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Experimental evaluation of the high-grade properties of recycled concrete aggregates and their application in concrete road pavement construction

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Abstract

In Flanders, up to 20 % of the coarse natural aggregates in concrete mixtures for certain applications in road pavement construction may be replaced by high-grade recycled concrete aggregates (RCA). The RCA and resulting recycled aggregate concrete (RAC) have to comply with the high-grade criteria specified in the Flemish 'Standard Tender Specifications 250 version 3.1' and require extensive and time-consuming testing procedures, leading to reluctance in effectively prescribing and using recycled aggregates. The objective of this case study is therefore to draw up practical recommendations for the rapid identification of high-grade RCA. RCA from different sources are investigated and subsequently used in two concrete road pavement construction applications, namely linear elements and applications within the Flemish concrete construction class 'BF' (i.e. cycle paths, footpaths and agricultural roads). The experimental results indicate that the aggregate density along with the water content appear to be good predictors for the resistance to abrasion (i.e. the Los Angeles coefficient). The aggregate experiments also show that, in order to fulfill the aforementioned tender specifications criteria, it is important to demolish and store the source material in such a way that no contamination with non-concrete materials (such as ceramics) takes place, maintaining a high specific density. The experiments on RAC, on the other hand, show that an aggregate replacement rate of up to 40 % of the coarse fraction has no detrimental effect on the mechanical and durability performance. When comparing the results of both aggregate and concrete experiments, they show that freeze-thaw resistance of the concrete aggregates has slight to no impact on the freeze-thaw resistance of the concrete.

Keywords:
Recycled concrete aggregates, Recycled aggregates concrete, Concrete road pavement construction, Freeze-thaw resistance

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1. Introduction and previous research

Most aggregates used in concrete are still of natural origin, i.e. mined in quarries or dredged in rivers and seas. The advantage is their homogeneous nature, yet the disadvantage is that these raw materials are not available in unlimited quantities and their exploitation has an immense influence on the local fauna and flora. The use of recycled concrete aggregates (RCA) to replace natural aggregates represents a major step towards a circular economy. Moreover, in Flanders concrete plants are nearby or temporarily built on construction sites in which avoiding the use of finite primary raw materials leads to a reduced transportation footprint due to the local availability of the recycled materials and to a reduction of waste dumping. However, the use of RCA is still limited, in particular in road pavement construction, since the aggregate and concrete properties have to meet the high-grade criteria specified by the Flemish 'Standard Tender Specifications 250 version 3.1' [1] which require extensive testing procedures, often beyond the practical capabilities of concrete production plants.

The mechanical properties of RCA such as the density, water absorption, and Los Angeles (*LA*) coefficient are dependent on the quantity and quality of the adhering mortar [2, 3]. More specifically, the quality of the mortar depends on the water/cement ratio of the source concrete and the quantity depends on the crushing process and the compressive strength of the source concrete [4, 5]. In general, high-strength concrete with a low water/cement ratio leads to RCA with higher densities and lower water absorption coefficients. Moreover, previous studies [6, 7, 8] indicate that also the *LA* coefficient is influenced by the strength of the source concrete. Furthermore, Li et al. [9] indicate that the *LA* coefficient can be improved by adjusting the crushing process. Finally, research by the Public Waste Agency of Flanders (OVAM) [10] has shown that these mechanical properties only depend to a very limited extent on the equipment of the sorting installations.

The main characteristic of recycled aggregates that separates them from natural aggregates, is the water absorption, which is usually measured in a time span of 24 hours (WA_{24}). In this process, recycled aggregates absorb five to ten times more water due to the increased porosity of the adhered mortar [11]. This absorption is mainly between 3 and 8 % for RCA, whereas this is limited to a few percents (0.5 – 1.5 %) for natural aggregates [4, 12]. Furthermore, RCA have a 5 to 15 % lower particle density (2000 – 2400 kg/m^3) than natural aggregates because the density of the adhered mortar is lower than the density of the natural agregates [13]. Subsequently, the water absorption shows a strong relationship with the density of the concrete aggregates [2, 4, 14, 15]. In addition, Younis et al. [16] determined a strong relation between ρ_{rd} and the *LA* coefficient. Finally, Omary et al. [17] also found a relationship between the water absorption and the *LA* coefficient.

A lot of knowledge has already been collected related to the use of RCA in concrete mixtures for building construction applications, specifically focusing on the increased water requirement of RCA. Sami and Thomas et al. [6, 18] found that the compressive strength of recycled aggregate concrete (RAC), in case of using high-grade RCA, did not differ much from the reference concrete made using only natural aggregates. In general, it can be concluded that the difference in compressive strength is minimal when the replacement rate is less than 30 % of the coarse fraction [9, 19, 20, 21]. This seems to be an optimum, since higher replacement rates may lead to lower compressive strengths.

Limited research has been done on road construction applications, in which different and often stricter requirements are set compared to RAC for use in buildings. For instance, durability is a crucial parameter for concrete road construction as the concrete is exposed to rain, frost and de-icing salts. Recent pre-normative research in Belgium [22] showed that for replacements rates of 20 up to 50 % no detrimental effects are to be expected on the concrete properties. Hasaba et al. [8] noted that mainly the adhered mortar on the RCA degrades in concrete which is subjected to freeze-thaw cycles. However, Yamato et al. [23] indicated that the freeze-thaw resistance of RAC did not diverge significantly from the reference NAC, in case of limited replacements rates of up to 30 %. In addition, Buck, Strand, Hendriks and Kaihua et al. [24, 25, 26, 27] also showed that the RAC had a comparable resistance to freeze-thaw cycles as the reference NAC, which is also confirmed by Gokce et al. [28] in which the source concrete was air-entrained. It can thus be concluded from the previous studies that the freeze-thaw resistance of RAC is good in general, but inferior aggregates can cause a reduced durability [11].

2. Research significance and objectives

Concrete road construction has an important contribution to the processing and application of RCA where, in Flanders, the latter are mainly used in foundations and sub-foundations. However, this is regarded as 'downcycling' because the potential of these RCA is not fully utilized. Nevertheless, the prevailing Flemish 'Standard Tender Specifications 250 version 3.1' (S250) [1] allows to replace a maximum of 20 % of the coarse fraction of the natural aggregates with high-grade RCA, but only in the bottom layer of two-layered pavements and in linear elements such as curbs. In future these RCA may also be used in concrete pavements of less loaded roads such as cycle paths, footpaths and agricultural roads, all belonging to construction class 'BF' in Flanders. However, the question arises whether this percentage can be increased and whether the current criteria for high-grade RCA, are sufficient or, on the contrary, too strict for obtaining a high-grade concrete end product. Moreover, as mentioned in the introduction, in order to assess the high-grade criteria for RCA, an extensive and time-consuming testing program is necessary, often exceeding the capabilities and time conditions of concrete plants. A first objective of this study is therefore to develop an accelerated and practical method to identify high-grade concrete aggregates. In a second stage, two road construction applications, linear elements and roads belonging to the aforementioned construction class 'BF', and corresponding concrete mixtures are investigated in which the coarse fraction of the natural aggregates are replaced by RCA variants. This is performed for a replacement rate of 20 % and 40 %, thus going beyond the current S250 specifications [1]. The freeze-thaw tests on the hardened concrete have been carried out according to prNBN B15-100 [29] which is based on the slab test [30], but the preparation of the specimens is different.

3. Experimental program

3.1. Recycled concrete aggregates

A total of twelve different RCA batches from different crushers in Belgium with various origin are defined by source and crushing process (see Table 3). The compressive strength of the source concrete is unknown. First, it can be observed from the grain size distributions in Figure 1, determined according to EN 933-1 [31], that the grain sizes are not in all cases within the requested fraction range [4 – 20] mm. In a next step, an identification test is carried out in accordance with EN 12620 [32] in which the content of the concrete/stone fraction Rcu, asphalt content Ra, glass and other content XRg, and the floating materials FL are determined. The high-grade specifications by S250 [1] require that the RCA meet the following identification test requirements: $Rcu \geq 95$ %, $Ra \leq 1$ %, $XRg \leq 0.5$ %, and $FL \leq 2$ %. S250 [1] also requires that the flakiness index, determined according to EN 933-3 [33], $FI \leq 20$ %, and the fine particle content, measured according to EN 933-1 [31], $f \leq 1.5$ %. On the other hand, it is required that the water absorption after 24 hours of immersion $WA_{24} \leq 10$ % and the oven-dry density $\rho_{rd} \geq 2200$ kg/m^3. Both parameters are determined in accordance with EN 1097-6 [34]. Furthermore, S250 [1] specifies that the resistance to abrasion $LA \leq 35$ %, which is determined according to EN-1097-2 [35]. Finally, the resistance to freeze-thaw cycli F is measured according to EN 1367-1 [36].

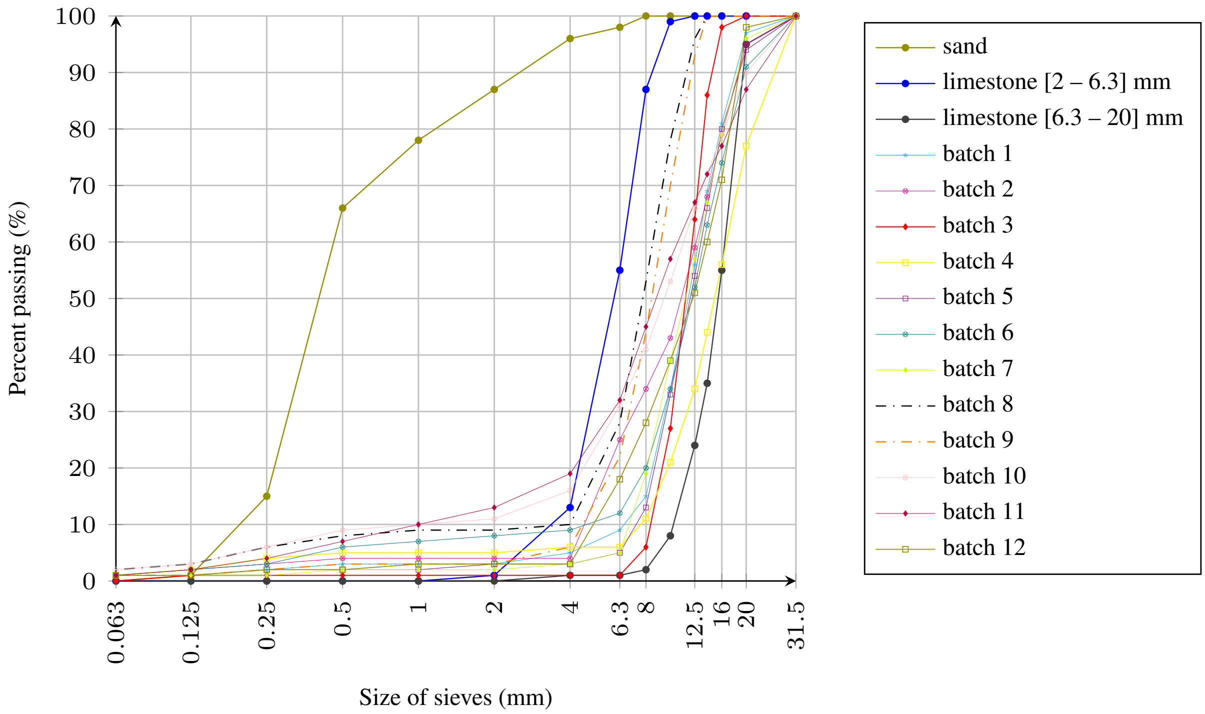


Figure 1: Grain size distribution of the twelve RCA batches, sand, and limestone used in this study.

3.2. Recycled aggregates concrete

3.2.1. Materials and mixtures

As a first application, concrete mixtures are designed for linear elements (denoted with 'LE') and secondly for concrete of construction class 'BF'. The composition of the mixtures for each application is in first instance defined for the reference, natural aggregate concrete (NAC). Subsequently, this mixture is adopted for each RAC mixture in which replacement rates of 20 and 40 % of the course natural aggregates with fraction [6.3 – 20] mm are considered according to the volume. As listed in Table 1, sand with fraction [0 – 4] mm and limestone with fractions [2 – 6.3] and [6.3 – 20] mm are used for both applications in order to obtain a good compactable concrete in which the grading is fit to the Fuller curve by the least squares method. No extra sieving of the RCA has be done in order to compensate for the different grading curves in Figure 1 resulting in concrete with different grading. The cement used in this study is CEM-III/A 42.5 LA in order to protect the concrete against alkali-silica reactions (ASR). On the one hand, a cement dosage of 360 kg/m^3 is used for the mixtures of the linear elements (S250 requires ≥ 350 kg/m^3) and, on the other hand, a cement dosage of 375 kg/m^3 is used for the concrete of construction class 'BF' (S250 requires ≥ 375 kg/m^3). Furthermore, regular tap water is used as mixing water to manufacture the concrete, where the effective water/cement ratio is 0.45 for the linear elements and 0.50 for the concrete mixtures 'BF' (S250 specifies ≤ 0.50). The effective water/cement ratio is related to the amount of water that is added to the concrete mixture which contributes to the workability, which implies that the water which is absorbed by the RCA cannot be taken into account because it does not contribute to a better workability. Finally, a plasticizer type TM (33 % per mass of cement) and an air-entraining agent type TM AEA-B (5 % per mass of cement) are also added to the mix, in correspondence with typical road pavement concrete.

Table 1: Concrete mix proportions used in this study.

	Application 1: Linear elements						Application 2: Construction class 'BF'					
	LE-NAC		LE20		LE40		BF-NAC		BF20		BF40	
Materials	$\frac{l}{m^3}$	$\frac{kg}{m^3}$	$\frac{l}{m^3}$	$\frac{kg}{m^3}$	$\frac{l}{m^3}$	$\frac{kg}{m^3}$	$\frac{l}{m^3}$	$\frac{kg}{m^3}$	$\frac{l}{m^3}$	$\frac{kg}{m^3}$	$\frac{l}{m^3}$	$\frac{kg}{m^3}$
Sand [0 – 4] mm	283	736	283	736	283	736	257	669	257	669	257	669
Limestone [2 – 6.3] mm	101	281	101	281	101	281	84	232	84	232	84	232
Limestone [6.3 – 20] mm	290	804	232	643	174	482	302	839	242	671	181	503
RCA 10-21 [6.3 – 20] mm			58		116				60		121	
Cement	124	360	124	360	124	360	129	375	129	375	129	375
Effective water	162	162	162	162	162	162	188	188	188	188	188	188
Air content	40		40		40		40		40		40	
Plasticizer	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
Air-entrainer	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72

3.2.2. Mixing method

The development of the water absorption over time of the RCA with fraction [4 – 20] mm as presented in Figure 2 is, with the exception of batches 8 and 9, characterized by a rising trend in the first two hours of immersion followed by a limited linear growth. The RCA show a relative water absorption after two hours of immersion (WA_2/WA_{24}) between 71.51 and 90.23 %, which is in line with the values found by Garcia-González et al. [37]. It can be noted that the development of the water absorption of batches 8 and 9 deviates strongly from the other curves, which may be explained by the largest grain size of 12.5 mm, which is significantly smaller than the other batches. In this regard, it was stressed by Garcia-González et al. [37] that the particle size, the ceramic particles content, and the quantity and quality of the adhered mortar have a significant influence on the saturation development of recycled aggregates.

All the aggregates in this study are used in oven-dry state (stage 1 of Figure 2) with adding additional water to the necessary mixing water, instead of using pre-saturated recycled aggregates, in order to control the effect of the of the higher water absorption of the recycled aggregates as recommended by Ferreira et al. [38]. Consequently all dosages of the total mixing water in the RAC mixtures are calculated by adding the water absorption of the RCA after two hours of immersion (WA_2), because of the high relative water absorption value, to the amount of the effective water used in the reference concrete. As a consequence, the total water volume will increase for increasing replacement rates of the coarse aggregates. The effective water/cement ratio is expected to be the same for each application because no consequences to the volumetric proportioning of materials exist, since the added additional water will be absorbed by the aggregates and will not contribute to the concrete volume. In this way, it is possible to enable a practical and objective comparison of the properties of the fresh and hardened concrete with different mixtures, according to the recommendation of Laserna et al. [39]. Mixing is done using the three-stage method in which the concrete aggregates are, in first instance, mixed with 25 % of the total mixing water for two minutes, in order to give the concrete aggregates time to absorb the water. Subsequently, the natural aggregates are added to the mixture. Finally, the cement is added along with the remaining part of the total mixing water (75 %) and the additives.

3.2.3. Testing of concrete

The slump and VeBe test methods according to EN 12350-2 [40] and EN 12350-3 [41], respectively, are used for the determination of the consistency of the fresh concrete mixtures. Immediately after mixing, the density and the air content are also measured according to EN 12350-6 [42] and EN 12350-7 [43], respectively. For the water immersion curing of the concrete, regular tap water is used and kept at a temperature between 20 and 22 °C, according to EN 12390-2 [44]. After the curing period, the compressive strength is determined at the age of 7 and 28 days according to EN 12390-3 [45], three cubes/age ($150 \times 150 \times 150$ mm^3) are manufactured. In addition, the durability is examined by the freeze-thaw resistance according to prNBN B15-100 [29] which is based on the slab test specified in the Technical Specification CEN/TS 12390-9 [30]. During the tests, the freeze-thaw resistance is measured after 7, 14, and 28 days. The fresh and hardened RAC must comply with the requirements specified in the S250 [1] as summarized in Table 2, in order to obtain a high-grade certification.

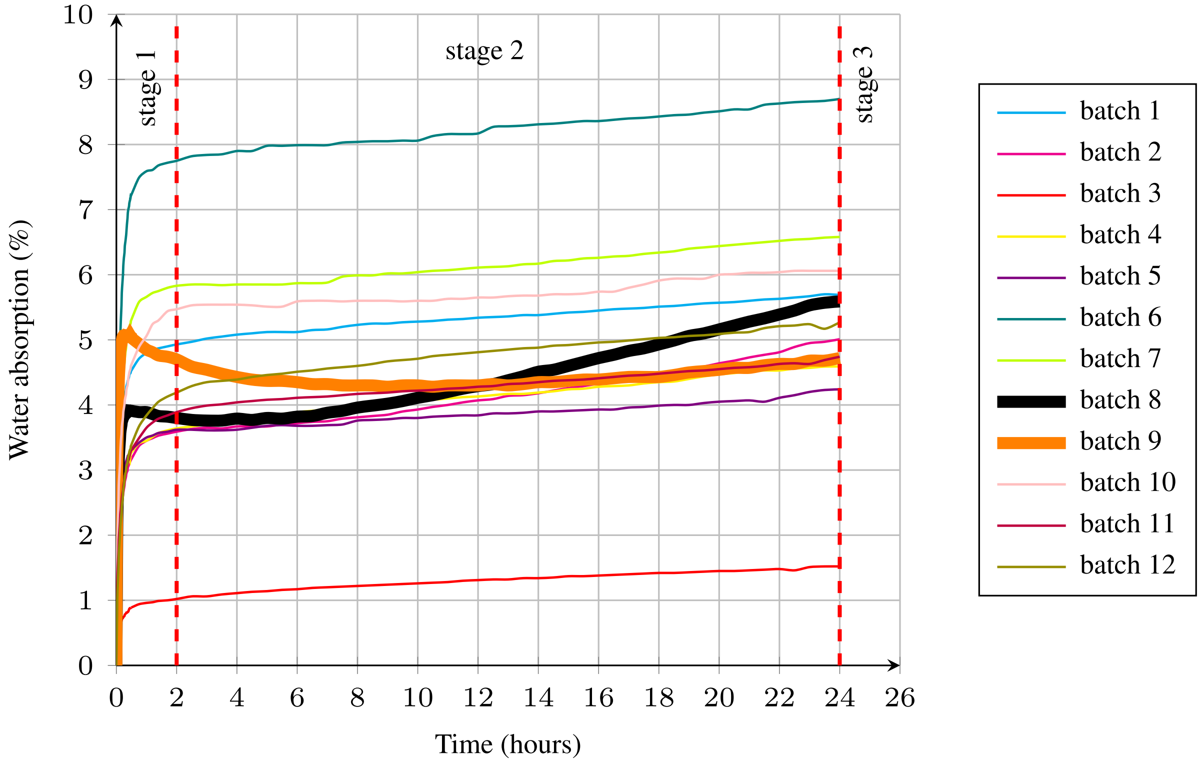


Figure 2: Water absorption of concrete aggregates.

Table 2: High-grade requirements for concrete mixtures with an air content ≥ 3 %, for linear elements (LE) and construction class 'BF' (BF) [1].

Requirements by S250	LE	BF
Slump (mm)	10 – 40	20 – 60
Compressive strength after 7 days (N/mm^2)	20	20
Compressive strength after 28 days (N/mm^2)	30	30
Freeze-thaw resistance after 28 days (kg/m^2)	3	3

4. Results and discussion

4.1. Recycled concrete aggregates

Table 3 shows the results of the aggregate tests in which the high-grade requirements set by S250 [1] are summarized in the bottom row. The table also includes the results of nine other RCA batches (13 – 21) of which no information is available regarding the crushing process and water absorption after 10 minutes. These results were obtained in a previous research campaign performed by the authors and are used here for statistical purposes, i.e. to enrich the data used in the correlation analyses. It can be noted that the density of batch 3 is rather high for concrete aggregates, which leads to the conclusion that batch 3 presumably originates from crushing cobblestones, and cannot be considered as RCA. In addition, batches 1, 2, 4, 5, 9, 11, 13, 14, 20, and 21 meet all the requirements and can consequently be regarded as high-grade concrete aggregates.

If the concrete aggregates properties are associated with the origin and the crushing process, it can be observed that crushing the same batch three times, as done for batch 9, compared to crushing twice, as done for batch 8, results in a lower flakiness index (FI) and water absorption value (WA_{24}), whereas the density increases from 2288 to 2328 kg/m^3. Finally, it can be noticed that the LA value is between 31 and 35 % after a two-stage crushing process (except for batch 15, which has a too low concrete/stones content and contains more than twice as much glass as allowed), whereas the LA value in this research is less than 30 % after a three-stage crushing process.

When investigating the correlations between the different properties, Figure 3 shows that a strong relation (R^2 = 0.93 – red regression line) can be found between the water absorption after 10 minutes and 24 hours of immersion. The correlation is based on the results of the first twelve batches, excluding batches 8 and 9 since their water absorption behavior deviates significantly from the other batches, as was mentioned in Section 3.2.2. In order to safe time in a practical context, the expression

$$WA_{24} = 1.3744 \times WA_{10\,\text{min.}} + 1.1613 \tag{1}$$

could thus give a good indication of the water absorption after 24 hours, based on only 10 minutes of immersion of the RCA. It should be noted that the influence of batch 3 (the batch with the very high ρ_{rd} value, indicated in blue in Figure 3) is limited since $R^2 = 0.91$ (black regression line) when this batch is not considered. Finally, a multilinear regression analysis of the results of all 21 RCA batches listed in Table 3 results in the prediction formula

$$\ln(LA) = 15.3188 + 0.3535 \times \ln(WA_{24}) - 1.6124 \times \ln(\rho_{\text{rd}}) \tag{2}$$

which gives a good indication (R^2 = 0.80) for the LA values, without carrying out an (expensive) Los Angeles abrasion test. Moreover, the required water absorption and oven-dry density values are obtained by performing only one test according to EN 1097-6 [34].

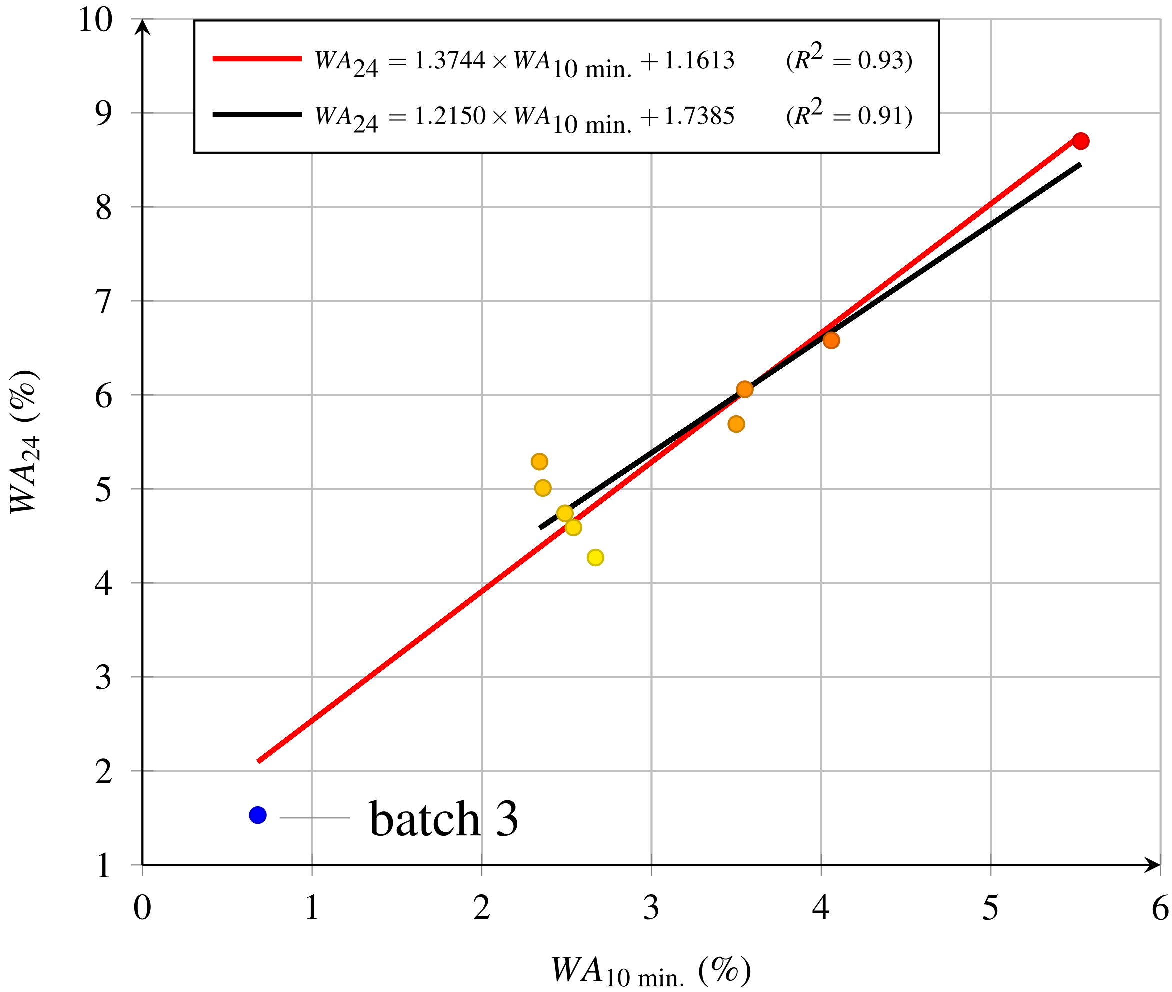


Figure 3: Correlation between the water absorption after 24 hours WA_{24} and the water absorption after 10 minutes $WA_{10\text{ min.}}$. The black regression line is constructed without considering batch 3 (indicated in blue).

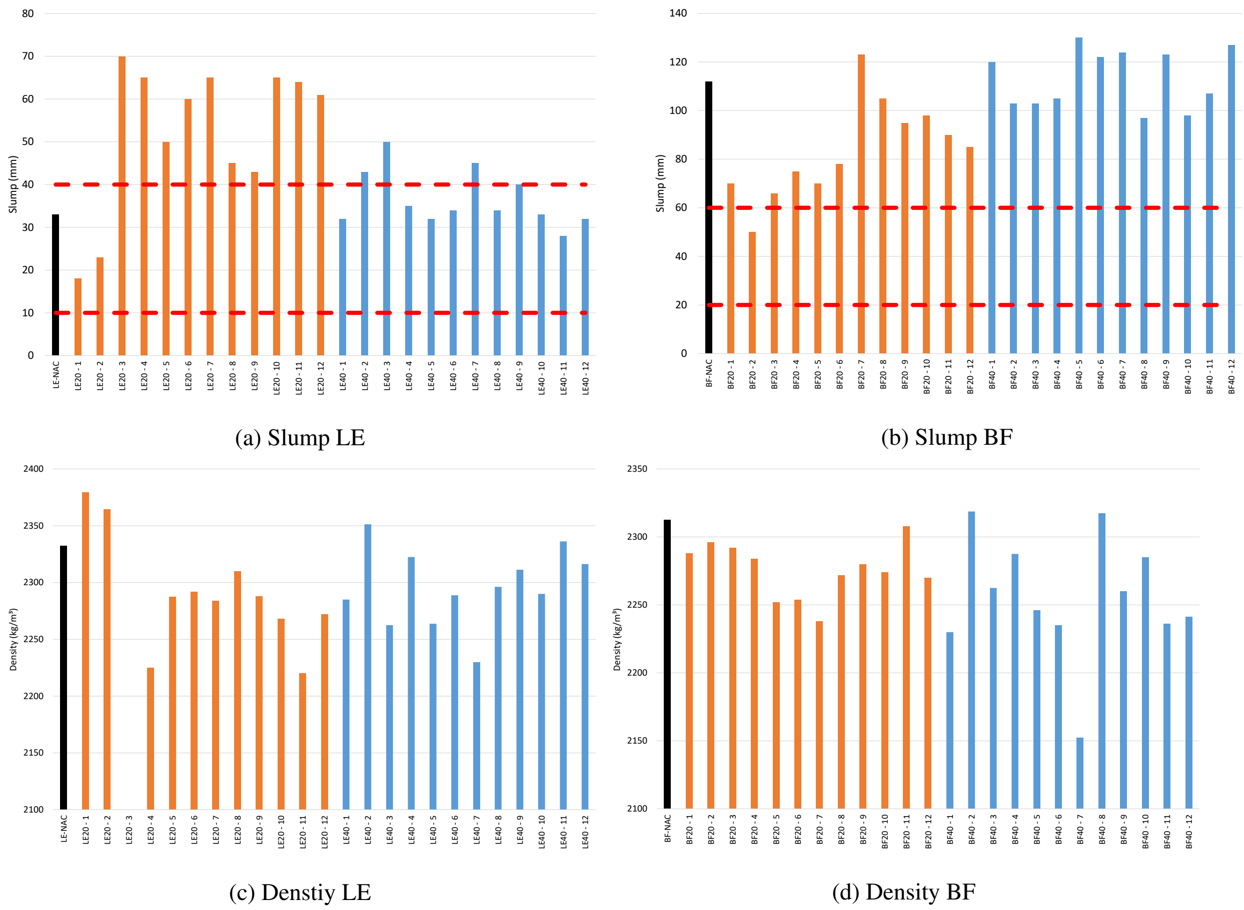
Table 3: Identification, physical and mechanical properties of the RCA used in this study. The values in red do not satisfy the high-grade requirements set by S250 (bottom row) [1].

RCA	Identification				Physical and mechanical properties							High-grade	Origin	Preprocessing	Crushing process	Postprocessing
	Rcu (%)	Ra (%)	XRg (%)	FL (%)	FI (%)	f (%)	LA (%)	$WA_{10\text{ min.}}$ (%)	WA_{24} (%)	ρ_{rd} (kg/m^3)	F (%)					
1	99.3	0.5	0.1	0.1	6	0.8	34	3.5	5.7	2262	10.8	yes	roads/pavements/residuals	jaw crusher	1 × impact crusher	wind sift
2	98.3	0.5	0.2	1	12	1.1	28	2.4	5.0	2347	10.7	yes	variable	crusher	1 × impact crusher + 1 × 20/40	washing/sift/picking
3	100	0	0	0	6	0.4	15	0.7	1.5	2628	1.0	yes	roads/precast/natural rubble	jaw crusher	1 × impact crusher + 1 × 20/40	(none)
4	98.8	0.5	0.2	0.5	8	1.3	31	2.5	4.6	2350	8.4	yes	roads	jaw crusher	1 × impact crusher	(none)
5	99.8	0.1	0	0.1	8	0.9	23	2.7	4.3	2418	3.9	yes	roads	crusher	jaw crusher/magnet/ 1 × impact crusher	magnet/sift
6	98	0	0.2	0	5	1.4	34	5.5	8.7	2165	14.5	no	residual concrete	jaw crusher	1 × impact crusher	(none)
7	96.5	3	0.2	0.3	10	0.5	33	4.1	6.6	2175	13.4	no	buildings/hollow core slabs	hand picking	jaw crusher/sift/water bath/ 1 × impact crusher	picking
8	99.9	0	0	0.1	9	1.6	34	3.7	5.6	2288	4.9	no	hollow core slabs	crusher	1 × impact crusher	magnet/sift
9	99.9	0	0	0.1	3	0.7	29	4.9	4.7	2328	2.4	yes	hollow core slabs	crusher	2 × impact crusher	magnet/sift
10	98.5	0.1	0.1	1	10	1.9	31	3.6	6.1	2256	10.5	no	roads and others	jaw crusher	1 × impact crusher	magnet/sift
11	100	0	0	0	5	1.5	33	2.5	4.7	2277	3.7	yes	precast	(none)	1 × impact crusher	(none)
12	95	0.8	1	2	8	0.9	35	2.3	5.3	2278	8.4	no	roads and others	(none)	1 × impact crusher	(none)
13	100	0	0	0	4	0.8	28	n/a	3.8	2416	1.0	yes	precast	(unknown)	(unknown)	(unknown)
14	100	0	0	0	7	1.0	27	n/a	5.7	2377	4.6	yes	precast	(unknown)	(unknown)	(unknown)
15	94.46	0.69	1.21	0	12	2.4	40	n/a	7.2	2288	20.8	no	roads	(unknown)	(unknown)	(unknown)
16	95.64	3.04	0	0	9	2.2	32	n/a	6.0	2355	8.2	no	roads	(unknown)	(unknown)	(unknown)
17	98.18	0.24	0	0.02	11	2.1	33	n/a	5.9	2311	8.0	no	roads	(unknown)	(unknown)	(unknown)
18	95.51	0.63	0.79	0	15	1.5	31	n/a	6.2	2333	7.5	no	roads	(unknown)	(unknown)	(unknown)
19	97.33	2.27	0.34	0	9	1.2	25	n/a	3.8	2317	2.3	no	roads	(unknown)	(unknown)	(unknown)
20	97.96	0	0.31	0.01	10	0.9	31	n/a	4.8	2300	10.1	yes	roads	(unknown)	(unknown)	(unknown)
21	99.98	0	0	0.02	12	1.2	32	n/a	6.1	2296	7.4	yes	roads	(unknown)	(unknown)	(unknown)
S250	≥ 95	≤ 1	≤ 0.5	≤ 2	< 20	< 1.5	< 35		≤ 10	≥ 2200						

4.2. *Recycled aggregates concrete*

4.2.1. *Compressive strength tests*

Figure 4 and 5 show the results of the experiments performed on the fresh and hardened concrete. It can be observed that the slump (Figure 4a) of the twelve RAC mixtures for the linear elements (denoted 'LE*xx*-*y*' where *xx* is the replacement rate and *y* represents the batch number) is not always within the S250 limits of 10 and 40 mm (Table 2, slump classes S1 and S2). In case of a 40 % replacement rate of the coarse aggregates (showed in blue), the slump is for most cases smaller than the upper limit of 40 mm. With the exception of BF20-2, the slump of all concrete mixtures related to construction class 'BF' (Figure 4b) is too high with respect to the S250 limit of 60 mm (slump classes S2 and S3), which is mainly caused by the higher water/cement ratio.



(a) Slump LE

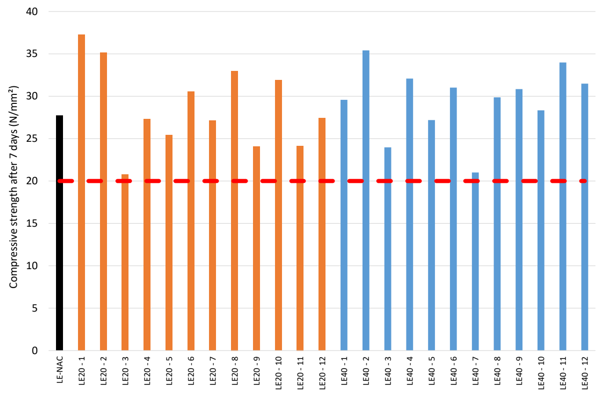
(b) Slump BF

(c) Denstiy LE

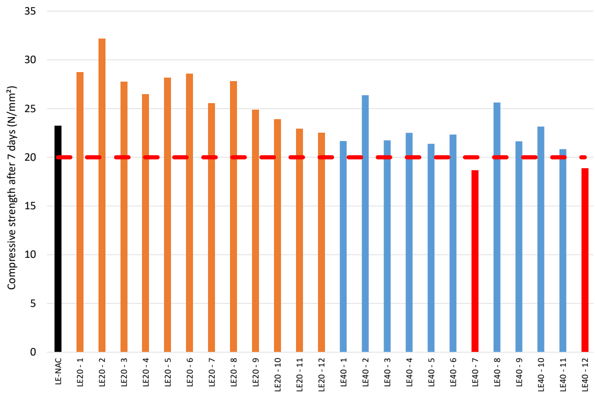
(d) Density BF

Figure 4: Results of tests on fresh concrete: (a and b) the slump and (c and d) density. The dashed lines correspond to the high-grade criteria of S250 (Table 2), whereas results in red indicate that the respective mixtures fail to reach these criteria.

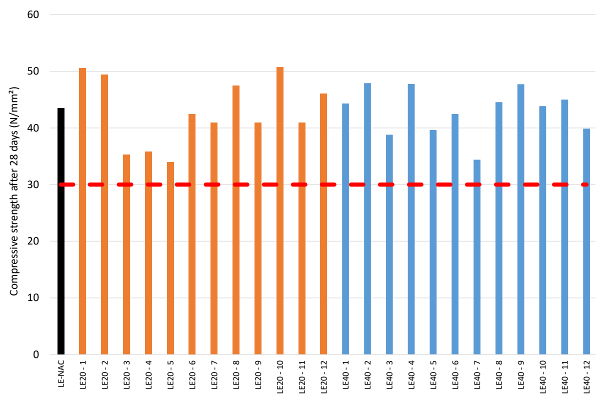
It can also be noted that the slump of the mixtures for the linear elements mainly decreases for an increasing replacement rate, whereas the slump tends to be more similar for mixtures of construction class 'BF'. This may be due to the fact that less effective water is available for the mixtures of the linear elements (162 l), for which extra water is added to compensate this shortage as discussed in Section 3.2.2. For the mixtures of construction class ‘BF’ sufficient water is already available so the slump tends to be less affected by different replacement rates. Furthermore, the density of the fresh concrete mixtures (see Figure 4c and 4d) does not need to comform to a specific requirement in S250 [1], but it is noteworthy that in general the densities of the NAC mixtures (indicated in black) are higher than for the RAC mixtures (indicated in blue and brown). Finally, regarding the compressive strengths after 7 (Figure 5a and Figure 5b) and 28 days (Figure 5c and Figure 5d), it can be concluded that all the mixtures meet the high-grade requirements of S250 (indicated by a dashed red line in the figures), with the exception of batch 7 in case of a 20 % and 40 % replacement rate and batch 12 in case of a 40 % replacement rate for construction class ‘BF’ (indicated in red). For the mixtures of the linear elements, no clear difference is visible between both replacement rates, whereas for the mixtures concerning construction class ‘BF’, the compressive strength is generally lower for a 40 % replacement rate. The compressive strength of the RAC does not differ much from the NAC for most mixtures concerning construction class ‘BF’, which is in line with the findings reported in the literature referred to in Section 1. No such clear trend can be noticed for the mixtures of the linear elements.



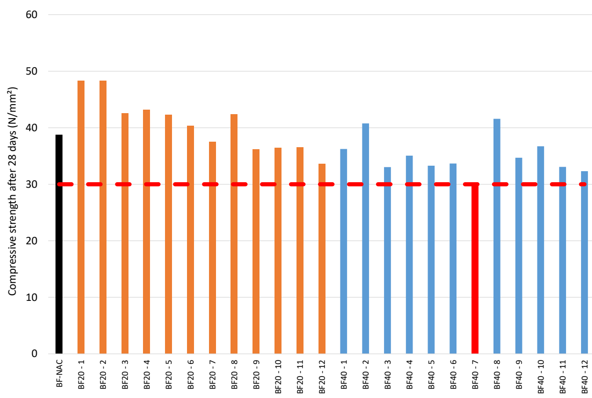
(a) Compressive strength after 7 days LE



(b) Compressive strength after 7 days BF



(c) Compressive strength after 28 days LE

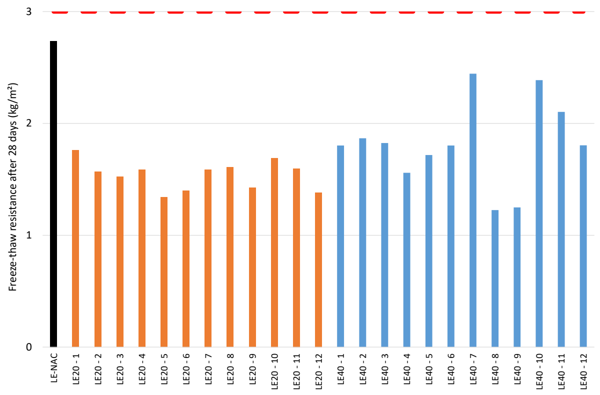


(d) Compressive strength after 28 days BF

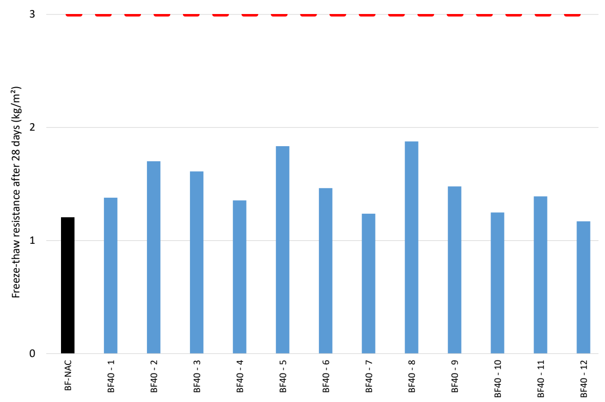
Figure 5: Results of compressive strength tests: (a and b) after 7 days and (c and d) after 28 days. The dashed lines correspond to the high-grade criteria of S250 (Table 2), whereas results in red indicate that the respective mixtures fail to reach these criteria.

4.2.2. Freeze-thaw tests

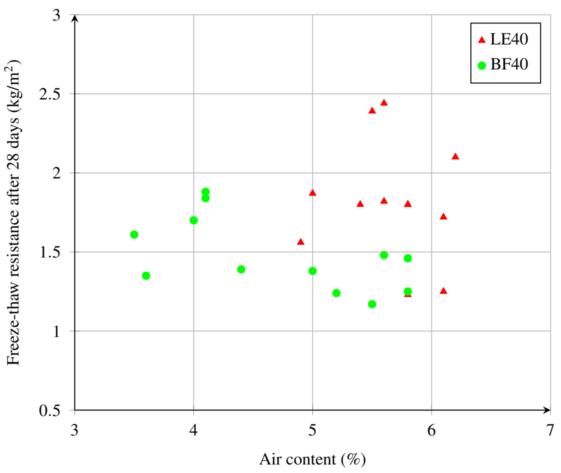
From the overview of the freeze-thaw test results in Figure 6a and 6b, it can be noticed that the differences between the different applications and replacement rates are limited. The obtained values for the mass loss after 28 days are in all cases well below the high-grade requirement of 3 kg/m^3 (Table 2), which is illustrated by the red dashed line. After 28 days, the mass loss due to freeze-thaw cycles for the linear elements is generally higher when a higher replacement rate is used. When considering only construction class 'BF', it can be observed that the values are smaller compared to the linear elements. This better freeze-thaw resistance could be explained by the higher cement content (see Table 1). Figure 6c demonstrates that the air content does not appear to play a significant role on the freeze-thaw resistance in case of both replacement rates and applications. In addition, the freeze-thaw resistance of the concrete can also not be associated with the aggregates properties such as the freeze-thaw resistance (F), as can be seen in Figure 6d.



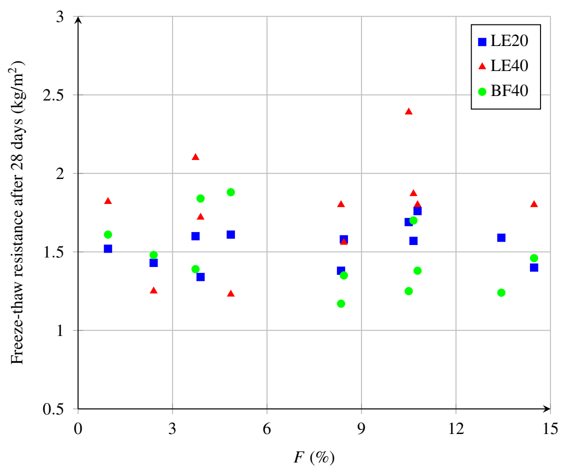
(a) Freeze-thaw after 28 days LE



(b) Freeze-thaw after 28 days BF



(c) Air content



(d) Freeze-thaw aggregates

Figure 6: Results of the freeze-thaw tests on concrete after 28 days: (a) for LE, (b) for BF, (c) freeze-thaw resistance in relation to the air content, and (d) freeze-thaw resistance of the concrete in relation to the freeze-thaw resistance of the aggregates (F).

5. Conclusions

The use of recycled concrete aggregates in road pavement construction is still limited in Flanders, since the aggregates and concrete have to meet the high-grade criteria specified by the Flemish 'Standard Tender Specifications 250 version 3.1' [1] which require extensive testing procedures, often beyond the practical capabilities of concrete production plants. The main objective of this study was therefore to investigate if the potential high-gradeness of RCA and RAC can be assessed based on a more limited number of experiments. The aggregates tests in this study have indeed shown that the water absorption (WA_{24}) in combination with the specific density (ρ_{rd}) can give a good indication of the resistance to abrasion (LA). The tests to determine the quality of RCA can therefore, in first instance, be limited to the water absorption test according to EN 1097-6 [34], which thus serves as a high-grade predictor in order to achieve an early identification in an accelerated and practical way.

In a second stage, twelve RCA batches from different sources were applied in two concrete road pavement construction applications, in which 20 and 40 % of the coarse fraction of limestone was replaced by RCA, going beyond the current allowed replacement rate of 20 % as specified by S250. Nevertheless, the mechanical properties as well as the resistance to freeze-thaw cycles of the specific RAC mixtures in this research still meet the S250 high-grade requirements. Furthermore, it was observed that a good control of the air content is crucial for obtaining a sufficiently high compressive strength. However, the air content appeared to have only a slight influence on the freeze-thaw resistance, whereas the freeze-thaw resistance of the concrete aggregates used in this study had slight to no impact on the finally obtained freeze-thaw resistance of the manufactured concrete.

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[1] Agentschap Wegen & Verkeer, Standaardbestek 250 versie 3.1, `http://wegenenverkeer.be/standaardbestek-250-versie-31` (2016).

[2] M. S. de Juan, P. A. Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate, Construction and Building Materials 23 (2) (2009) 872–877.

[3] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cement and Concrete Research 37 (5) (2007) 735–742.

[4] R. Silva, J. de Brito, R. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Construction and Building Materials 65 (2014) 201–217.

[5] T. C. Hansen, H. Narud, Strength of recycled concrete made from crushed concrete coarse aggregate, Concrete International 5 (01) (1983) 79–83.

[6] S. W. Tabsh, A. S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Construction and Building Materials 23 (2) (2009) 1163–1167.

[7] J. de Brito, F. Alves, Concrete with recycled aggregates: The Portuguese experimental research, Materials and Structures 43 (1) (2010) 35–51.

[8] S. Hasaba, M. Kawamura, K. Toriik, K. Takemoto, Drying shrinkage and durability of the concrete made of recycled concrete aggregate, Transactions of the Japan Concrete Institute 3 (3) (1981) 55.

[9] J.-B. Li, J.-Z. Xiao, J. Huang, Influence of recycled coarse aggregate replacement percentages on compressive strength of concrete, Jianzhu Cailiao Xuebao (Journal of Building Materials) 9 (3) (2006) 297–301.

[10] Openbare Vlaamse Afvalstoffenmaatschapij (OVAM), Staalname en analyse van puin afkomstig van container- en sorteerbedrijven, Tech. rep., OVAM (2013).

[11] J. Vrijders, J. Desmyter, Een hoogwaardig gebruik van puingranulaten stimuleren, Tech. rep., BBRI for OVAM (2008).

[12] F. Agrela, M. S. De Juan, J. Ayuso, V. L. Geraldes, J. Jiménez, Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete, Construction and Building Materials 25 (10) (2011) 3950–3955.

[13] I. Nováková, K. Mikulica, Properties of concrete with partial replacement of natural aggregate by recycled concrete aggregates from precast production, Procedia Engineering 151 (2016) 360–367.

[14] M. Joseph, Durability of recycled aggregate concrete, 2014,
`https://lirias.kuleuven.be/bitstream/123456789/473061/1/presentatieresearchday2014JosephMiquel.pdf`.

[15] B. Mas, A. Cladera, J. Bestard, D. Muntaner, C. E. López, S. Piña, J. Prades, Concrete with mixed recycled aggregates: Influence of the type of cement, Construction and Building Materials 34 (2012) 430–441.

[16] K. H. Younis, K. Pilakoutas, Strength prediction model and methods for improving recycled aggregate concrete, Construction and Building Materials 49 (2013) 688–701.

[17] S. Omary, E. Ghorbel, G. Wardeh, Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties, Construction and Building Materials 108 (2016) 163–174.

[18] C. Thomas, J. Setién, J. Polanco, P. Alaejos, M. S. De Juan, Durability of recycled aggregate concrete, Construction and Building Materials 40 (2013) 1054–1065.

[19] C. Jin, X.-p. Wang, O. O. Akinkurolere, C.-r. Jiang, Experimental research on the conversion relationships between the mechanical performance indexes of recycled concrete, Concrete 11 (2008) 014.

[20] T. Jie, Preliminary study on compressive strength of recycled aggregate concrete, Sichuan Building Science 4 (2007) 050.

[21] S. C. Kou, C. S. Poon, D. Chan, Influence of fly ash as cement replacement on the properties of recycled aggregate concrete, Journal of Materials in Civil Engineering 19 (9) (2007) 709–717.

[22] K.-S. Lauch, J. Vrijders, B. Dooms, Defining limits for standardization on concrete incorporating recycled concrete aggregates, in: High Tech Concrete: Where Technology and Engineering Meet, Springer, 2018, pp. 2347–2355.

[23] T. Yamato, Y. Emoto, M. Soeda, Y. Sakamoto, Some properties of recycled aggregate concrete, in: Proceedings of the 2nd International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, Tokyo, Japan, 1988, pp. 7–11.

[24] A. D. Buck, Recycled concrete as a source of aggregate, in: Journal Proceedings, Vol. 74, 1977, pp. 212–219.

[25] D. L. Strand, Designing for quality, concrete pavement rehabilitation and recycling on wisconsin's interstate highways, in: Third International Conference on Concrete Pavement Design and Rehabilitation, 1985.

[26] C. F. Hendriks, The use of concrete and masonry waste as aggregates for concrete production in the Netherlands, in: Environmental Technology, Springer, 1987, pp. 431–440.

[27] K. Liu, J. Yan, Q. Hu, Y. Sun, C. Zou, Effects of parent concrete and mixing method on the resistance to freezing and thawing of air-entrained recycled aggregate concrete, Construction and Building Materials 106 (2016) 264–273.

[28] A. Gokce, S. Nagataki, T. Saeki, M. Hisada, Freezing and thawing resistance of air-entrained concrete incorporating recycled coarse aggregate: The role of air content in demolished concrete, Cement and Concrete Research 34 (5) (2004) 799–806.

[29] European Comittee for Standardisation, prNBN EN B15-100: Methodology for the evaluation and certification of the suitability of cement and additives for concrete (2017).

[30] European Comittee for Standardisation, CEN/TS 12390-9: Testing hardened concrete - part 9: Freeze-thaw resistance - scalling (2006).

[31] European Comittee for Standardisation, NBN EN 933-1: Test methods for geometrical properties of aggregates - part 1: Determination of the

particle size distribution - sieving method (2012).
[32] European Comittee for Standardisation, NBN EN 12620: Aggregates for concrete, aggregates for bituminous mixtures and surface treatments for roads, airfields and other (2013).
[33] European Comittee for Standardisation, NBN EN 933-3: Test methods for geometrical properties of aggregates - part 3: Determination of the shape index (2012).
[34] European Comittee for Standardisation, NBN EN 1097-6: Testing the physical and mechanical properties of aggregates - part 6: Density and water absorption (2013).
[35] European Comittee for Standardisation, NBN EN 1097-2: Tests for mechanical and physical properties of aggregates - part 2: Methods for the determination of resistance to fragmentation (2016).
[36] European Comittee for Standardisation, NBN EN 1367-1: Tests for thermal and wheathering properties of aggregates - part 1: Determination of resistance to freezing and thawing (2007).
[37] J. García-González, D. Rodríguez-Robles, A. Juan-Valdés, J. M. Morán-del Pozo, M. I. Guerra-Romero, Pre-saturation technique of the recycled aggregates: Solution to the water absorption drawback in the recycled concrete manufacture, Materials 7 (9) (2014) 6224–6236.
[38] L. Ferreira, J. de Brito, M. Barra, Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties, Magazine of Concrete Research 63 (8) (2011) 617–627.
[39] S. Laserna, J. Montero, Influence of natural aggregates typology on recycled concrete strength properties, Construction and Building Materials 115 (2016) 78–86.
[40] European Comittee for Standardisation, NBN EN 12350-2: Testing of concrete - part 2: Slump (2009).
[41] European Comittee for Standardisation, NBN EN 12350-3: Testing of concrete - part 3: Vebe test (2009).
[42] European Comittee for Standardisation, NBN EN 12350-6: Testing of concrete - part 6: Density (2009).
[43] European Comittee for Standardisation, NBN EN 12350-7: Testing of concrete - part 7: Air content - pressure method (2009).
[44] European Comittee for Standardisation, NBN EN 12390-2: Testing hardened concrete - part 2: Making and curing specimens for strength tests (2009).
[45] European Comittee for Standardisation, NBN EN 12390-3: Test of hardened concrete - part 3: Compressive strength of test specimens (2009).