Use of recycled concrete aggregates from precast block for the production of new building blocks: an industrial scale study

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Abstract:

Large amounts of construction and demolition (C&D) waste are generated annually and will increase in the future. Until now, only a small fraction of concrete by-products is re-used as recycled concrete aggregates (RCA) for the manufacture of concrete. In this paper, the feasibility of using RCA obtained from old precast concrete block was investigated for the industrial scale production of new blocks. Concrete building blocks with different substitution rates (0%, 30% and 100%) of natural aggregates (NA) by the same volume fraction of RCA were manufactured in a factory and the mechanical properties and durability of concrete blocks were monitored. The results show that incorporating RCA slightly decreases the compressive strength and impairs the durability of concrete blocks. However, the compressive strength of concrete blocks made with 100% RCA could reach 11.1 MPa after 28 days, which is within the requirement in Belgian codes for this type of block. The concrete blocks produced with 30% and 100% of RCA reached the strength, capillary water absorption, drying shrinkage and freeze-thaw resistance requirements for concrete blocks specified by Belgian codes. A cradle-to-gate life cycle assessment (LCA) was performed on both "classical" blocks with only NA and with substitution of NA by RCA. When considering the additional use of RCA from a nearby C&D waste recycling centre, the substitution of 30% or 100% of NA by RCA led to a reduction in the land use category, in addition to supporting the implementation of the circular economy.

1. Introduction

Very large quantities of construction and demolition (C&D) waste are produced every year around the world. The European Union (EU) produces 820 million tonnes of C&D waste (Gálvez-Martos et al., 2018), which is one of the heaviest and most voluminous waste streams generated in the EU (approximately 25% - 30% of all wastes). The composition of C&D waste is heterogeneous and may consist of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic and excavated soil. The main constituent of C&D waste is concrete (varies from 32% to 75% depending on the origin), ceramics and masonry (Batayneh et al., 2007; Bianchini et al., 2005; Sani et al., 2005; Xiao et al., 2012). On the other hand, more than 2.7 billion tonnes of aggregates are produced every year in the EU according to European Aggregates Association (UEPG, 2017). Therefore, it is very important to recycle C&D waste and substitute natural aggregates in order to protect the environment and save natural resources. EU Waste Framework Directive (2008/98/EC) has provided a framework for moving towards a European recycling society with a high level of resource efficiency. In particular, Article 11.2 stipulates that "Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous C&D waste excluding naturally occurring material defined in category 17 05 04 in the list of waste shall be prepared for re-use, recycled and other material recovery (including backfilling operations using waste to substitute other materials)" (European Commission, 2008).

Up to now, most of recycled C&D waste has been used as a base or sub-base material in road construction (“down cycling”), engineering fill or landfill engineering (Barbudo et al., 2012; Poon and Chan, 2006a), while only a small proportion is re-used as recycled aggregates in the concrete industry (high-value application) (Courard et al., 2010; Delvoie et al., 2018; Huang et al., 2002; Xiao et al., 2013; Zhao et al., 2018).

Recently the use of recycled aggregates in structural concrete has been included in the European standard. EN 206:2013+A1. “Concrete – Specification, performance, production and conformity” (CEN, 2016) only concerns the use of coarse recycled aggregates; their use is restricted to less severe environments. Table 1 shows limits for the replacement of natural normal-weight coarse aggregates by coarse recycled aggregates in relation to exposure classes. This table is valid for coarse recycled aggregates (categories Type A and B) conforming to standard EN 12620 (CEN, 2013a). The physical-mechanical properties of recycled concrete aggregates and recycled masonry aggregates (such as acid-soluble chloride ion content, water soluble sulphate content, fines content, flakiness index, resistance to fragmentation, oven dried particle density, water absorption) could affect their use in concrete (Limbachiya et al., 2000; Oikonomou, 2005; Silva et al., 2014). Concrete made with recycled concrete aggregates should be tested to confirm their mechanical and durability properties such as freeze-thaw and sulphate resistance for their intended use (Debied et al., 2010; Zhao et al., 2013).

All over Europe, more than 5500 companies with around 8000 production plants are producing concrete precast products. It is estimated that the sector generated 24 billion euros in 2015 according to European Federation of the Precast Concrete Industry (BIBM, 2016). The European Federation of the Precast Concrete Industry estimates that about 25% of concrete production is represented by concrete precast products (Delvoie et al., 2018).

Concrete precast producers consume large quantities of aggregates and generate voluminous amounts of concrete waste, generally about 1-2% of total production. Concrete building blocks are a commodity product and its profit margin is low (Soutsos et al., 2011) with a local distribution area. The raw materials used to manufacture blocks could be virgin aggregate, lightweight or recycled materials from C&D waste.

Table 1

Maximum percentage of replacement of coarse aggregates (% by mass) according to EN 206:2013+A1 (CEN, 2016)

Recycled aggregate type	Exposure classes			
	X0[c]	XC1, XC2[c]	XC3, XC4, XF1, XA1, XD1[c]	All other exposure classes[a]
Type A: (Rc_{90}, Rcu_{95}, Rb_{10}, Ra_1, FL_2, XRg_1)[d]	50%	30%	30%	0%
Type B[b]: (Rc_{50}, Rcu_{70}, Rb_{30}, Ra_5, FL_2, XRg_2)[d]	50%	20%	0%	0%

[a] Tyep A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%.
[b] Tyep B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.
[c] X0: Exposure class for no risk of corrosion or attack;
XC1 to XC4: Exposure classes for risk of corrosion induced by carbonation (XC1: Dry or permanently wet; XC2: Wet, rarely dry; XC3: Moderate humidity; XC4: Cyclic wet and dry);
XF1: Exposure class for risk of freeze/thaw attack (Moderate water saturation, without de-icing agent);
XA1: Exposure class for risk of chemical attack (Slightly aggressive chemical environment);
XD1: Exposure class for risk of corrosion induced by chlorides other than from see water (Moderate humidity).
[d] Rc_{90}: mass percentage of concrete products is higher than 90% (50% for Rc_{50});
Rcu_{95}: mass percentage of concrete products and unbound aggregate is higher than 95% (70% for Rcu_{70});
Rb_{10}: mass percentage of clay masonry units (i.e. bricks and tiles) is lower than 10% (30% for Rb_{30});
Ra_1: mass percentage of bituminous materials is lower than 1% (5% for Ra_5);
FL_2: volume percentage of floating material is lower than 2%;
XRg_1: other non-floating materials (i.e. clay, soil, plastic, gypsum) and glass is lower than 1% (2% for XRg_2).

22 million tonnes of C&D waste is generated annually in Belgium, excluding excavated soils. Recycling of inert C&D waste has become an obligation since 1998 in Flanders and since 2006 in Wallonia. In Belgium, the total annual quantity of concrete produced is estimated at 40.8 million tonnes (equal to 3.6 tonnes per capita), while the quantity of precast concrete products approaches 12 million tonnes per year (equal to 1.1 tonnes per capita). Estimates of concrete wastes can be based on the assumption that concrete precast producers generate 1-2% of total produced concrete, i.e. concrete wastes is 0.18 million tonnes per year in Belgium

(Delvoie et al., 2019). For example, a medium-sized precast blocks factory can use up to 600 tonnes of aggregate per day and generate 10 tonnes of concrete wastes per day. These concrete wastes are exempt of any contamination, thus high-quality RCA could be obtained from them; indeed, RCA obtained from C&D waste are usually contaminated with other elements such as wood, plastic, bricks, gypsum, glass, excavated soil etc. (Zhao et al., 2017b, 2015).

The feasible use of recycled aggregates from C&D waste in the production of concrete blocks has recently attracted more research interest (Table 2) (Guo et al., 2018; Poon et al., 2009; Poon and Chan, 2007, 2006b; Soutsos et al., 2011; Xiao et al., 2012).

Table 2

Summary of recent studies on the feasible use of recycled aggregates in the production of concrete blocks

Reference	Origin of recycled aggregates	Block type	Test conditions	Replacement levels	Main results
Poon and Chan (2006b)	RCA from recycling facility and crushed clay brick	Paving blocks	Laboratory test	Two series on 0, 25, 50 and 75%	Feasible to produce paving blocks prepared with 25% crushed clay brick that satisfied the compressive strength requirement
Poon and Chan (2007)	RCA from recycling facility and other contaminants	Paving blocks	Laboratory test	Two series on 100% RCA and 10% other contaminants	An allowable contamination level in the RCA can be increased from 1% to a maximum of 10% in the production of paving blocks
Poon and Lam (2008)	Recyclded crushed glass and RCA (Concrete rubble from C&D waste recycling facility)	Paving blocks	Laboratory test	Six series (two series on 0, 25, 50, 75 and 100%)	Recommend to produce the blocks with 50% RCA and 50% recycled crushed glass and with A/C ratoi of 4 or below
Poon et al. (2009)	Low grade RCA from C&D waste recycling facility with high content of no concrete components	Non-structural concrete blocks	Laboratory test	Three series (one series on 0, 25, 50, 75 and 100%)	Potential to use low grade RCA for making non-structural concrete blocks; optimal percentage of recycde fine aggregate is 50%
Soutsos et al. (2011)	RCA and masonry derived aggregate (RMA) from local demolition company	Concrete building blocks	Laboratory test and factory trial	Four series laboratory tests and factory trial	The maximum replacement levels were 60% for coarse fraction RCA and 20% for fine fraction RCA; 20% for coarse fraction RMA and 20% for fine fraction RMA
Guo et al. (2018)	RCA from 30 MPa waste concrete	Concrete building	Laboratory test and	Two mixtures (0 and 75%)	Concrete blocks made with 75% RCAs exhibit

		blocks	factory trial	laboratory tests and a factory trial	favoirable mechanical and durability performances and satisfy Chinese standard
Xiao et al. (2011)	RCA (Concrete rubble waste from earthquakes) and crushed clay brick	Concrete masonry partition wall blocks	Laboratory test	Four series on 0, 25, 50, 75 and 100%	The amount of crushed clay brick should be controlled at less than 25% for coarse aggregates and within 50-75% for fine aggregates.
Zhao et al. (2017a)	RCA from precast concrete block waste	Concrete building blocks	Laboratory test	0, 30 and 100%	The compressive strength of concrete made with 100% RCA could reach 8 MPa after 28 days without increasing the cement content of the concrete mix.

Poon and Lam (2008) evaluated the effects of aggregate-to-cement ratio and the influences of the combinations of aggregates on the properties of blocks. RCA was mainly obtained by concrete rubble sources from a C&D waste recycling facility in Hong Kong. The maximum size of all aggregates was less than 5mm. RCA (water absorption = 10.3%) was used to replace 25%, 50%, 75% and 100% natural crushed aggregate, respectively, in the production of concrete blocks (200 mm × 100 mm × 60mm); an aggregate-to-cement ratio of four was used. The blocks were manufactured in the laboratory with three layers. The authors found that the compressive strength of the paving blocks decreased as the aggregate-to-cement ratio increased. The use of RCA as a replacement of natural crushed aggregate in the production of concrete blocks reduced the density and strength but increased the water absorption of the blocks. The compressive strengths of the blocks after 28 days were 79.9, 67.4, 65.8, 63.5 and 64.8 MPa, respectively, with 0%, 25%, 50%, 75% and 100% replacement of natural crushed aggregate by RCA.

Poon et al. (2009) reported the influence of low grade recycled aggregates on the properties of concrete blocks. The low grade recycled aggregates were obtained from a construction waste sorting facility and they were contaminated with higher percentages of no-concrete components (e.g. > 10% soil, brick, tiles etc.). The blocks were prepared using coarse recycled aggregate and an aggregate to cement ratio of 10:1. Fine recycled aggregate replaced the crushed fine sand at differing levels of 25, 50, 75 and 100%. They discovered that the mechanical strength of blocks decreased with the increasing low grade recycled fine aggregate content (the compressive strengths of the blocks were 37 and 25 MPa respectively for the reference block and 100% fine recycled aggregate block). The drying shrinkage of the blocks increased with an increase in fine recycled aggregate content.

Soutsos et al. (2011) investigated the effect of partially replacing limestone aggregate by recycled demolition aggregates in the manufacture of precast concrete building blocks. A specifically modified electric hammer drill was used to compact the blocks in the laboratory. The maximum replacement levels were 60% for coarse fraction RCA and 20% for fine fraction RCA, respectively: this had no significant detrimental effect on the mechanical properties of blocks. For all the mixes with 100 kg/m^3 of cement below the maximum replacement level, the compressive strength of blocks is around 7.5-8.5 MPa after 28 days, which is higher than the target strength (7 MPa). They found that the maximum replacement levels were 20% for coarse fraction recycled masonry aggregate and 20% for fine fraction recycled masonry aggregate. Factory trials showed that there were no practical problems with the use of recycled demolition aggregate in the manufacture of building blocks.

Guo et al. (2018) explored the possible use of RCA to produce concrete building blocks by using 75% of RCA. The results indicated that the incorporation of RCA slightly declined the compressive strength and impaired the durability of concrete blocks. However, concrete blocks with 75% RCAs satisfied the strength, drying shrinkage and freeze-thaw resistance requirements for concrete blocks specified by Chinese standards. The compressive and shear performances of masonry prisms made with recycled aggregate blocks were similar to those of conventional concrete masonry.

The research above demonstrates that RCA can be successfully used for the production of paving blocks. However, most existing studies were based on laboratory test experience and used RCA from the C&D waste recycling facility. They focused principally on the mechanical properties and specific durability of concrete blocks. Knowledge from industrial scale experiences remains limited. Moreover, only a few studies have recently been carried out covering the environmental impact of using recycled aggregates in the production of concrete blocks (Groslambert et al., 2018). More research is needed to better evaluate the environmental impact of using recycled aggregates in industrial scale production of concrete building blocks.

The objectives of this work were twofold:

1) To study the feasibility of using RCA obtained from precast concrete block by-products in industrial scale production of precast concrete blocks; and

2) To evaluate the environmental impact of industrial concrete blocks with RCA via a life cycle assessment.

In this study, concrete block by-products (concrete block wastes: C8/10) from a Belgian precast company were crushed using an industrial scale impact crusher and the different fractions of produced RCA were characterized. Concrete building blocks with different substitution rates of natural aggregates (0%, 30% and 100%) by the same volume fraction of RCA were manufactured in the precast factory. The mechanical properties and durability of new precast concrete building blocks were controlled and investigated. The environmental impact of industrial produced concrete blocks with RCA was also evaluated via a life cycle assessment.

2. Materials and methods

2.1. Materials

2.1.1. Cement

The cement used in the concrete blocks was blast furnace cement (CEM III/A 42.5 N LA, provided by Heidelberg CBR company) with a density of 3.01 g/cm^3. The mineralogical composition of the cement is shown in Table 3.

Table 3

Mineralogical composition of cement determined by XRD-Rietveld

	C_3S	C_2S	C_3A	C_4AF	Anhydrite	Gypsum	Arcanite	Portlandite	Slag
CEM III/A 42.5 N LA (%)	35.10	7.91	3.29	5.22	0.16	0.86	2.33	1.08	44.01

2.1.2. RCA and natural sands

Concrete block wastes (C8/10) were collected in the company and crushed with an industrial scale impact crusher. Then, RCA were separated into four granular fractions (0/2, 2/6.3, 6.3/14 and 14/20 mm). RCA were characterized by measuring the density, porosity and water absorption. Only the fraction 2/6.3 mm was used for the manufacture of precast concrete building blocks.

The particle size distributions of natural aggregate, natural sand and RCA are shown in Fig. 1. RCA and natural aggregate had similar size distribution curves, and both were continuous. Natural limestone aggregate (noted as NA 2/7) and natural river sand (noted as NS 0/2) were used for the manufacture of concrete blocks. The water absorption of RCA 2/6.3 mm is 3.43% and its apparent density is 2.51 g/cm^3 (whereas it is 0.37% and 2.7 g/cm^3 for natural aggregate) according to European standard EN 1097-6 (CEN, 2013b). The higher value of water absorption and low value density of RCA are due to the presence of hardened cement paste (which is much porous than natural aggregate) adhering to the natural aggregate for the RCA (Zhao et al., 2018).

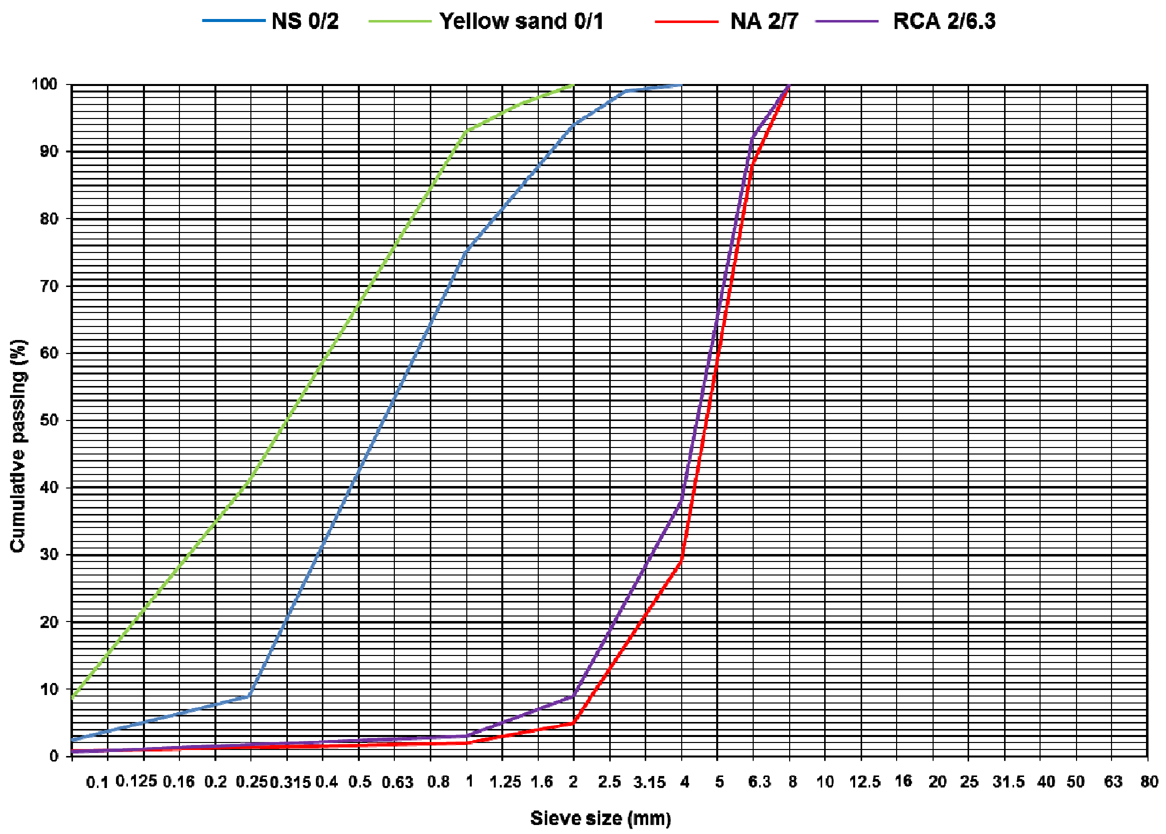

Fig. 1. Grading curves of used aggregates

2.2. Experimental methods

2.2.1. Manufacture of concrete blocks

Three concrete building blocks with different substitution rates (0%, 30% and 100%; these substitution rates were determined according to preliminary laboratory tests) of natural aggregates by the same fraction of RCA (only fraction 2/6.3 mm) were manufactured on the production site (in real industrial conditions). Table 4 shows the composition of concrete building blocks (dimension 39 cm × 14 cm × 19 cm with two holes, see Fig. 2 right) for masonry unit. European standard EN 206:2013+A1 was applied in the concrete blocks mix design. CEM III/A 42.5 cement and a water/cement ratio of 0.5 were used for block production. The air-dried recycled aggregates were used for the concrete blocks production. The absorbed water of natural and recycled aggregates was adjusted according to the water content of the aggregates and their water absorption in the mixer (Table 4). More water was used for the concrete blocks made with recycled aggregates (an additional 28.5 kg of water was used for the concrete blocks B_RCA100 compared with the reference concrete block – see Table 4) due to the higher porosity and water absorption of recycled aggregates compared to the natural aggregates. After mixing, the fresh concrete blocks were placed by mechanical vibrations (Fig. 2, left photo). The block was stored in a wet chamber at 20°C for three days (Fig. 2, right photo). After that, the blocks were stored outside for two weeks. They were then stored in the laboratory at a temperature of 20 ± 2°C and relative humidity of 60% ± 2% until the tests were conducted.

Table 4

Compositions of concrete building blocks - production of a wall unit (1 m^3)

	B_RCA0	B_RCA30	B_RCA100
NA 2/7 (kg)	1010	707	0
RCA 2/6.3 (kg)	0	282	940
NS 0/2 (kg)	822	822	822
Yellow sand 0/1 (kg)	63	63	63
Cement CEM III/A 42.5 (kg)	175	175	175
Efficient water (kg)	87.5	87.5	87.5
Absorbed water (kg)	9.49	18.04	38
W_{eff}/C	0.50	0.50	0.50

Fig. 2. Production of block with RCA on the production site, under real industrial conditions (left: installation for mechanical vibration; right: marking and storage)

2.2.2. Hardened properties of blocks

2.2.2.1. Dimensions

The dimensions of the concrete blocks were measured according to European standard EN 772-16 (CEN, 2011a). The length, width and height of the specimens were measured with an appropriate device. The deviations of dimensions and tolerances were determined and compared according to European standard EN 772-13 (CEN, 2000) for all concrete blocks.

2.2.2.2. Hardened density

The density of concrete blocks specimens was determined according to European standard EN 772-13. The specimens of blocks were dried until constant mass $M_{dry,b}$ in a ventilated oven at a temperature of 70°C ± 5°C. The net volume of blocks $V_{net,b}$ was determined from the total volume (length × width × height: determined according to European standard EN 772-16) subtracting the volume of all voids (length × width × height: determined according to European standard EN 772-16). The hardened density ρ_b was calculated using Equation 1.

$$\rho_b = M_{dry,b} / V_{net,b} \qquad \text{Equation 1}$$

2.2.2.3. Capillary water absorption

The water absorption values of concrete block masonry units due to capillary action were determined according to European standard EN 772-11 (CEN, 2011b). At the age of 28 days, the specimens were dried until constant mass $M_{dry,b}$ in a ventilated oven at a temperature of 70°C ± 5°C. Specimens were cooled at room temperature and the dimensions of the faces to be immersed were measured in order to calculate the gross areas A_s. The specimens were immersed in water up to a depth of 5 mm ± 1 mm for the duration of the test. After specific immersion times T_{im} (10 mins, 30 mins, 1 h, 4 h, 6 h and 24 h), the surface water was wiped and the mass of specimens $M_{im,b}$ was measured. The coefficient of water absorption due to capillary action (C_{wa}) of blocks was calculated at T_{im}=10 mins using Equation 2.

$$C_{wa} = \left(M_{im,b} - M_{dry,b}\right) / \left(A_s \times T_{im}\right) \qquad \text{Equation 2}$$

2.2.2.4. Compressive strength

The mechanical properties of concrete blocks were measured according to European standard EN 772-1 (CEN, 2011c). The surface of concrete blocks was flattened by fresh mortar, and then the compressive strength of concrete blocks was measured with a loading rate of 0.05 MPa/s. The maximum load was reached and recorded. The compressive strength of concrete blocks at 28 and 360 days were analyzed. The 360 days' compressive strength was chosen to investigate the long term curing on properties of concrete blocks. Three specimens were tested for each mix proportion.

2.2.2.5. Drying shrinkage

The drying shrinkage of concrete blocks was determined according to BS 6073 (British Standards Institution, 1981). Many researchers have obtained reliable results using this method (Poon et al., 2009; Xiao et al., 2011). After 28 days curing, the concrete blocks were immersed in water at room temperature for 24 h, and then the initial length of the specimens was measured. After the initial measurement, the concrete specimens were stored in the laboratory chamber at a temperature of 20 ± 2°C and a relative humidity of 60% ± 2%. Length of the specimens was measured again after 1, 3, 7 and 14 days, respectively.

2.2.2.6. Freeze-thaw resistance

The freeze-thaw resistance of concrete blocks was determined according to NBN B 15-231 (Belgian standard, 1987). The concrete block specimens were placed in a freeze-thaw chamber where they were subjected to the 14 freeze-thaw cycles shown in Fig. 3 (24 h per cycle from -15°C to +10°C, freezing at -15°C in air and thawing in water at 10°C). The evaluation of freeze-thaw resistance was carried out on the base of mass loss and reduction of resonant frequency. The resonant frequencies of concrete blocks before and after the freeze-thaw action were determined according to NBN B 15-230 (Belgian standard, 1976). In addition, a visual evaluation of surface scaling was conducted after freeze-thaw action.

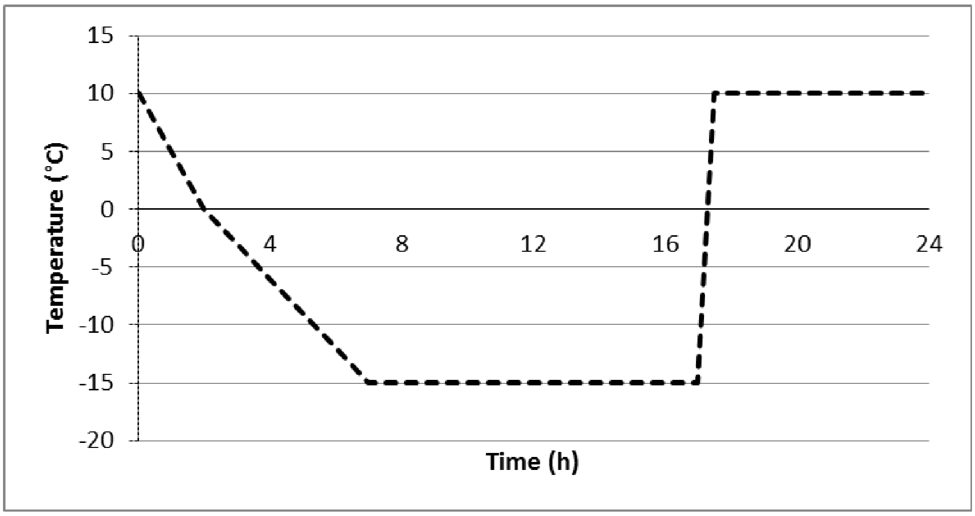

Fig. 3. Freeze-thaw cycle according to NBN B 05-203 (Belgian standard, 1977)

2.2.3. Life cycle assessment of concrete blocks

Life cycle assessment is a well-recognized scientific method to assess the environmental impact of a technical solution, a material or a service (Ding et al., 2016; Kurad et al., 2017; Kurda et al., 2018; Marinković et al., 2010). It considers a broad range of environmental impacts and follows ISO standardization (Hauschild et al., 2018). The present LCA was conducted in accordance with ISO 14040:2006 (ISO, 2006a) and 14044:2006 standards (ISO, 2006b) and the four mandatory key steps were carried out; namely, (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

2.2.3.1. Goal and scope definition

The goal is to study the influence of natural aggregates (NA) substitution by recycled concrete aggregates (RCA) from precast concrete block waste, in order to produce precast concrete building blocks.

The scope is to conduct a cradle-to-gate comparative LCA between the "classical" concrete blocks of Prefer (B_RCA0) and the blocks with a substitution of 30% and 100% of NA by RCA from precast block waste (B_RCA30 and B_RCA100), as described in the Section 2.2.1. The functional unit (FU) is 1 m³ of concrete blocks, on the basis of a one-year production cycle.

The system boundaries for the B_RCA0 include the raw materials and their transport to the two production sites of Prefer (Engis and Flémalle), the processing of the blocks (mixing and pressing), the transport of the waste and its disposal in an inert landfill (Fig. 4).

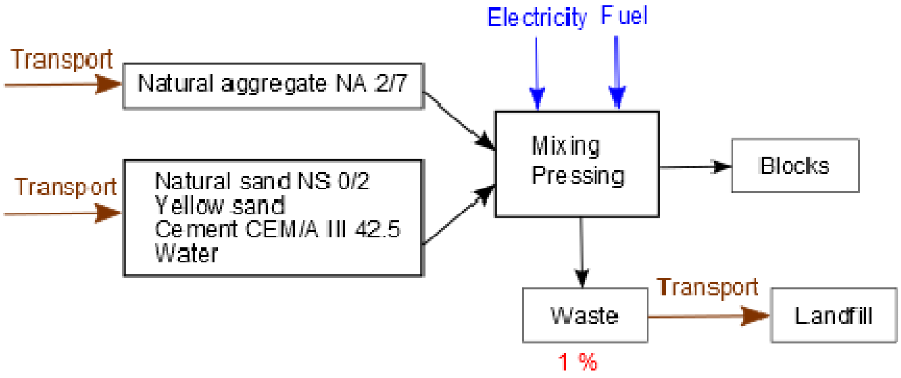

Fig. 4. System boundaries for the production of B_RCA0 (NA only)

The system boundaries for the B_RCA30 and B_RCA100 include the raw materials and their transport to the two production sites of Prefer (Engis and Flémalle), the processing of the blocks (mixing and pressing), the transport of the waste blocks from the Engis site to the Flemalle site, the crushing of all the waste blocks with a mobile crusher and their sorting, the transport of the mobile crusher to a Prefer site and its fuel consumption, the recycling of the RCA 2/6.3 mm as substitute of NA for the blocks, and the transport of the ultimate waste (RCA 0/2 mm) and its disposal (Fig. 5). The remaining fractions (6.3/14 mm and 14/20 mm) are included in the boundaries as avoided burden, as they are recycled with other internal products (e.g. concrete components manufactured with these coarse recycled aggregates in the substitution of NA for the barrier wall to stock the materials) by Prefer. It means that all the

RCA used in internal recycling (2/6.3, 6/14 and 14/20 mm) are considered as potential substitution of NA in the model (system extension).

Since the amount of RCA produced from the waste blocks is insufficient to ensure annual production at Prefer, another source of RCA is considered as a complementary supply. It consists the use of RCA 2/6.3 mm from a nearby C&D waste recycling site. The proposed site is the Richopré quarry and recycling site which belongs to Eloy Construction located in Chanxhe, which is 25 km from Prefer's facilities. The C&D waste is supposed to be crushed and sorted at Richopré site. The amount of recycled product is the one allowing an annual production of blocks including 30% or 100% of RCA.

Some elements are excluded from the system boundaries: buildings and infrastructure, ground occupation, internal conveying of the raw materials, of the blocks and of waste.

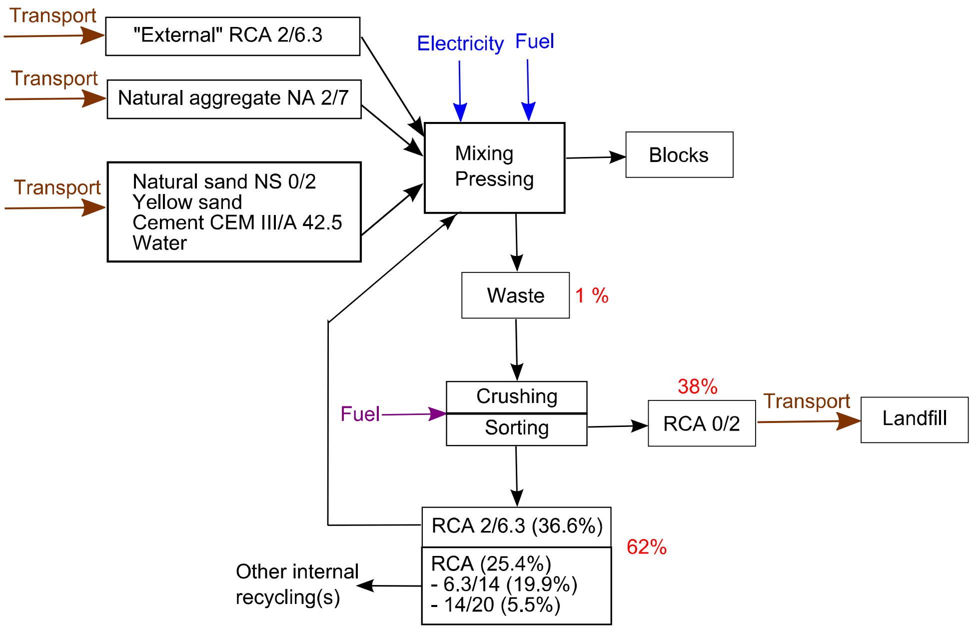

Fig. 5. System boundaries for the production of B_RCA30 and B_RCA100

2.2.3.2. Life cycle inventory

The composition of the blocks is described in Table 4. Prefer produces 101500 m³ of blocks per year (on a 10-month activity basis) on two sites, Flémalle and Engis, which produces 65.5% and 34.5% of the blocks respectively. The reference scenario is the business as usual production of B_RCA0 concrete blocks.

Waste represents 1% of the production, which is 1015 m³/year (or 2202550 kg). It is very low and the most plausible assumption is to surmise that a mobile crusher comes once a year to transform all the waste into aggregates. The alternative scenario with recycling of the waste blocks assumes that the waste is stored for one year at the two facilities, and that the crusher comes to Flémalle once a year. Waste from Engis is transported by road to Flémalle. The waste is crushed and sorted in four fractions: 0/2 mm (38%), 2/6.3 mm (36.6%), 6.3/14 mm (19.9%) and 14/20 mm (5.5%). The RCA 0/2 mm is ultimate waste and disposed at an inert landfill (transported by road). The RCA 2/6.3 mm is incorporated into the concrete blocks at the level of 30% of substitution of NA, and the last two fractions (6.3/14 and 14/20 mm – 25.4%) are recycled with other internal products by Prefer. They are considered "avoided burden" in the alternative scenario. The RCA 2/6.3 mm represents 805015 kg/year. It is possible to produce 2855 m³ of B_RCA30 with this amount of aggregates, or 856 m³ of B_RCA100, which corresponds only to 3% (respectively 1.3%) of the annual production of blocks. Therefore, the internal production of RCA has to be completed with "imported RCA" from a nearby sorting centre to meet the demand of Prefer’s customers. The burden of the waste processing, i.e. the transportation and operation of the mobile crusher, are allocated to the whole annual production along with the avoided burden due to the other fractions of RCA. The inventory is calculated on a whole year basis and standardized by the overall annual production to be normalized to 1 m³ of blocks, i.e. the FU.

The raw material and waste are transported by road (30t truck, EURO5). The natural aggregates and sand comes from a nearby quarry (Ramioul, BE) – the yellow sand comes from Rotterdam (NL) and the cement CEM III/A from Tournai (BE). The inert landfill is located in Loncin (BE). The mobile crusher (Metso LT1213) travels by road on a truck (50t, EURO4) from Namur (BE). Its capacity is 250t/h and its specific consumption of fuel is 80.5 L/h of diesel. It is modelled on the Ecoinvent 3.5 process "Diesel, burned in building machine (GLO), market for, APOS, U". Block processing energy consumption is derived from the Ecoinvent 3.5 process "Concrete block production, (DE), APOS,U" and adapted to Prefer’s and Belgian specificities (electricity grid mix). The natural aggregates and sand production are modelled on the basis of the generic entries of Ecoinvent adapted to Belgian specificities for heat production and electricity mix (adaptation of "Gravel, round {CH}| gravel and sand quarry operation | APOS, U" and "Sand {CH}| gravel and quarry operation | APOS, U").

For the "import of external RCA" from Richopré scenario, the C&D waste is crushed and sorted in situ with a crusher of the same type as the mobile crusher used at Prefer. Only its fuel consumption is counted, and it is supposed to be similar to that of the mobile crusher. The RCA 2/6.3 mm is transported by road to Prefer’s production sites (25 km, 30t truck, EURO5).

2.2.3.3. Method for assessment

The Ecoinvent database (3.5, November 2018) (Wernet et al., 2016) was used to model the scenarios.

Impact assessment was evaluated with Simapro 9.0 software (2019) (Pré-Consultant, CH), with ILCD 2011 Midpoint+ (1.10) method (EC-JRC-IES, 2010), as recommended by the Joint Research Centre of the European Commission. The considered impact categories are: Climate change, Ozone depletion, Particulate matter, Photochemical ozone formation, Acidification, Terrestrial eutrophication, Freshwater eutrophication, Marine eutrophication, Land use and Mineral, fossil and renewable resource depletion.

3. Results and discussion

3.1. Hardened properties of concrete blocks

3.1.1. Dimensions

Table 5 shows the results with differing block dimensions and maximum deviations according to EN 771-3 (CEN, 2011d). The values are an average from three measurements. The results indicate that all the dimensions of the blocks were in the requirement of limit deviations regardless of the type of blocks (with RCA or without RCA). No visual differences were observed between the different types of blocks.

Table 5

Dimensions of blocks and limit deviations according to EN 771-3 (in millimeters)

	Length	Width	Height	Length deviation	Width deviation	Height deviation
B_RCA0	386.8	138.0	189.7	-3.2	-2.0	-0.3
B_RCA30	386.8	137.7	190.6	-3.2	-2.3	0.6
B_RCA100	386.3	138.0	190.4	-3.7	-2.0	0.4
Standard size	390.0	140.0	190.0	-	-	-
Tolerance category	-	-	-	D1: -5, +3	D2: -3, +1	D4: -1, +1

3.1.2. Hardened density

The hardened density values of the block specimens are reported in Fig. 6. The values are an average from three measurements. The results show that the hardened density of blocks slightly decreased with an increase in RCA content, which is due to the fact that RCA had a lower density compared to the natural aggregate (the apparent density of RCA 2/6.3 mm is 2.51 g/cm^3, whereas it is 2.7 g/cm^3 for natural aggregate). The lower value density of RCA is due to the presence of hardened cement paste, which is much more porous than natural aggregate (the hardened cement paste content of RCA 2/6.3 mm was reported as 8.5%

according to Zhao et al., 2018). On the other hand, due to the higher apparent porosity, the concrete blocks containing RCA have lower density compared to the reference block. This finding agrees with the results of other authors (Courard et al., 2010; Guo et al., 2018; Poon and Chan, 2007, 2006b). Moreover, all the blocks were in the category of class ρ 2.2 (1900 kg/m^3 < ρ ≤ 2200 kg/m^3) according to the density category given in PTV 21-001 (PROBETON, 2011).

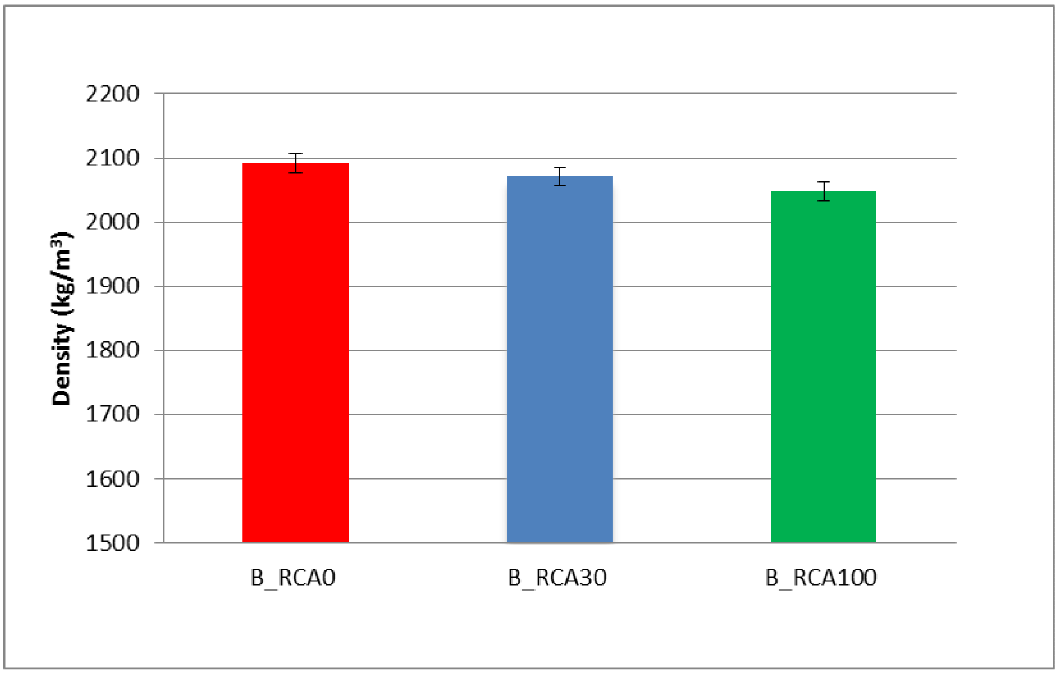

Fig. 6. Hardened density of concrete building blocks

3.1.3. Capillary water absorption

Capillary water absorption of the concrete blocks is presented in Fig. 7. Block specimens containing RCA had higher water absorption values compared to the block prepared with natural aggregates. As might be expected, water absorption of concrete with recycled aggregates was significantly higher than that of natural aggregate concrete, which was also reported by other researchers (Debieb et al., 2010; Poon and Lam, 2008; Xiao et al., 2011). This outcome is due to the higher water absorption capacity of RCA (higher porosity as a result of the presence of adherent hardened cement paste in RCA) versus natural aggregates.

The capillary water absorption of concrete blocks increased as the substitution of natural aggregates by RCA increased. The increased amount of water absorption of the blocks was caused by the greater porosity of the specimens with RCA – the presence of RCA creates more and longer capillaries as a consequence of its own porosity, which increases capillary stress. This increase in the amount of capillary pores associated with the absorption by the RCA ends up promoting a greater suction of the water. The values of the capillary water absorption coefficient (C_{wa} obtained at 10 mins) of blocks were 4.11, 5.56, 6.70 g/m^{2}s for the concrete block B_RCA0, B_RCA30 and B_RCA100 respectively. These concrete blocks however meet the capillary water absorption requirements prescribed in PTV 21-001 for grade A2 blocks (max 8 g/m^{2}s).

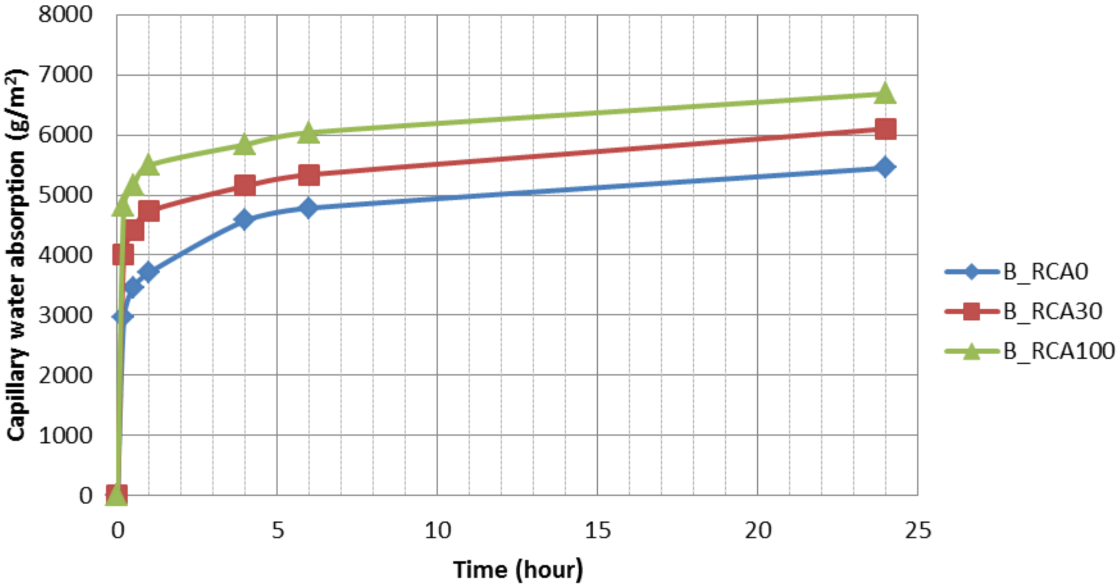

Fig. 7. Capillary water absorption of concrete blocks

3.1.4. Compressive strength

The 28-day and 360-day compressive strength of the blocks are given in Fig. 8. The values are an average from three measurements. It can be seen that the compressive strengths of concretes with RCA were lower than those of concrete with natural aggregates. The compressive strength of the block specimens slightly decreased with an increase of RCA content. The compressive strength of concrete block made with 100% RCA at 28 days deceased 16.5% compared to the reference concrete, while the concrete block made with 30% RCA at 28 days decreased 6.0%. The lower mechanical strengths are caused by the poorer physical properties of RCA in comparison to natural aggregates used, i.e. the presence of adherent cement paste led to higher porosity and worse mechanical and physical properties of RCA (less resistant) compared to the natural aggregates (Xiao et al., 2007, 2013; Zhao et al., 2015). It could also be associated with an increase in the water/cement ratio, from the higher initial free water content in the concrete mixture (since the RCA was used at the air-dried condition with moisture content of aggregate much lower than the water absorption, about 28.5 kg more water was used for the concrete blocks B_RCA100 compared to the reference concrete block), due to the existence of a second zone of transition. The compressive strength of concrete block made with 100% RCA could reach 11.1 MPa after 28 days and 12.7 MPa after 360 days. The normalized compressive strength of masonry unit (f_{bm}, $f_{bm} = d \times f_b$) can be determined by the shape factor d and mean compressive strength of masonry specimens (f_b) according to EN 772-1. The shape factor d is defined as being a multiplying factor used to convert the mean compressive strength of the masonry specimens to the normalized compressive strength of masonry unit f_{bm} (d =1.18 for all blocks: the shape factor is equal to 1 for specimen with height and width each equaling 100mm according to the EN 772-1). The normalized compressive strength of concrete block made with 100% RCA was 13 MPa, which is within the requirement for this type of block according to PTV 21-001 (class f10, $f_{bm} \geq 10$ MPa). Moreover, all types of concrete block made with RCA or without RCA were in the quality category of class “10/2.2” according to PTV 21-001 (category of class f10 with $f_{bm} \geq 10$ MPa and category ρ 2.2 with $1900 \text{ kg/m}^3 < \rho \leqslant 2200 \text{ kg/m}^3$).

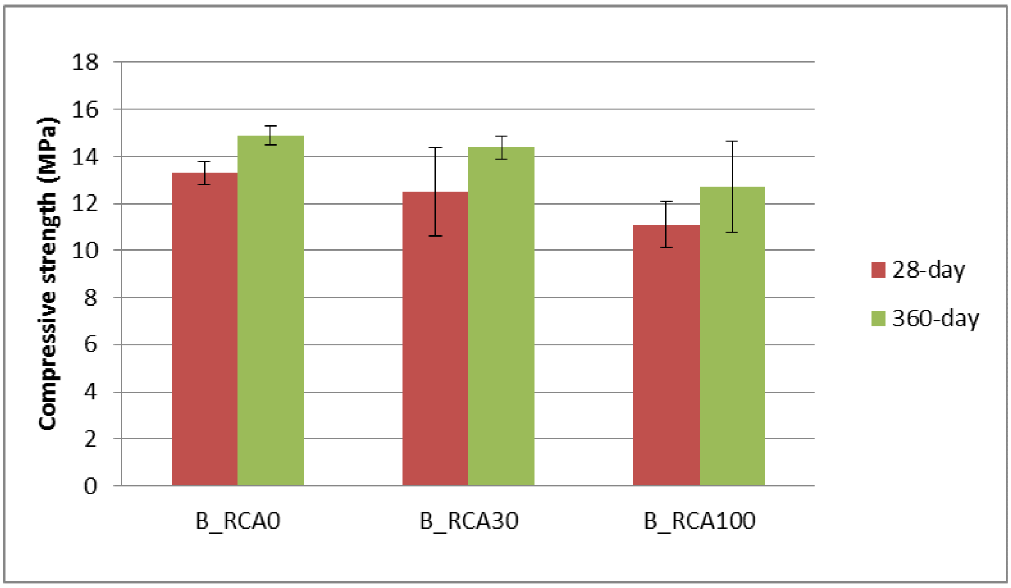

Fig. 8. Compressive strengths of concrete blocks at 28-day and 360-day.

3.1.5. Drying shrinkage

The drying shrinkage of the concrete blocks is shown in Fig. 9. The values are an average from three measurements. The drying shrinkage of the blocks increased with an increase in RCA content. The hardened cement paste attached to the RCA contributed to an increase in the volume of the paste (old hardened cement paste in RCA + new), thus increasing the drying shrinkage of the resulting concrete. This is consistent with the results of previous studies (Guo et al., 2018; Poon et al., 2009). In addition, the shrinkage of blocks with 100% of RCA in this test (i.e., 0.052%) is consistent with the result obtained by Poon et al. (2009) (⩽ 0.06%). Moreover, the drying shrinkage values of the blocks were beneath the limit (⩽ 0.06%) prescribed by BS 6073 regardless of the type of block.

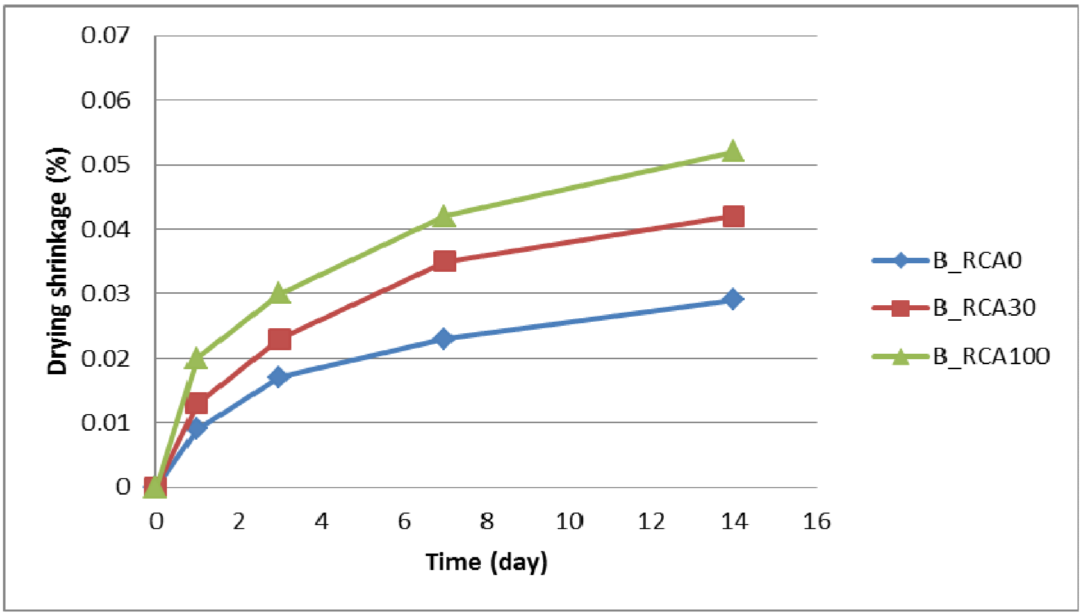

Fig. 9. Drying shrinkage of concrete blocks

3.1.6. Freeze-thaw resistance

After 14 freeze-thaw cycles, a visual inspection of the specimen did not reveal any significant deterioration in all the blocks (this is in line with the requirement for this type of block according to PTV 21-001). The loss of mass in all the concrete blocks did not exceed 1% in any case (the mass loss of concrete blocks were 0.25%, 0.27% and 0.47% for B_RCA0, B_RCA30 and B_RCA100, respectively). The mass loss of concrete blocks made with RCA was higher than those of the reference concrete blocks. The residual resonant frequency of concrete blocks is shown in Fig. 10. The residual resonant frequency of blocks made with RCA after freeze-thaw cycles was lower than that of the reference concrete blocks (the scope of reduction in resonant frequency of the blocks after freeze-thaw cycles were 7.91%, 8.32% and 15.84% respectively for B_RCA0, B_RCA30 and B_RCA100). As can be seen, the specimens containing RCA were less durable in freeze-thaw action, which is due to their higher initial water/cement ratio and consequent higher capillary porosity. This is a direct consequence of the higher porosity of RCA and their lower stiffness (Bogas et al., 2015) and is consistent with the results of a previous study (Guo et al., 2018).

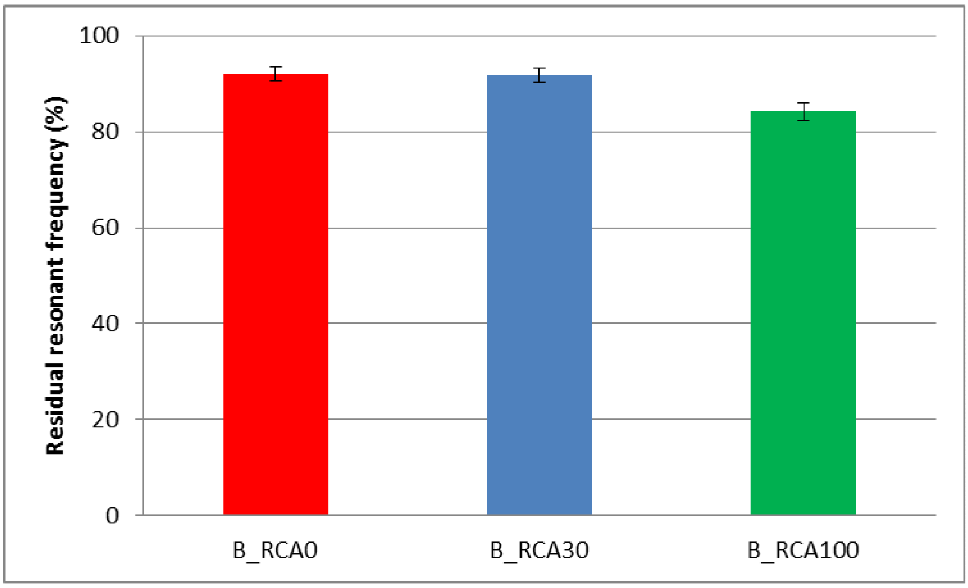

Fig. 10. Residual resonant frequencies of concrete blocks after freeze-thaw action

3.2. Life cycle assessment of concrete blocks

The comparative LCA of concrete blocks without RCA (B_RCA0) and with 30% and 100% of RCA in substitution of NA (B_RCA30 and B_RCA100) do not show significant differences across almost all impact categories (Fig. 11, Table 5) with the exception of land use, especially for the 100% substitution case (in green in Fig. 11). The benefits are respectively 16.1% and 53.1% for the B_RCA30 and the B_RCA100 compared to the NA scenario. Although these findings appear obvious without even doing a LCA, it is worthwhile to be able to quantify objectively the potential gains from the substitution of NA by RCA.

Table 5

Comparison of the impact of the production of 1 m³ of concrete blocks with NA only (B_RCA0 – reference scenario) and the production of 1 m³ of blocks with the substitution of 30% (B_RCA30) and 100% (B_RCA100) of NA by RCA – Characterization ILCD 2011 Midpoint+ (1.10)

	Units	B_RCA0	B_RCA30	B_RCA100
Climate change	kg CO_2 eq	1.09E+02	1.08E+02	1.08E+02
Ozone depletion	kg CFC-11 eq	6.30E-06	6.32E-06	6.51E-06
Particulate matter	kg PM2.5 eq	3.36E-02	3.29E-02	3.17E-02
Photochemical ozone formation	kg NMVOC eq	3.01E-01	2.99E-01	2.97E-01
Acidification	molc H^+ eq	3.82E-01	3.79E-01	3.74E-01
Terrestrial eutrophication	molc N eq	1.15E+00	1.14E+00	1.14E+00
Freshwater eutrophication	kg P eq	2.90E-03	2.85E-03	2.76E-03

Marine eutrophication	kg N eq	1.00E-01	9.98E-02	9.93E-02
Land use	kg C deficit	1.86E+02	1.56E+02	8.72E+01
Mineral, fossil & ren resource depletion	kg Sb eq	7.81E-02	7.81E-02	7.81E-02

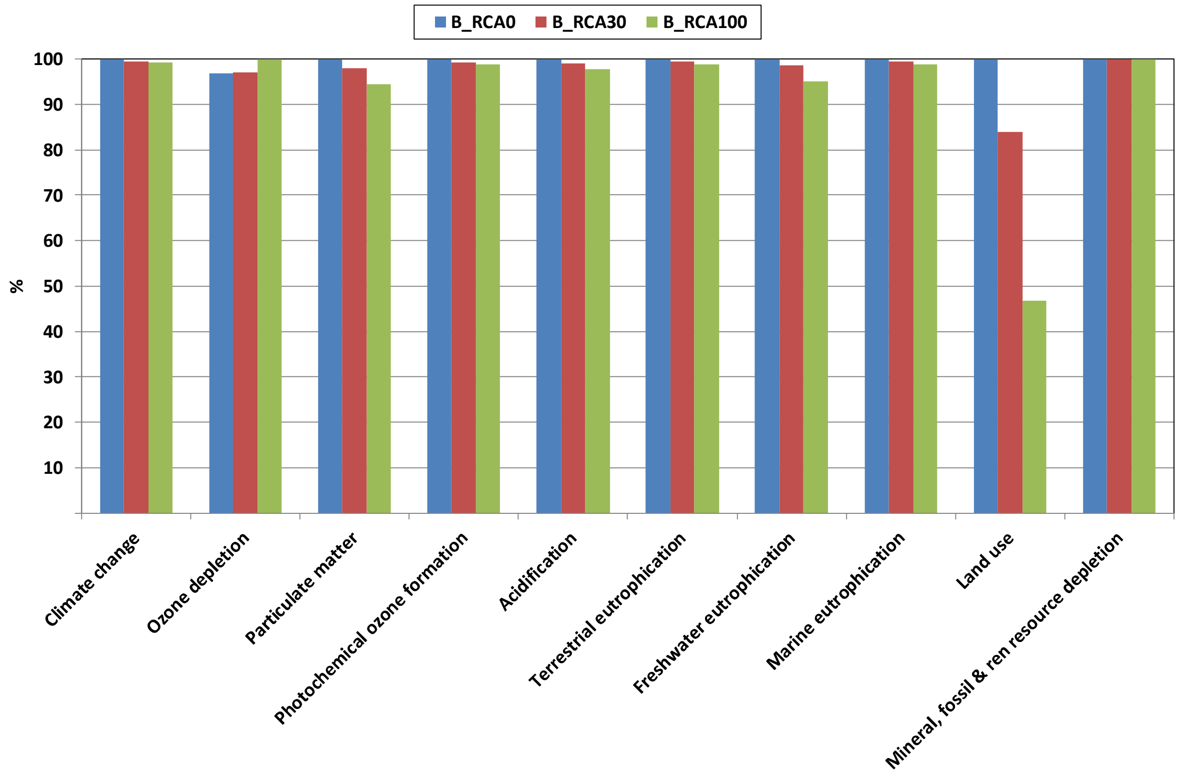

Fig. 11. Comparison of the impacts of the production of 1 m³ of concrete blocks with NA only (B_RCA0 – reference scenario) and the production of 1 m³ of blocks with the substitution of 30% (B_RCA30) and 100% (B_RCA100) of NA by RCA – Characterization ILCD 2011 Midpoint+ (1.10)

Usually cement is the main influential element when evaluating the environmental burden of concrete (as it is for instance for a generic concrete entry in Ecoinvent database) (Wernet et al., 2016). The natural aggregates (*gravel* in the inventory) only represent a small part of the impact in a classical formulation of a concrete. This has been verified in the test.

Fig.12 presents the detailed impact of the different elements of the inventory of B_RCA0 concrete blocks. The cement (in violet in Fig. 12) is clearly the element with the most impact in all categories except land use. This category is mainly affected by natural aggregates and sand. Natural aggregates or sand have no impact in the mineral resource depletion category because there is no characterisation factor associated with the "gravel" in the ILCD method (nor in any other method). This is due to the fact that gravel is not considered a potentially missing mineral resource by any method. However, NA and sand have a rather large impact in the land use category since they are crushed stones coming from quarries, with occupation of land for the mineral extraction site. Land uses (occupation and transformation) are generic data included in the entries of Ecoinvent database (Wernet et al., 2016). This fact explains why even a small substitution of NA can bring gains in this category (see Fig. 11).

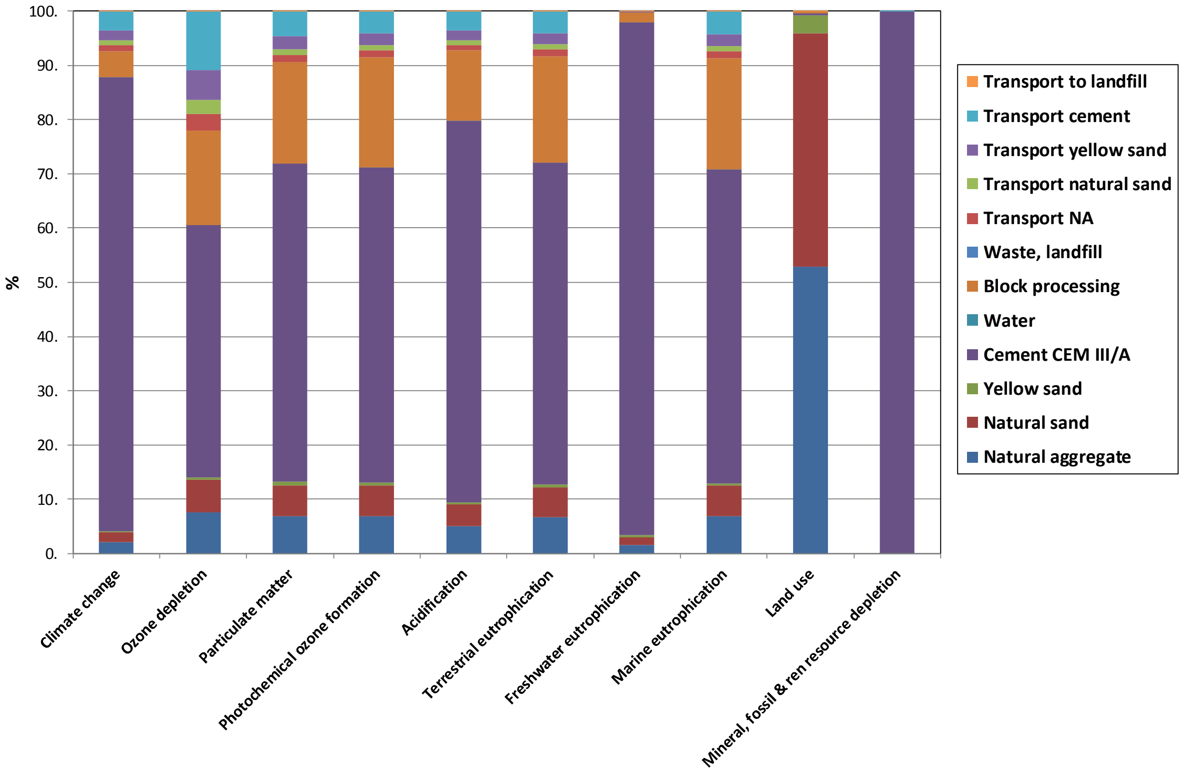

Fig. 12. Impact of the production of 1 m³ of concrete blocks with NA only (B_RCA0 – reference scenario) – Characterization ILCD 2011 Midpoint+ (1.10)

The internal production of RCA 2/6.3mm from old block waste for the production of B_RCA30 blocks can only substitute 3% of the global production of concrete blocks at Prefer because a large quantity of materials is needed for the global production of concrete blocks. As the block waste in Prefer is limited, recycled materials from a nearby C&D waste sorting site could be another solution (that is why the scenario of life cycle assessment of B_RCA30 and B_RCA100 by using the RCA 2/6.3 mm from old block waste plus RCA from a nearby

C&D waste recycling site was included). Further investigation is needed for the production of blocks based on recycled materials obtained from the unknown source.

The use of RCA in the production of concrete blocks is interesting. It can decrease the quantity of natural aggregate used in production and protect the environment. Meanwhile, block waste can be reused in the production of new blocks and therefore the amount of waste sent to landfills can be reduced. From an economic point of view, waste recycling is worthwhile when the recycled product is competitive with natural resources in terms of cost and quality. This study has demonstrated that RCA can be successfully used for the production of concrete blocks on an industrial scale. Due to a reduction in transportation costs, recycled materials will be more competitive in regions with scarce raw materials.

4. Conclusions

The feasibility of using RCA obtained from precast concrete block by-products for the production of new precast concrete building blocks on an industrial scale was investigated. Results clearly showed that the substitution with RCA slightly decreases the compressive strength and impairs the durability of concrete blocks. However, the concrete building blocks produced with 30% and 100% of RCA without increasing cement content can satisfy the hardened density, strength, capillary water absorption, drying shrinkage and freeze-thaw resistance requirements specified in Belgian codes. Therefore, the use of RCA can be considered in production of new precast concrete building blocks. The main conclusions that can be drawn are listed as follows:

1) The hardened density and compressive strength of concrete building blocks slightly decreased with an increase in the RCA content. The compressive strength of concrete blocks produced with 100% RCA at 28 days decreased up to 16.5% compared to the reference block

and up to 6.0% for the concrete block with 30% RCA. However, the compressive strength of concrete blocks made with 100% RCA could even reach 11.1 MPa after 28 days, which is within the Belgian code requirements for this type of block.

2) Block specimens containing RCA had higher water absorption values compared to the block prepared with natural aggregates. The capillary water absorption of concrete blocks increased as the substitution of natural aggregates by RCA increased. Nevertheless, all the concrete blocks meet the capillary water absorption requirements prescribed in PTV 21-001.

3) The incorporation of RCA slightly impaired the durability of concrete blocks in terms of drying shrinkage and freeze-thaw resistance. The drying shrinkage of the blocks increased with an increase of RCA but remained under the limit (⩽ 0.06%) regardless of the type of block. Freeze-thaw resistance results clearly confirmed that all concrete blocks satisfy the requirements.

4) A cradle-to-gate life cycle assessment of the production of concrete blocks including RCA did not show significant gain in most of the impact categories because the element with the most impact in the blocks is cement. Due to the very low available amount of waste, it is necessary to import external RCA 2/6.3 mm from a nearby C&D waste recycling site. The substitution of NA by RCA shows a very limited gain in most categories, except in the land use category, especially with a level of 100% of substitution (up to 53.1% of gain). Globally, from a circular economy perspective, substituting NA with RCA recycled from concrete blocks, combined with externally importing RCA, is an interesting development route to decrease the environmental impact of producing concrete building blocks.

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References

Barbudo, A., Agrela, F., Ayuso, J., Jiménez, J.R., Poon, C.S., 2012. Statistical analysis of recycled aggregates derived from different sources for sub-base applications. Constr. Build. Mater. 28, 129–138. doi:10.1016/j.conbuildmat.2011.07.035

Batayneh, M., Marie, I., Asi, I., 2007. Use of selected waste materials in concrete mixes. Waste Manag. 27, 1870–1876. doi:10.1016/j.wasman.2006.07.026

Belgian standard, 1987. NBN B 15-231 Concrete testing - Resistance to freezing.

Belgian standard, 1977. NBN B 05-203 Resistance of building materials to freezing and thawing cycles.

Belgian standard, 1976. NBN B 15-230 Concrete testing - Non destructive testing - Measurement of the resonant frequencies.

Bianchini, G., Marrocchino, E., Tassinari, R., Vaccaro, C., 2005. Recycling of construction and demolition waste materials: A chemical-mineralogical appraisal. Waste Manag. 25, 149–159. doi:10.1016/j.wasman.2004.09.005

BIBM, 2016. European Precast Concrete Industry. Factbook 2016.

Bogas, J.A., de Brito, J., Ramos, D., 2015. Freeze-thaw resistance of concrete produced with fine recycled concrete aggregates. J. Clean. Prod. 115, 294–306. doi:10.1016/j.jclepro.2015.12.065

British Standards Institution, 1981. BS 6073: Part 1. Precast concrete masonry units, specification for precast concrete masonry units.

CEN, 2016. EN 206:2013+A1 Concrete - Specification, performance, production and conformity.

CEN, 2013a. EN 12620 Aggregates for concrete.

CEN, 2013b. EN 1097-6 Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption.

CEN, 2011a. EN 772-16 Methods of test for masonry units - Part 16: Determination of dimensions.

CEN, 2011b. EN 772-11 Methods of test for masonry units - Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorptio.

CEN, 2011c. EN 772-1 Methods of test for masonry units - Part 1: Determination of compressive strength.

CEN, 2011d. EN 771-3 Specification for masonry units - Part 3: Aggregate concrete units (Dense and lightweight aggregates).

CEN, 2000. EN 772-13 Methods of test for masonry units - Part 13: Determination of net and gross dry density of masonry units (except for natural stone).

Courard, L., Michel, F., Delhez, P., 2010. Use of concrete road recycled aggregates for Roller Compacted Concrete. Constr. Build. Mater. 24, 390–395. doi:10.1016/j.conbuildmat.2009.08.040

Debieb, F., Courard, L., Kenai, S., Degeimbre, R., 2010. Mechanical and durability properties of concrete using contaminated recycled aggregates. Cem. Concr. Compos. 32, 421–426. doi:10.1016/j.cemconcomp.2010.03.004

Delvoie, S., Zhao, Z., Michel, F., Courard, L., 2019. Market analysis of recycled sands and aggregates in NorthWest Europe: Drivers and barriers. IOP Conf. Ser. Earth Environ. Sci. 225. doi:10.1088/1755-1315/225/1/012055

Delvoie, S., Zhao, Z., Michel, F., Courard, L., 2018. WP T1 Market analysis and formal regulations in NWE.

Ding, T., Xiao, J., Tam, V.W.Y., 2016. A closed-loop life cycle assessment of recycled aggregate concrete utilization in China. Waste Manag. 56, 367–375. doi:10.1016/j.wasman.2016.05.031

EC-JRC-IES, 2010. European Commission (EC) - Joint Research Centre (JRC) - Institute for Environment and Sustainability (IES) (2010) International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance.

European Commission, 2008. DIRECTIVE 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain Directives, Official Journal of the European Union.

Gálvez-Martos, J.L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B., 2018. Construction and demolition waste best management practice in Europe. Resour. Conserv. Recycl. 136, 166–178. doi:10.1016/j.resconrec.2018.04.016

Groslambert, S., Breuil, R., Courard, L., Zhao, Z., Léonard, A., 2018. Valorization of construction and demolition waste , a route to circular economy : the Valdem project. The 8th edition [aveniR] conference. 7-8 november 2018, Lille, France

Guo, Z., Tu, A., Chen, C., Lehman, D.E., 2018. Mechanical properties, durability, and life-cycle assessment of concrete building blocks incorporating recycled concrete aggregates. J. Clean. Prod. 199, 136–149. doi:10.1016/j.jclepro.2018.07.069

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment: Theory and Practice, Life Cycle Assessment: Theory and Practice. doi:10.1007/978-3-319-56475-3

Huang, W., Lin, D., Chang, N., Lin, K., 2002. Recycling of construction and demolition waste via a mechanical sorting process. Resour. Conserv. Recycl. 37, 23–37. doi: 10.1016/S0921-3449(02)00053-8

ISO, 2006a. ISO 14040: 2006 Environmental Management–Life Cycle Assessment–Principles and Framework. International Standard Organisation, Geneva, Switzerland

ISO, 2006b. ISO 14044:2006 - Environmental management - Life Cycle Assessment Requirements and Guidelines. International Standard Organisation, Geneva, Switzerland

Kurad, R., Silvestre, J.D., de Brito, J., Ahmed, H., 2017. Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete. J. Clean. Prod. 166, 485–502. doi:10.1016/j.jclepro.2017.07.236

Kurda, R., Silvestre, J.D., de Brito, J., 2018. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. Resour. Conserv. Recycl. 139, 407–417. doi:10.1016/j.resconrec.2018.07.004

Limbachiya, M.C., Leelawat, T., Dhir, R.K., 2000. Use of recycled concrete aggregate in high-strength concrete. Mater. Struct. 33, 574–580. doi:10.1007/BF02480538

Marinković, S., Radonjanin, V., Malešev, M., Ignjatović, I., 2010. Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag. 30, 2255–2264. doi:10.1016/j.wasman.2010.04.012

Oikonomou, N.D., 2005. Recycled concrete aggregates. Cem. Concr. Compos. 27, 315–318. doi:10.1016/j.cemconcomp.2004.02.020

Poon, C.S., Chan, D., 2007. Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. Constr. Build. Mater. 21, 164–175. doi:10.1016/j.conbuildmat.2005.06.031

Poon, C.S., Chan, D., 2006a. Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. Constr. Build. Mater. 20, 578–585. doi:10.1016/j.conbuildmat.2005.01.045

Poon, C.S., Chan, D., 2006b. Paving blocks made with recycled concrete aggregate and crushed clay brick. Constr. Build. Mater. 20, 569–577. doi:10.1016/j.conbuildmat.2005.01.044

Poon, C.S., Kou, S. cong, Wan, H. wen, Etxeberria, M., 2009. Properties of concrete blocks prepared with low grade recycled aggregates. Waste Manag. 29, 2369–2377. doi:10.1016/j.wasman.2009.02.018

Poon, C.S., Lam, C.S., 2008. The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks. Cem. Concr. Compos. 30, 283–289. doi:10.1016/j.cemconcomp.2007.10.005

PROBETON, 2011. PTV 21-001 Elements de maçonnerie en béton (granulats courants et légers).

Sani, D., Moriconi, G., Fava, G., Corinaldesi, V., 2005. Leaching and mechanical behaviour of concrete manufactured with recycled aggregates. Waste Manag. 25, 177–182. doi:10.1016/j.wasman.2004.12.006

Silva, R. V., De Brito, J., Dhir, R.K., 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr. Build. Mater. 65, 201–217. doi:10.1016/j.conbuildmat.2014.04.117

Soutsos, M.N., Tang, K., Millard, S.G., 2011. Concrete building blocks made with recycled demolition aggregate. Constr. Build. Mater. 25, 726–735. doi:10.1016/j.conbuildmat.2010.07.014

UEPG, 2017. European Aggregates Association – Annual Review 2016-2017, Brussels, Belgium.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. doi:10.1007/s11367-016-1087-8

Xiao, J., Li, W., Corr, D.J., Shah, S.P., 2013. Cement and Concrete Research Effects of interfacial transition zones on the stress – strain behavior of modeled recycled aggregate concrete. Cem. Concr. Res. 52, 82–99. doi:10.1016/j.cemconres.2013.05.004

Xiao, J.-Z., Li, J.-B., Zhang, C., 2007. On relationships between the mechanical properties of recycled aggregate concrete: An overview. Mater. Struct. 39, 655–664. doi:10.1617/s11527-006-9093-0

Xiao, J., Li, W., Sun, Z., Lange, D.A., Shah, S.P., 2013. Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation. Cem. Concr. Compos. 37, 276–292. doi:10.1016/j.cemconcomp.2013.01.006

Xiao, J., Xie, H., Zhang, C., 2012. Investigation on building waste and reclaim in Wenchuan earthquake disaster area. Resour. Conserv. Recycl. 61, 109–117.

doi:10.1016/j.resconrec.2012.01.012

Xiao, Z., Ling, T.C., Kou, S.C., Wang, Q., Poon, C.S., 2011. Use of wastes derived from earthquakes for the production of concrete masonry partition wall blocks. Waste Manag. 31, 1859–1866. doi:10.1016/j.wasman.2011.04.010

Zhao, Z., Courard, L., Michel, F., Remond, S., Damidot, D., 2018. Influence of granular fraction and origin of recycled concrete aggregates on their properties. Eur. J. Environ. Civ. Eng. 22(12), 1457–1467. doi:10.1080/19648189.2017.1304281

Zhao, Z., Courard, L., Michel, F., Remond, S., Damidot, D., 2017a. Properties of concrete blocks made with recycled concrete aggregates : From block wastes to new blocks, in: HISER International Conference: Advances in Recycling and Management of Construction and Demolition Waste. pp. 174–177.

Zhao, Z., Remond, S., Damidot, D., Courard, L., Michel, F., 2017b. Improving the properties of recycled concrete aggregates by accelerated carbonation. Proc. Inst. Civ. Eng. - Constr. Mater. 171, 1–7. doi:10.1680/jcoma.17.00015

Zhao, Z., Remond, S., Damidot, D., Xu, W., 2015. Influence of fine recycled concrete aggregates on the properties of mortars. Constr. Build. Mater. 81, 179–186. doi:10.1016/j.conbuildmat.2015.02.037

Zhao, Z., Remond, S., Damidot, D., Xu, W., 2013. Influence of hardened cement paste content on the water absorption of fine recycled concrete aggregates. J. Sustain. Cem. Mater. 2, 186–203. doi:10.1080/21650373.2013.812942