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CIRCULAR CONCRETE: VALIDATING NEW TECHNOLOGIES IN THE LAB AND ON-SITE

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Abstract.

The growing importance of a circular economy also holds possibilities for concrete. Some of the principles of circularity, like the re-use of "waste" as secondary raw material and the optimisation of the design with regards to lifespan, environmental impact and re-use, can be applied. Several technological innovations in this domain are in an advanced stage of development. However, the transition from research to full commercial applications is held back, mostly due to the absence of documented experience and the lack of a technical framework (prescriptions). In order to accelerate the adoption of new technologies, the Belgian Building Research Institute (BBRI) started the project "Circular.Concrete". In this paper, the results are presented of validation tests regarding 1) smart crushing technology, 2) the carbonation of recycled aggregates, 3) concrete using only recycled aggregates and 4) the use of alternative binders and supplementary cementitious materials.

Keywords: Carbonatation, concrete recycling, pilot projects, recycled concrete aggregates (RCA), supplementary cementitious materials.

1. Introduction

Substantiated by the scientific consensus of global warming and climate change and propelled by the increased public awareness, environmental clauses are frequently added to the specifications for buildings for major clients. Concrete has a dubious reputation in this matter. This is mostly due to the enormous volumes of cement that are produced worldwide on a yearly basis ($\sim$4.5 billion tons, 2019), the CO_2-emissions during cement production ($\sim$ 800 kg of CO_2 per tonne of cement for CEM I), the extraction, processing and transportation of the raw materials and the important waste streams that are produced when concrete structures are demolished [1, 2].

The growing importance of a circular economy also holds opportunities for concrete. Some of its principles like the re-use of "waste" as secondary raw material and the optimisation of the design with regards to lifespan, environmental impact and re-use, can be applied.

Several technological innovations in this domain are in an advanced stage of development. However, the transition from research to real applications is held back, mostly due to the absence of documented experience and of a technical framework, i.e. technical prescriptions, standards etc. In order to accelerate the adoption of new technologies, the Belgian Building Research Institute (BBRI) started the project Circular.Concrete. The aim of this project is to translate research results into practice.

2. Validating innovative technologies

In a first stage of the Circular.Concrete project, different technological innovations were identified and their TRL (Technology Readiness Level) were estimated. The results have been summarized in a state-of-the-art report, which is available on the project website (`https://www.circular-concrete.be/`).

In a second stage a selection was made of technological innovations for further validation on laboratory-scale, based on their TRL, their scientific potential and their relevance for the Belgian market: 1) smart crushing technology, 2) the carbonation of recycled aggregates, 3) concrete using only recycled aggregates and 4) the use of alternative binders and supplementary cementitious materials. It should be noted that the scale of this validation was very limited and should be considered as exploratory.

2.1. Technology 1. Smart crushing

Using the smart crushing technology, concrete construction waste can supposedly be crushed and processed into its original components, i.e. the original fine and coarse aggregates and the binder, of which a part is non-hydrated (and still reactive) [3]. Since the obtained recycled aggregates don't have any mortar adhered, they can be used in new concrete as natural aggregates.

This technology was tested on four different Belgian concrete waste samples:

Figure 1. Sample 4: low quality concrete waste fraction 20-56 mm.

	Water absorption [%]	Particle density [kg/m^3]	Micro-Deval [−]
Sample 1	3.8	2440	23
Sample 2	6.1	2370	28
Sample 3	4.5	2400	23
Sample 4	4.3	2420	21
Limestone aggregate	0.5 − 1.0	2660 − 2800	15

Table 1. Characterization of the treated aggregate samples.

1. Concrete waste fraction 2-20 cm, originating from railway sleepers, with strength class C50/60 and no reinforcements or contaminants.
2. Concrete waste fraction 2-20 cm, originating from the precast industry, with strength class C45/55 and no reinforcements or contaminants.
3. Low quality concrete waste fraction 20-56 mm, composed of concrete (70 wt%), natural stone (25 wt%), and masonry and contaminants (5 wt%).
4. Low quality concrete waste fraction 20-56 mm, of which individual aggregates can be composed of concrete (80 wt%), fibre reinforced concrete (10 wt%), or asphalt (10 wt%) (Figure 1)

500 kg of each sample was sent to a smart crushing facility in the Netherlands to be processed. After processing, about 300 kg of material from each sample was returned.

2.1.1. Aggregate testing

Each treated sample was assessed visually and the grain size distribution was determined. All treated samples presented a very similar distribution curve (0/22).

The water absorption and particle density (on the fraction +4 mm, in accordance with EN 1097-6) and resistance to wear (on the fraction +10 mm, in accordance with EN 1097-1) was determined for the treated samples. The results are presented in Table 1. The values for the treated samples are very different from the typical values for crushed natural limestone aggregates.

These differences can be explained by the presence of mortar on the treated samples, which hasn't been removed by the smart crushing treatment. Belgian concrete is generally made with crushed limestone as coarse material, whereas Dutch concrete generally contains natural (round) gravel. Possibly this technology is more effective for concrete composed of rounded natural gravel.

2.1.2. Fines testing

From each treated sample, the fines (< 0.125 mm) were extracted and tested, to determine the potential presence of non-hydrated cement.

X-ray diffraction analysis (XRD) of the fines demonstrated that this fraction is dominantly composed of quartz representing aliquots of the silt and sand aggregate fraction of the primary concrete. Mortar bars were made (in accordance with EN 196-1) using standard sand and CEM I 52.5 N, and the fines as cement replacement (40 %). The fresh properties and the mechanical properties of the mortar bars after 7, 28 and 91 days were compared to those of reference mortar bars without cement replacement. The results of the mechanical tests (executed in accordance with EN 196-1) are presented in Table 2. The results indicate that the fines do not contribute to the strength development of the mortar. Possibly the evaluated fraction should be even finer (< 0.063 mm) to exclude as much as possible the presence of silt and sand.

2.1.3. Concrete testing

Using only the treated samples as received from the smart-crushing facility, concrete was prepared with each sample by adding 300 kg/m^3 CEM III/A 42.5 and water in a W/C ratio of 0.55. Due to an error in

	$R_{f,7d}$ [MPa]	$R_{c,7d}$ [MPa]	$R_{f,28d}$ [MPa]	$R_{c,28d}$ [MPa]	$R_{f,91d}$ [MPa]	$R_{c,91d}$ [MPa]
Sample 1	5.1	27.1	6.2	31.8	6.9	33.8
Sample 2	5.6	27.4	6.4	33.7	6.3	34.7
Sample 3	5.6	26.5	5.7	31.3	7.0	33.4
Sample 4	5.3	26.9	5.9	32.3	6.2	33.2
Reference mix	10.0	63.9	9.4	71.8	10.0	79.3

Table 2. Mechanical properties of the mortar mixtures with treated fines.

	$R_{c,28d}$ [MPa]	$R_{c,91d}$ [MPa]	Carbonation depth 56 d [mm]
Sample 1	21.9	28.8	13.5
Sample 2	22.2	23.5	15.5
Sample 4	20.3	24.9	17.3
Reference mix	30.5	45.8	11.3

Table 3. Compressive strength and carbonation resistance of the concrete mixtures with treated aggregates.

the mix design, a deviant concrete composition was obtained with sample 3, which lead to the rejection of this concrete mixture. Without adding superplasticizer but taking into account the water absorption of the treated samples, a very good workability was obtained of the concrete mixtures.

The compressive strength after 28 and 91 days (determined in accordance with EN 12390-3), and the resistance to carbonation (determined in accordance with EN 13295) were determined for the mixtures and compared with a reference concrete mixture, using only crushed natural limestone aggregates. The composed grain size distributions of the different concrete mixtures differ slightly. The results are presented in Table 3.

A clear influence can be observed of de total replacement of natural aggregates with the treated samples. After 28 days a strength reduction of about 30 % can be observed, after 91 days of about 40-50 %. The concrete with treated sample 3 shows deviant behaviour. The carbonation depth of the concrete after 56 days of exposure to 1.0 % CO_2 was about 20-50 % higher for the treated samples in comparison to the reference mix.

2.2. Technology 2. Carbonation of recycled aggregates

With the carbonation of recycled aggregates, their physical and mechanical properties can be enhanced and thus their applicability in concrete improved. At the same time CO_2 can be 'captured' inside the aggregates.

Recycled aggregates of different origins (concrete 'C', high quality concrete 'C A+', mixed 'M') and of different sizes (0/6.3, 6/22, 8/20, 0/40 and 10/40) were treated during 5 days in an autoclave at an increased pressure (2 bar) and a very high CO_2 concentration (100 %). Before and after the treatment, the water absorption and particle density (in accordance with EN 1097-6) and resistance to wear (in accordance with EN 1097-1) were determined for the aggregates. The results are presented in Table 4.

The CO_2-treatment clearly affected the water absorption and the particle density of the aggregates. As only the mortar fraction, adhered to the recycled aggregates, is influenced by the carbonation, the aggregate properties are affected proportionally in relation to the mortar content of the aggregates.

2.3. Technology 3. Maximum aggregate replacement

By replacing the natural aggregates in concrete by recycled or artificial aggregates, the need for primary raw aggregates can be reduced.

The influence of the presence of recycled aggregates (RA) and artificial aggregates on the properties of fresh and hardened concrete was evaluated by replacing a maximum quantity of natural aggregates in concrete mixtures (% vol). This maximum quantity was determined by combining the recycled and artificial aggregates as received with natural aggregates, while fitting the combined grain size distribution of the concrete to a reference grain size distribution. The following aggregate combinations were tested:

1. 10 % 0/1 natural sand + 90 % RA type 1 (0/8 + 8/22)
2. 100 % RA type 2 (0/8 + 6/20)
3. 10 % 0/1 natural sand + 90 % RA type 3 (0/8 + 6/20)
4. 10 % 0/1 natural sand + 26 % 0/4 treated polluted sand + 64 % crushed limestone (4/20)
5. 20 % 0/1 natural sand + 20 % 0/4 copper slag + 60 % crushed limestone (4/20)

	Water absorption [%]		Particle density [Mg/m^3]		Micro-Deval [–]	
	Before	After	Before	After	Before	After
0/40 C	6.8	5.4	2.20	2.29	25	27
10/40 M	7.6	7.4	2.04	2.08	42	47
0/6.3 C	6.3	5.9	2.29	2.33	/	/
8/20 C A+	4.3	3.7	2.42	2.44	16	13
8/20 C	4.4	3.5	2.37	2.43	24	16
6/22 C	4.3	3.8	2.34	2.37	11	12

Table 4. Characterization of the treated aggregates.

	Type 1 concrete			Type 2 concrete		
	$R_{c,28d}$ [MPa]	$R_{c,91d}$ [MPa]	Carbonation depth 56 d [mm]	$R_{c,28d}$ [MPa]	$R_{c,91d}$ [MPa]	Carbonation depth 56 d [mm]
Combination 1	30.3	33.8	14.8	40.0	36.0	9.8
Combination 2	26.6	25.9	17.5	32.8	32.3	14.0
Combination 3	29.7	31.4	13.8	37.2	37.8	10.5
Combination 4	40.9	53.1	11.0	51.3	58.0	6.3
Combination 5	32.7	44.4	11.3	43.2	61.8	8.8
Combination 6	29.9	41.4	12.0	57.6	61.7	7.5
Reference mix	30.5	45.8	11.3	55.9	62.8	7.3

Table 5. Compressive strength and carbonation resistance of the concrete mixtures with maximum aggregate replacement.

6. 10 % 0/1 natural sand + 50 % INOX steel slag (0/2 + 2/10) + 40 % crushed limestone (10/20)

Two types of concrete were made with those aggregate combinations: type 1 with 300 kg/m^3 CEM III/A 42.5 and a W/C ratio of 0.55, and type 2 with 340 kg/m^3 CEM III/A 42.5 and a W/C ratio of 0.45. Superplasticizer was added to the fresh concrete to obtain an initial consistence class S3 - S4 (in accordance with EN 206). The results were compared to a reference concrete mixture using only crushed natural limestone aggregates.

It is important to note that, while all concrete mixtures were designed using the same reference grain size distribution for the aggregates, differences exist between the actual grain size distributions. In addition, all the aggregates were applied in oven-dried state, and extra water was added to take into account their total water absorption. Considering the differences in the kinetics of the water absorption of the aggregates, the effective W/C ratio of the mixtures may be higher than the targeted values. This is particularly the case with combinations 1 to 3, given the high replacement rates and high water absorption of recycled aggregates. This should be taken into account when considering the results presented in this article.

The compressive strength after 28 and 91 days (determined in accordance with EN 12390-3), and the resistance to carbonation (determined in accordance with EN 13295) were determined of the concrete mixtures. The results are presented in Table 5.

For **type 1 concrete**, the influence of the maximum aggregate replacement on the compressive strength after 28 days is very low. Only the concrete with combination 4 seems to perform significantly better. After 91 days however, a clear influence on the compressive strength can be observed in the case of maximum aggregate replacement by RA (combinations 1 to 3), with reductions of about 25-45 %. The carbonation resistance of these RA concrete mixtures is also clearly lower than that of the reference mix.

For **type 2 concrete**, the maximum replacement of aggregates by RA (combinations 1 to 3) leads to a reduction of the compressive strength after 28 days of about $30-40$ % and after 91 days of 40-50 %. The carbonation resistance of these RA concrete mixtures is also significantly lower than that of the reference mix. The concrete with combinations 4 to 6 behaves similar to the reference concrete mix.

The freeze-thaw resistance was determined in accordance with CEN/TS 12390-9 of the hardened concrete mixtures (only type 2 concrete). The results are presented in Table 6. Overall, the influence of the maximum aggregate replacement on the freeze-thaw resistance does not seem to be important. Only the concrete with combination 2 (absence of natural sand) clearly performs worse than the other concrete mixtures. The air content of this concrete mixture (1.6 %) was lower than that of the other mixtures (2.0 – 4.8 %), which probably contributed to this re-

	Mean cumulative scaled material after				
	7 cycles [kg/m^2]	14 cycles [kg/m^2]	28 cycles [kg/m^2]	42 cycles [kg/m^2]	56 cycles [kg/m^2]
Combination 1	0.74	1.02	1.30	1.58	1.82
Combination 2	1.30	2.08	3.04	4.38	5.54
Combination 3	0.28	0.68	1.28	1.76	2.28
Combination 4	0.14	0.50	1.06	1.50	1.98
Combination 5	0.66	0.96	1.60	2.42	3.00
Combination 6	0.50	0.80	1.18	1.70	2.18
Reference mix	0.58	0.94	1.42	1.90	2.46

TABLE 6. Freeze-thaw resistance of the concrete mixtures with maximum aggregate replacement.

sult.

The resistance to chloride migration was determined in accordance with NT Build 492 of the hardened concrete mixtures (only type 2 concrete). The results are presented in Table 7. The maximum replacement of aggregates by RA (combinations 1 to 3) seems to lead to a reduction of the resistance to chloride migration. Again, the concrete mixture with combination 2 (absence of natural sand) clearly performs worse than the other RA concrete mixtures. The mixtures with slag aggregates (combinations 5 and 6) seem to perform slightly better than the reference mix.

	Non steady state chloride migration coefficient D_{nssm} [kg/m^2]
Combination 1	6.43
Combination 2	10.17
Combination 3	8.46
Combination 4	6.57
Combination 5	4.90
Combination 6	3.98
Reference mix	5.98

TABLE 7. Resistance to chloride migration of the concrete mixtures with maximum aggregate replacement.

2.4. TECHNOLOGY 4. ALTERNATIVE BINDERS AND SUPPLEMENTARY CEMENTITIOUS MATERIALS

By replacing the traditional Portland cement in concrete completely by alternative binders or partially by supplementary cementitious materials, the CO_2 emissions related to concrete production can be reduced substantially.

Four alternative binders ('C', replacing 100 % of traditional cement) and five supplementary cementitious materials ('F', replacing 40 % of the traditional cement) were selected. C1 and C2 are sulphoaluminate cements, currently available on the market. C3 is a CEM III/A 42.5 cement and C4 a CEM III/B 32.5 cement. F1 is a copper slag, F2 and F3 are INOX slags and F4 is a Granulated Blastfurnace slag. F5 consists of calcinated clay.

With CEM I 52.5 N as reference cement type and using standard sand, mortar mixtures conforming to EN 196-1 were made with the alternative binders and supplementary cementitious materials. The setting times of the mortar mixtures were evaluated conform EN 480-2. The results are presented in Table 8. Depending on the binder type, the alternative binders present a faster (C1 and C2) or a slower (C3 and C4) setting than the reference Portland cement. The supplementary cementitious materials all have slower setting times than the reference cement.

	Initial setting time [Minutes]	Final setting time [Minutes]
Reference mix	214	278
C2	103	145
C3	297	403
C4	358	584
F1	293	398
F2	321	418
F3	312	420
F4	267	382
F5	279	388

TABLE 8. Resistance to chloride migration of the concrete mixtures with maximum aggregate replacement.

The mechanical properties of the mortar mixtures with the alternative binders and supplementary cementitious materials were evaluated in accordance with EN 196-1. The results are presented in Table 9. All the alternative binders and supplementary cementitious materials lead to lowered mechanical properties of the resulting mortar.

3. CONCLUSIONS

The Circular.Concrete project aims to identify interesting innovative technologies in the domain of circular economy and enable or broaden their practical application. Four different innovative technologies were

	$R_{f,7d}$ [MPa]	$R_{c,7d}$ [MPa]	$R_{f,28d}$ [MPa]	$R_{c,28d}$ [MPa]	$R_{f,91d}$ [MPa]	$R_{c,91d}$ [MPa]
Reference	10.0	63.9	9.4	71.8	10.1	79.3
C1	5.7	39.5	6.3	43.4	7.0	45.2
C2	8.6	45.3	7.4	50.1	6.5	50.1
C3	6.2	30.4	7.5	42.8	9.6	56.6
C4	5.6	23.4	7.2	34.1	7.3	40.1
F1	6.3	33.0	5.9	35.0	5.6	37.1
F2	5.9	27.2	6.4	35.3	7.0	37.1
F3	4.9	21.4	5.3	26.7	6.0	31.8
F4	5.8	34.4	8.1	49.5	6.5	54.7
F5	6.0	29.0	6.7	40.0	7.7	47.3

Table 9. Mechanical properties of the mortar mixtures with alternative binders and supplementary cementitious materials.

selected and validated in laboratory-scale tests in order to increase their TRL. It has to be noted that the scale of this validation was very limited and should be considered as exploratory.

The smart crushing technology, which supposedly crushes the concrete into its original components, doesn't seem very effective for Belgian concrete, made with crushed limestone aggregates. The crushed secondary aggregates still contained a lot of adhered mortar. Possibly this technology is more effective with concrete with rounded natural gravel. The returned fines (< 0.125 mm) did not show hydraulicity as they are dominantly composed of quartz.

The carbonation of recycled aggregates has a clear positive, albeit not that important, influence on their physical and mechanical properties.

Replacement rates of natural aggregates in concrete of 90-100 % vol by recycled aggregates logically lead to reduced mechanical properties of the concrete (this effect becomes more important for higher concrete strength classes). The durability properties of the concrete are also reduced, although this cannot be concluded for the freeze-thaw resistance (the air content of the concrete seems to be the determining factor for this property). The partial replacement by artificial aggregates did not strongly impact the concrete properties.

All the evaluated alternative binders (replacing 100 % of the traditional cement) and supplementary cementitious materials (replacing 40 % of the traditional cement) lead to lowered mechanical properties of the resulting mortar.

This research demonstrates the importance of validating innovative technologies by independent laboratories before their application in concrete projects. One the one hand, claims can be validated, on the other hand, extra experience is being built to create the best application conditions in real scale projects.

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