Defining Limits for Standardization on Concrete Incorporating Recycled Concrete Aggregates

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Abstract. This study is part of a pre-normative research (BBRI/CRIC-OCCN/BRRC) to underpin the use of recycled concrete aggregates (RCA) in the production of ready-mixed concrete in the Belgian concrete standard (NBN B15-001). Therefore, mechanical and durability properties of concrete incorporating coarse recycled concrete aggregates, originating from different recycling plants, have been assessed.

Recycled aggregates of maximal particle size 20 mm have been thoroughly characterized in order to evaluate their current quality and aptitude for use in concrete, with a special focus on resistance to freezing, quantification of floating material and chemical composition since there was few data available.

Six types of recycled aggregates were selected for further testing on concrete. Concrete mixes (23 in total) with a water to cement ratio of 0.50 and a cement content of 320 kg/m^3 were produced, varying following parameters: type of RCA, replacement rate (0%, 20%, 30% and 50%), saturation state (dried, partially saturated and fully saturated) and type of cement (slag cement and ordinary Portland cement). The fresh and hardened properties of concrete were determined (slump, density, air content, compressive strength, modulus of elasticity, shrinkage and carbonation) in order to define the feasible but safe area of application for these RCA.

The results show that high quality recycled concrete aggregates can be produced and are suitable for use in concrete. This enables the production of concrete with relatively constant and predictable behaviour. Similar performance as reference concrete, even at high replacement rates, can be obtained.

Keywords: Recycled concrete aggregates (RCA) · Recycled aggregates concretes (RAC) · Mechanical properties · Sustainability · Durability

1 Introduction

The use of recycled concrete aggregates (RCA) into new concrete is a compelling solution to lower the environmental impact of concrete (extraction and depletion of natural resources) and at the same time to reduce the huge amount of construction and demolition waste (CDW) (Bravo et al. 2015). There have been various researches in the past years as presented in recent state of the art documents (Vyncke and Vrijders 2016

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and a report from RILEM Technical Committee 217-PRE 2013), but, as Bravo et al. highlighted, few studies analysed recycled aggregates from several CDW recycling plants for the use in concrete production, such as Barbudo et al. (2013) and Xiao et al. (2012). For example, Xiao et al. (2010) worked with crushed laboratory concrete cubes as recycled aggregates.

There is a general consensus that using about 30% of coarse recycled aggregates does not significantly alter the concrete properties (de Brito and Saikia 2013). The new concrete European standard EN 206: 2013 allows such replacement rate for outdoor applications but does not specify any strength class limit. That is why the Belgian Building Research Institute (BBRI) together with the National Centre for Scientific and Technical Research for the Cement Industry (CRIC-OCCN) and the Belgian Road Research Centre (BRRC) started a pre-normative research project to clearly define realistic application limits. The aim of this project is to study a large panel of recycled aggregates and their effects on the properties of concrete.

The first phase consisted in a thorough characterization of coarse RCA (> 4 mm) originating from 9 different recycling plants. Then 6 batches of RCA were selected for the production of concrete. The fresh and hardened properties have been assessed with the following study parameters: type of RCA, replacement rate, saturation state and type of cement. This paper only presents part of the research's results.

2 Experimental Program

2.1 Recycled Concrete Aggregates

Coarse recycled concrete aggregates of maximal particle size of 20 mm, coming from 9 different recycling plants, named A to I, were considered. They serve as a representative sample of the quality of RCA available in Belgium. Table 1 presents the characteristics (size, origin of debris and type of crusher) of the plants that provided the 6 selected batches for the concrete testing. It shows that some plants apply a selective intake (only road and precast concrete waste for example) and some use a two stage crushing process.

Table 1. Characteristics of the different recycling plants.

Plant	Size	Origin of debris	Type of crusher
A	8/20	Road and concrete plant waste	Impact crusher (twice)
B	4/20	Road, buildings, precast concrete waste	Jaw crusher and impact crusher
C	4/20	Various	Jaw crusher and cone crusher
D	8/20	Road and precast concrete waste	Jaw crusher and impact crusher
G	4/16	Various high quality applications	Impact crusher
I	6/20	Various	Jaw crusher

2.2 Concrete Mixes

23 concrete mixes with a water to cement ratio of 0.50 and a cement content of 320 kg/m^3 were produced, with an aimed strength class of C30/37. This type of concrete is specified by the Belgian standard NBN B15-001 for outdoor applications subjected to rain and frost (XC4 and XF3 classes). The study parameters and their designations are shown in Table 2. The natural aggregates (NA) consist in rolled sand and crushed limestone. The coarse NA were replaced in volume with RCA (20%, 30% and 50%). The same grading curve was used for all the mixes. The mainly used cement is a blast furnace slag cement CEM III/A 42,5 N LA. Some mixes have also been made with a Portland cement CEM I 42,5 N. The mix proportions of concretes B-0 (reference concrete) and B-30A are detailed in Table 3 as an example. The dosage of the polycarboxylic-ether superplasticiser was adjusted for each mix to reach a consistency class S4. The water absorbed by the aggregates and supplied by the admixture has been taken into account in the mixing water.

Table 2. Study parameters and their designation.

Study parameter	Designation	Meaning
Type of RCA	B-30**A** B-30**B**	Concrete with 30% recycled aggregates A or B which are pre-saturated
Replacement rate (in volume)	B-**20**A B-**50**A	Concrete with 20% or 50% recycled aggregates A which are pre-saturated
Saturation state	B-30A-**S0** B-30A-**SN**	Concrete with 30% recycled aggregates A which are dried or partially saturated
Type of cement	B-30A-**P**	Concrete with 30% recycled aggregates A which are pre-saturated, made with Portland cement CEM I 42,5 N instead of CEM III/A 42,5 N LA

Table 3. Concrete mix proportions (kg/m^3) of concrete mixes B-0 and B-30A.

Constituent	B-0	B-30A
Cement	320	320
Fines aggregates (rolled sand) 0/4	939	932
Coarse aggregates (crushed limestone) 4/20	926	653
Coarse recycled aggregates A	–	264
Superplasticiser[a] (%)	2.7	2.3
Mixing water	163	169

[a]The superplasticiser dosage (% by mass cement) was adjusted to reach a S4 consistency class.

The recycled aggregates are oven-dried and then pre-saturated in the mixer for 1 h with half of the mixing water. After the pre-saturation, the natural aggregates and cement are added and the whole is mixed for 2 min. Then the second half of the mixing water is added with the superplasticiser and the mixer runs for another 2 min. For some compositions, the recycled aggregates were directly used in dried (S0) or partially humid (SN) condition.

The concrete samples are conserved during 24 h at a temperature of 20° C and then placed under water at the same temperature for curing during a variable period depending on the test.

2.3 Testing Methods

The physical and chemical properties of the recycled concrete aggregates were determined according to standard EN 12620 "Aggregates for concrete". Some characteristics are presented in this paper: fines content (according to EN 933-1), density and water absorption (according to EN 1097-6), resistance to fragmentation (according to EN 1097-2), resistance to freezing and thawing (according to EN 1367-1), acid soluble chloride salts content (according to EN 1744-5), water soluble sulphates content (according to EN 1744-1 Sect. 10), lime soluble alkalis (according to XP P18-544) and the classification of the constituents (according to EN 933-11).

The fresh properties of concrete made with recycled concrete aggregates were measured according to standards EN 12350-2, EN 12350-6 and EN 12350-7 respectively for the slump, density and air content.

The compressive strength was measured at 28 days according to EN 12390-3 on three cubes of 15 cm side, which were cured under water at 20° C. The (static compression) modulus of elasticity was determined at 28 days on some mixes according to standard NBN B15-203 on 3 prisms of 10 cm × 10 cm × 40 cm. Total shrinkage deformations were measured on the same compositions with the same prisms size according to NBN B15-216 during 3 months. For the modulus of elasticity, the prisms were kept under water for 7 days and then conditioned 21 days in a climatic chamber at 20° C and 60% of relative humidity. For the shrinkage measurements, the samples were directly conditioned in a climatic chamber at 20° C and 60% of relative humidity.

Accelerated carbonation tests were performed according to EN 13295. Three prisms of 10 cm × 10 cm 40 cm in size were tested for each mix. After 28 days of curing under water, the samples were conserved in a climatic chamber at 20 ± 2° C and 60 ± 10% relative humidity during 14 days. Then they were transferred in the carbonation chamber with a CO_2 concentration of 1% at a temperature of 20 ± 2° C and relative humidity of 60 ± 10%.

3 Results and Discussion

3.1 Characterization of Recycled Concrete Aggregates

The physical and chemical properties of the 6 selected types of RCA are presented in Table 4 and their composition is shown in Table 5. The results show that RCA type A presents the highest density (2500 kg/m^3), lowest water absorption (2.9%), highest resistance to fragmentation (25%) and to freezing and thawing (1.2%), while RCA type C presents generally the worst characteristics (2280 kg/m^3 density, 6.6% WA_{24} and 36% LA). This might be explained by the origin of the debris collected by the recycling plants: road and concrete plant waste, thus good concrete for RCA type A, and various debris, thus containing a lot of contaminants (1.1% of ceramics Rb and 1.1% of asphalt Ra), for RCA type C. This could also explain the high sulphate content (0.2%) of type C. Recycling plant D also sorts the incoming CDW, resulting in RCA with better properties. RCA type G is characterised by a low density (2320 kg/m^3), high water absorption (5.8%), high LA (31%), the worst damage to freezing and thawing (15.2% F) and the highest chloride content (0.11%), while the recycling plant takes waste from various high quality applications. This difference might be explained by the different particle size (4/16 compared with 8/20 from RCA type A and D) and the use of one crusher compared to a two stage crushing process for A and D. RCA type G contains more contaminants (0.5% of ceramics Rb, 0.9% of asphalt Ra and 0.1% of wood, plastics) than A and D.

Table 4. Physical and chemical properties of the recycled concrete aggregates.

Property	Criteria	A	B	C	D	G	I
Fines (%)	≤ 1.5%	1.7	1.6	2.1	2.0	2.3	4.4
ρ_{rd} (kg/m^3)	≥ 2200 kg/m^3	2500	2320	2280	2400	2320	2310
WA_{24} (%)	≤ 10%	2.9	5.3	6.6	4.3	5.8	5.7
LA (%)	≤ 35%	25	30	36	25	31	31
F (%)	–	1.2	4.7	5.4	3.4	15.2	11.2
Cl (%)	–	0.06	0.04	0.05	0.06	0.11	0.09
SS (%)	≤ 0.2%	0.10	0.12	0.20	0.08	0.13	0.11
Alkalis (% Na_2O_{eq})	–	0.01	0.02	0.02	0.01	0.02	0.02

When comparing the results to the criteria for recycled aggregates for use in concrete from standard NBN B15-001, indicated in Tables 5 and 6, they all meet the requirements, except for the fines content and for RCA type C (LA > 35% and Ra > 1%). It was observed that the high fines contents differ from the results measured in situ. This divergence shall be further investigated.

Table 5. Composition of the recycled concrete aggregates (% in mass)

Constituent	Criteria	A	B	C	D	G	I
Concrete, mortar, unbound natural aggregates (Rcu)	≥ 95%	99.2	98.7	97.7	99.9	98.6	96.8
Ceramics (Rb)	–	0.0	1.0	1.1	0.1	0.5	0.6
Asphalt (Ra)	≤ 1%	0.0	0.0	1.1	0.0	0.9	2.6
Glass (Rg)	–	0.0	0.0	0.0	0.0	0.0	0.0
Wood, plastics, metals (X)	–	0.0	0.3	0.0	0.0	0.1	0.0
Floating material (FL cm^3/kg)	≤ 2 cm^3/kg	0.0	0.1	0.0	0.1	0.3	0.1

3.2 Fresh Properties of Concrete

The results on fresh concrete (slump, density and air content) as well as the dosage of superplasticiser (SP) are indicated in Table 6. The dosage of SP is higher for mixes with Portland cement and stays relatively constant for all the mixes with cement CEM III/A. Except for B-30B and B-20A, all the concrete mixes reached a S4 consistency class (slump of 160–210 mm). Concrete mixes made with RCA present a lower density than concretes with NA but the decrease is not proportional to the replacement rate. For example, concrete B-30C with 30% of RCA has a similar density as B-20C with 20%. The difference in density between B-30G (30%) and B-50G (50%) is not significant either.

The high air content ($\geq 3\%$) observed for most concrete mixes may be due to the relative high dosages of superplasticiser. There is a relationship between the air content and density but the linear correlation is not pronounced.

3.3 Hardened Properties of Concrete

The hardened concrete properties (compressive strength, modulus of elasticity, shrinkage deformations and carbonation depth) of the 23 mixes are shown in Table 6.

The compressive strengths at 28 days of all the mixes are not significantly different. The effects of the replacement rate, type of RCA (see Fig. 1) and pre-saturation are not obvious. The average compressive strength is reduced by 7%, 11% and 13% respectively for concrete mixes with 20%, 30% and 50% replacement rate. Concrete mixes with Portland cement shows in general slightly higher strengths. All the concrete mixes reach the aimed strength class C30/37.

The carbonation depths after 28 days at 1% concentration of CO_2 are higher or lower for concrete mixes with RCA than for reference concretes. The effects of the

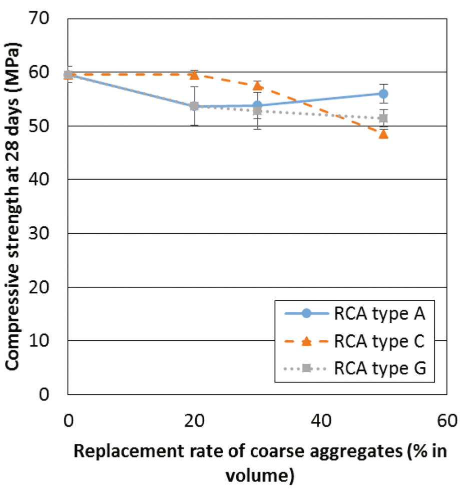

Fig. 1. Compressive strength versus replacement rate.

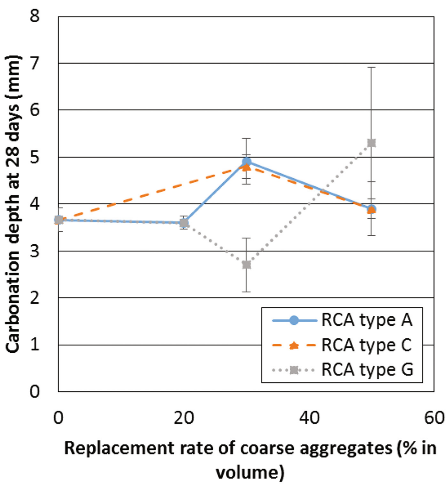

Fig. 2. Carbonation depth versus replacement rate.

Table 6. Fresh and hardened properties of the 23 concrete mixes.

Concrete mix	Dosage SP(%)	Slump (mm)	Density (kg/m^3)	Air content (%)	Compressive strength at 28 days (MPa)	Modulus of elasticity at 28 days (GPa)	Total shrinkage at 91 days (μm/m)	Carbonation depth at 28 days (mm)
B-0	2.7	182	2357	2.9	59.6	34.3	413	3.7
B-30A	2.3	183	2348	2.9	53.8	–	–	4.9
B-30C	2.3	175	2319	2.9	57.5	–	–	4.8
B-30G	2.1	155	2286	3.8	52.8	–	–	2.7
B-30B	2.7	150	2271	3.8	51.1	–	–	2.5
B-30D	2.5	190	2273	3.8	54.9	–	–	4.2
B-30I	2.5	165	2290	3.2	49.2	–	–	4.5
B-20A	2.2	150	2295	4.1	53.7	33.9	440	3.6
B-20C	2.5	180	2314	3.2	59.6	35.1	–	3.5
B-20G	2.5	170	2304	3.2	53.7	–	–	3.6
B-50A	2.5	180	2280	4.4	56.0	30.5	469	3.9
B-50C	2.5	200	2254	3.3	48.6	–	–	3.9
B-50G	2.3	165	2276	3.8	51.5	–	–	5.3
B-30A-S0	2.3	160	2288	3.9	50.5	–	–	4.3
B-30C-S0	2.3	160	2281	3.8	50.1	–	–	1.3
B-30G-S0	2.4	170	2296	3.0	46.7	–	–	4.8
B-30A-SN	2.5	190	2360	2.4	60.8	–	–	3.7
B-30C-SN	2.5	205	2323	2.0	56.6	–	–	3.7
B-30G-SN	2.5	170	2345	2.9	53.8	–	–	3.7
B-0-P	3.0	200	2365	2.7	61.0	–	–	0.8
B-30A-P	2.8	170	2353	3.0	59.3	–	–	0.4
B-30C-P	2.8	190	2370	2.1	55.6	–	–	0.5
B-30G-P	2.8	160	2335	3.0	59.3	–	–	0.7

parameters are not clear, as illustrated in Fig. 2. The carbonation depth of concrete B-0-P is 77% lower than concrete B-0. It is well known that Portland cement has a better resistance to carbonation than blast furnace slag cement, as it contains more calcium hydroxide.

The modulus of elasticity of concrete mixes B-0 (reference), B-20A and B-20C are not substantially different. The result of B-50A with a 50% replacement rate decreases by 11% compared with B-0. This limited decrease might be due to the use of RCA type A which presents the best characteristics. The total shrinkage deformations of concrete mixes B-20A and B-50A are similar to the reference concrete B-0.

4 Conclusions

The characterization of the recycled concrete aggregates (RCA) coming from different recycling plants in Belgium shows that most of the RCA are of good quality (density > 2300 kg/m^3, water absorption < 6% and limited contaminants), due to the selective intake (high quality debris) and specific crushing process (two crushers).

The effects of the different types of RCA, replacement rate of coarse aggregates and pre-saturation on the properties of concrete are not substantially distinct, while the influence of the cement type is more pronounced. In general, the mechanical performance (compressive strength, modulus of elasticity, shrinkage) of concrete mixes with RCA is similar to reference concretes with only natural aggregates. The resistance to carbonation depth of concrete mixes with RCA is often lower than reference concretes but some mixes show a better resistance as well.

The results of this study show that it is possible to produce concrete with RCA with relatively constant and predictable behaviour. Even at 50% replacement rate, the performance of concrete can be similar to the reference concrete. The authors suggest that the use of concrete with 30% replacement rate can be considered safe and feasible for outdoor applications subjected to carbonation, especially when RCA of good quality is used. The resistance to freezing and thawing will be further examined.

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