength, elastic modulus and surface electrical resistivity. Prismatic specimens 100 mm × 100 mm × 500 mm were used to determine the carbonation resistance. Cylindrical specimens Ø113 mm × 50 mm were used to determine the freeze-thaw resistance with de-icing salts. The cylindrical specimens were cured in water at a temperature of (20 ± 2) °C until 28-day age. The prismatic specimens were cured in the climate room with the temperature of (20 ± 2) °C and the relative humidity of (80 ± 10) % until 7-day age, and then dried under indoor ambient conditions until 28-day age. Cubic specimens were cured in water until 7-day age and then dried under ambient conditions. At 21-day age, cylindrical specimens Ø113 mm × 50 mm were drilled and sawed out of these cubic specimens, and then dried under ambient conditions. At 28-day age, the test surfaces of the cylindrical specimens were saturated with water. At 31-day age, the water was replaced by 3% NaCl solution, and the prepared specimens were placed into a freeze-thaw chamber.

Table 2. Mix proportions and design parameters

Component [kg/m^3]	H40-0	H40-30	H40-50	H40-100	H30-0	H30-30	H30-50	H30-100
Cement	424	424	424	424	492	492	492	492
Water	170	170	170	170	148	148	148	148
Compensation w	10	18	23	37	10	18	23	37
Sand 0/4	758	758	758	758	758	758	758	758
Limestone 2/6.3	191	191	191	191	191	191	191	191
Limestone 6.3/14	763	534	381	0	763	534	381	0
RCA 6.3/14	0	207	345	691	0	207	345	691
Superplasticizer	1.9	1.9	1.9	1.9	4.4	4.4	4.4	4.4
w/c_{eff}	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30
Paste [m^3/m^3]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Agg. [m^3/m^3]	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
RCA [m^3/m^3]	0	0.09	0.15	0.29	0	0.09	0.15	0.29

2.3 Test

The consistency of the freshly mixed concrete was determined according to NBN EN 12350-2 [24]. The air content of freshly mixed concrete was determined according to NBN EN 12350-7 [25]. The density of hardened concrete was determined according to NBN EN 12390-7 [26]. The ultrasonic pulse velocity of concrete was determined according to NBN EN 12504-4 [27]. The compressive strength was determined according to NBN EN 12390-3 [28]. The secant modulus of elasticity was determined according to NBN EN 12390-13 [29]. The surface electrical resistivity was determined using Proceq Resipod. The resistance to carbonation was determined according to NBN EN 13295 [30]. The freeze-thaw resistance with de-icing salts was determined according to NBN B 15-100 [31], but the saw cut surface, instead of the side, was used as the test surface according to CEN/TS 12390-9 [32].

3 Experimental results and discussion

3.1 Physical properties of fresh and hardened concrete

For the slump test, according to visual inspections, all concrete cones remained substantially intact and symmetrical, and thus these slump tests were valid. The results are shown in **Table 3**. For the H40 series mixes, the concrete with RCA achieved similar or even higher slump than NAC. As reviewed by Verian et al. [33], due to the high water absorption, rough surface and irregular particle shape of RCA, the replacement of natural aggregate by RCA usually decreased the workability of concrete. However, in this study, a certain amount of water was already used to compensate the high water absorption of RCA. For the H30 series mixes, the slump varied largely, and the variation in fines content was considered one of the decisive parameters.

The measured air contents of fresh concrete are shown in **Table 3**. No clear relation between the RCA content and the air content was observed. According to ACI 318 [34], for the concrete considered in this study, the minimum entrained air content is required to be 4% to 6% to resist damage from freeze-thaw cycles.

The results of density and ultrasonic pulse velocity of hardened concrete are shown in **Table 3**. As expected, an increase in RCA content reduced the density and ultrasonic pulse velocity. The ultrasonic pulse velocity was not less than 4.50 km/s [7], indicating excellent performance for normal weight concrete (density of 2400 kg/m^3).

Table 3. Physical properties of freshly mixed and hardened concrete at 28-day age

Notation	Slump class	Air content	No. of samples	Density		Ultrasonic pulse velocity	
				μ	σ	μ	σ
		[%]		[kg/m^3]		[km/s]	
H40-0	S4	3.9	9	2380	10	4.97	0.05
H40-30	S4	3.5	12	2360	10	4.89	0.03
H40-50	S5	3.7	12	2340	10	4.85	0.02
H40-100	S4	4.3	12	2330	10	4.50	0.03
H30-0	S4 [a]	4.2	12	2420	40	5.00	0.04
H30-30	S3 [b]	2.9	6	2400	10	4.99	0.02
H30-50	S3	3.2	12	2390	10	4.94	0.02
H30-100	S5	3.0	12	2370	10	4.85	0.01

[a] The second batch of concrete obtained S1 slump class, showing a low workability. After 15s of vibration, the fresh concrete liquefied and the top surface leveled, showing that the concrete was well compacted, so the produced specimens were retained for tests.

[b] The first batch of concrete obtained no slump, and the fresh concrete did not liquefy after compaction, so this batch of concrete was rejected.

3.2 Mechanical properties of concrete

The results of the compressive strength tests are presented in **Table 4**. For both series, the concrete with RCA obtained lower compressive strength than NAC, and the maximum strength loss was 8.0% when comparing H30-50 with H30-0, but H40-100 reached a similar compressive strength to H40-0. González-Fonteboa et al. [35] developed a database and reported that in most cases the use of coarse recycled aggregates decreased the compressive strength, and in a few cases increased the strength. In the current study, the variation in the water absorption of RCA might cause a change in the real *w*/*c* ratio of concrete, resulting in a scatter in concrete strength.

Fig. 3 presents the rate of compressive strength developed at 18 hours to that at 28 days. According to EN 1992-1-1 [36], when CEM 52.5 R is used, the compressive strength of concrete at the age of 18-hour is estimated to be 36% of the concrete strength at the age of 28 days, which was lower than the values in the current study.

Gonzalez et al. [7] reported a similar case study on precast concrete in which cement dosage was only 380 kg/m^3, no mineral additions were used, and the slump was S1. Their concrete achieved about 55%~75% of the 28-day strength at 1-day age.

The results of elastic modulus are shown in **Table 4**. For both series mixes, the concrete with RCA obtained lower elastic modulus than NAC, and the maximum decline was 7.8% when comparing H40-100 with H40-0, but H40-30 and H30-50 obtained similar values to NAC. Gonzalez et al. [7] reported a clear decline in the elastic modulus of concrete with RCA, and they commended that elastic modulus seemed to be more sensible than strength to the RCA content. Verian et al. [33] commented that the variation in the elastic modulus of concrete appeared to be lower compared to the compressive strength. The current study obtained a similar tendency but with a certain variation. In addition, the H40 series mixes showed relatively high values of elastic modulus. **Fig. 4** presents the test data for each test specimen, and estimations according to ACI 318 [34], CEB-FIP [37] and EN 1992-1-1 [36].

Table 4. Compressive strength and elastic modulus of concrete

Notation	$f_{cm,cyl-18h}$			$f_{cm,cyl-28d}$			$E_{c,s-28d}$		
	n	μ	σ	n	μ	σ	n	μ	σ
		[MPa]			[MPa]			[GPa]	
H40-0	3	35.4	0.6	9	71.3	1.5	3	43.4	1.3
H40-30	6	31.8	2.6	12	66.7	2.7	6	43.9	1.6
H40-50	6	32.7	1.1	12	65.9	2.6	6	40.7	0.8
H40-100	6	36.1	2.3	12	70.2	4.6	3	40.0	0.9
H30-0	3	54.5	1.0	12	91.5	2.6	6	44.5	1.9
H30-30	3	55.3	0.3	6	85.6	2.9	3	42.9	0.8
H30-50	3	52.4	0.5	12	84.2	2.4	6	44.8	1.4
H30-100	3	54.1	0.8	12	85.4	6.8	6	43.0	1.7

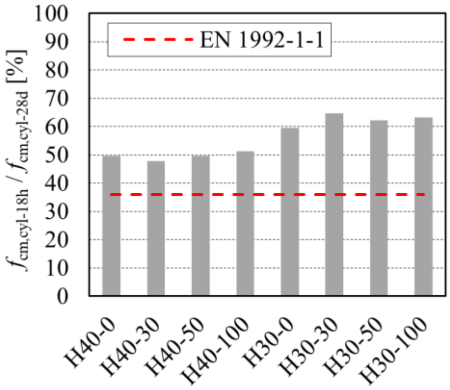

Fig. 3. Ratio of the compressive strength developed at 18 hours to the compressive strength at 28 days

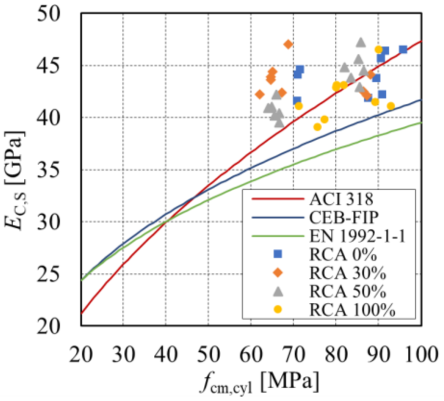

Fig. 4. Relationship between the secant elastic modulus and the cylindrical compressive strength

3.3 Durability of concrete

The results of surface electrical resistivity are shown in **Table 5**. The higher the surface electrical resistivity, the lower the likelihood of corrosion. The H30 series mixes achieved higher resistivity than the H40 series mixes. It was likely due to the fact that a lower *w*/*c* ratio or a lower amount of mixing water resulted in less porosity of hardened concrete. This was consistent with the change in concrete density. For both series mixes, an increase in RCA content decreased the resistivity, and the maximum reduction was 7.6% when comparing H30-100 with H30-0. Langford et al. [38] proposed the following four corrosion risk levels: very high (0~5 kΩcm), high (5~10 kΩcm), moderate (10~20 kΩcm) and low (larger than 20 kΩcm). Gonzalez et al. [7] reported resistivity of about 10~33 kΩcm for HPC with or without RCA. Therefore, all the concrete mixes considered in the current study showed a low or moderate risk to corrosion.

The results of carbonation depth are shown in **Table 5**. Both series mixes did not exhibit a clear carbonation front. Mixes of the H40 series had fade edges, whereas mixes of the H30 series had negligible edges, so the latter achieved higher resistance than the former. It was likely due to the fact that a lower *w*/*c* ratio or a higher amount of ordinary Portland cement resulted in less porosity and higher CO_2 buffer capacity in concrete. Sáez del Bosque et al. [39] adopted derivative thermogravimetry (DTG) to analyze the carbonation profile, and then compared with the carbonation depth determined by the phenolphthalein method. Both methods showed that the degree of carbonation in recycled aggregate concrete was higher than that in NAC. In the current study, the concrete with RCA showed comparable resistance to carbonation as NAC. A continuation of this test is necessary to draw further conclusions.

Table 5. Surface electrical resistivity, carbonation depth and salt scaling of concrete

Notation	ρ_s				$d_{\text{k-56d}}$	$d_{\text{k-91d}}$		S_{28}		S_{56}	
	n	μ	σ	n	μ	μ	n	μ	σ	μ	σ
		[kΩcm]			[mm]	[mm]		$[\text{kg/m}^2]$		$[\text{kg/m}^2]$	
H40-0	9	14.0	0.3	2	1.9	2.2	12	0.06[a]	0.06	0.20[a]	0.21
H40-30	12	13.4	0.3	2	2.0	2.1	6	0.18	0.13	0.26	0.16
H40-50	12	13.1	0.3	2	2.0	2.2	6	0.27	0.24	0.47	0.45
H40-100	6	12.6	0.7	2	2.0	2.3	6	0.07[a]	0.10	0.12[a]	0.13
H30-0	12	22.3	1.6	2	0	1.2	6	0.01	0.02	0.03	0.02
H30-30	6	22.1	0.3	2	0	0.6	6	0.06	0.04	0.09	0.04
H30-50	12	21.3	0.7	2	0	1.0	6	0.06	0.06	0.10	0.08
H30-100	12	19.4	1.3	2	0	0.9	6	0.15	0.04	0.23	0.04

[a] Test surfaces were formed surfaces.

The results of freeze-thaw test with de-icing salt are shown in **Table 5**. The H30 series mixes obtained lower mass loss than the H40 series mixes. It was likely due to the fact that a lower *w*/*c* ratio or a lower amount of mixing water resulted in higher strength and less capillary pores in the hardened cement paste. For both series, the concrete with RCA obtained higher mass loss than NAC, except for H40-100 which obtained lower mass loss. Based on visual inspection, it was observed that the scaling was strongly related to the RCA exposed on the saw cut surface. In particular, the attached mortar and crushed mortar particles in the RCA were prone to crumbling and peeling off under freeze-thaw attack with deicing salts. In addition, all concrete mixes exhibited limited scaling. NBN EN 13877-2 [40] specifies three freeze-thaw resistance categories (FT0, FT1 and FT2) for concrete pavements cast in situ and recommends the tests in accordance with CEN/TS 12390-9 [32]. In fact, the two test methods specified in NBN B 15-100 [31] and CEN/TS 12390-9 [32] are based on the so-called slab test [41]. The main differences lie in the size of the test specimens, the test surface of specimens and the methods of evaluating the degree of freeze-thaw damage. In the current study, the salt scaling on the saw cut surface was studied, and all the concrete mixes were considered to achieve high salt scaling resistance and conform to the FT2 category.

4 Conclusions

A Belgian case study was carried out to evaluate the feasibility of using commercial high-quality coarse RCA to develop HPC for precast industry. The following conclusions were drawn:

Concrete with RCA achieved workability and air content comparable with NAC. However, fines present in the RCA may largely decrease the workability.

Concrete with RCA obtained density and ultrasonic pulse velocity lower than NAC.

Concrete with RCA showed 18-hour compressive strength comparable with NAC, and 28-day compressive strength and elastic modulus lower than NAC.

Concrete with RCA obtained surface electrical resistivity lower than NAC carbonation resistance comparable with NAC, and freeze-thaw resistance with de-icing salts lower than NAC. The salt scaling mainly occurred at the attached mortar and crushed mortar particles present in the RCA.

Although the incorporation of RCA affects various properties of concrete, HPC can be developed when low water/cement ratio, superplasticizer, compensation water and two-stage mixing approach are considered.

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