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Innovative technologies for recycling End-of-Life concrete waste in the built environment

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ABSTRACT

Currently, natural resources are consumed at an alarming rate than their production (United Nations Environment Programme, 2014). This imposes unprecedented pressure on the environment. The problem seems to get worse with the present increase in population and demand for infrastructures. To alleviate these and other related problems, a circular approach to construction material flow is crucial. Recycling construction and demolition wastes (C&DW) to generate high-quality materials is essential to ensure materials circularity in the construction sector.

This article, therefore, describes the development of two large-scale technologies called Advanced Dry Recovery (ADR) and Heating Air classification System (HAS). ADR and HAS are industrial-scale technologies aimed to recycle End-of-Life (EoL) concrete into coarse, fine and ultrafine particles. While ADR is used to sort out clean coarse aggregates, HAS is used to produce clean fine aggregates by heating and separating the ultrafine hydrated cement components. The process parameters and the quality of aggregates are briefly described. Accordingly, concrete made of recycled coarse and fine aggregates displays comparable mechanical properties as the reference concrete which is made of natural aggregates. Both technologies are designed to be mobile so that EoL concrete wastes are processed at the site of demolition or close to ready-mix concrete plants, reducing the heavy traffic related to construction activities. These technologies, in general, have a potential in increasing sustainability and thereby greening the construction sector. This is by far a convenient contribution towards sustainable development and a big step towards closing the recycling loop in the construction sector.

1. Introduction

The primary sources of concrete wastes originate from construction, maintenance and refurbishment, deconstruction and demolition of buildings and civil works. Such activities are diverse in nature and therefore, the waste composition varies from place to place. In the EU, construction and demolition activities include a wide range of materials such as, excavation materials, construction and maintenance materials, concrete and other stony materials, out of which concrete is the major component after excavated soil (European commision, 2017). The amount of recycled concrete aggregates produced in the EU is about 9.4% compared to the total aggregate demand (European commision, 2017). Despite the demand for recycled aggregates, only a limited amount can be supplied. In the Netherlands, for instance, the production of recycled aggregates comprises about 25% of the total aggregate production (European Aggregate Association, 2017), in which, most of the recycled aggregates are down cycled in road construction projects.

The construction and infrastructure sector consumes large amount of raw materials and produces the most waste. The sector is also responsible for the emission of a large amount of greenhouse gases not only due to the use of cement but also the heavy traffic created due to construction activities, which is directly linked to increased levels of CO_2 and NOx emissions. During the last century, the global volume of natural resources used in buildings and transport infrastructure has increased 23-fold (Krausmann et al., 2017). Sand and gravel are the most extracted group of materials worldwide, exceeding fossil fuels (Torres, Brandt, Lear, and Liu, 2017). This problem seems to get worse with the present global increase in population and demand for infrastructures. The shortage of sand has been already envisaged and is a subject of current debate (United Nations Environment Programme, 2014; Krausmann et al., 2017; Torres et al., 2017;

Abbreviations: ADR, Advanced dry recovery; HAS, Heating air and classification system; EoL, End- of-life; RA, Recycled Aggregates; C&DW, Construction and Demolition waste; HCP, hydrated cement paste

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Bendixen, Best, Hackney, and Iversen, 2019). One option to address these problems is to make use of the large amount of material stock accumulating in buildings and infrastructure by improving the recycling rate of material resources. In fact, the continuous growth of material stock in buildings/infrastructure remains a challenge to close the materials loop and this may hinder the ambition of the construction sector towards circularity. Nevertheless, the need for large scale recycling facilities to improve the recycling rate proportionally to the extent of waste generation is unquestionable.

Construction undertaken during the economic growth of the 1950s will reach its end of life in the coming decade(s). As such, the generation of C&DW is expected to rise rapidly, especially in Europe. The 28 member states of Europe generates about 350 Million tons of C&DW (European commision, 2017), out of which concrete and other stony rubbles are the dominant wastes. If the EoL concrete waste is landfilled, it would occupy large amount of space. Recycling/upcycling is the most feasible solution to these streams of wastes. Commonly, recycling of concrete begins with crushing EoL concrete waste to produce a granular product of given particle size. Current crushing trends include a combination of jaw crushers and secondary impact crushers (Kahn et al., 2018). Jaw crushers fracture the particles by shearing across the main tension plane of compression, whereas impact crushers pick the concrete into fast-moving rotor and smash against an impact plate repeatedly until the desired size fraction is achieved. The crushed components are then sieved to generate coarse and fine recycled aggregates. Although this presents a suitable solution to treat C&DWs while providing environmental and economic benefits, the current rate of recovery/recycling is devoted to low-grade applications, mostly as a base or sub-base material in road construction and pavements (Nataatmadja and Tan, 2001; Poon and Chan, 2006; Poon, Qiao, and Chan, 2006; Mohammadinia, Arulrajah, Disfani, and Darmawan, 2019). Yet, the intrinsic material value of recycled aggregates has been justified for better applications such as structural concrete (Malešev, Radonjanin, and Marinković, 2010; Razaqpur et al., 2010; Marinković, Ignjatović, Radonjanin, and Malešev, 2012).

The use of recycled coarse aggregate (≥ 4 mm) in a new concrete has been reported to display comparable compressive strength with that of natural aggregates, in some cases even better performance was reported (Malešev et al., 2010; Lotfi et al., 2014). As such, the European concrete standard EN 206:2013, annex E and EN 13369:2012 contain recommendations on the use of coarse recycled aggregates in concrete (ECRA, 2015). On the other hand, the fine fraction of recycled aggregates (< 4 mm) is composed of sand, hydrated cement paste and other pollutants. This fraction accounts for about 30% of the crushed EoL concrete, thus, presents an environmental and economic burden because it has no proper use. Further treatments are necessary to entirely separate the hydrated cement paste from the sandy fraction, amongst which thermal treatment methods took the upper hand in recycling the fine fraction (Shui, Xuan, Wan, and Cao, 2008; Florea, Ning, and Brouwers, 2013; Florea, Ning, and Brouwers, 2014; Gastaldi et al., 2015). Consequently, efforts are undergoing to turn the fine fraction of recycled aggregates into clean fine fraction by separating the adhered cement either by further crushing or by thermally activating the hydrated cement paste. According to Shui et al. (2008), when recycled fine aggregates (RFA) and hydrated cement paste (HCP) recovered from EoL concrete is subject to heating up to 800 °C, it has the ability to dehydrate and improve its binding capability. The addition of cementitious materials such as fly ash further increases the density of hydration products and thereby the mechanical property of mortar made of recycled fine fraction. Since the fine fraction is rich in hydrated cement paste, it can also be used as a raw meal for the production of low carbon clinker (Gastaldi et al., 2015).

Most of the research on recycling EoL concrete waste focuses on coarse aggregates and aims to prove its suitability in a new concrete mix, often overlooking the big picture in developing recycling technologies. Even so, several attempts have been made to recycle EoL concrete wastes into reusable aggregate fractions. These attempts range from lab scale mechanical crushing and sieving techniques to industrial-scale technologies (Shima, Tateyashiki, Matsuhashi, and Yoshida, 2005; Menard et al., 2013). According to Shima et al. (2005), high-quality aggregates are produced by applying heating- and- rubbing method. This technology uses heating the concrete from the demolition site at 300 °C and milling to detach the cement paste from the aggregate surface. The oven-dry density and absorption of these recycled aggregates was found to be optimum. Nevertheless, this method overlooks recycling and reusing the ultrafine cement paste. The smart crusher (Florea, Ning, and Brouwers, 2013) is another technology developed to produce clean aggregates by liberating cement paste from the aggregate surface and claims to produce much more recycled concrete fines and cleaner aggregates compared to conventional crushers. Likewise, this technology also lacks clarity on details on life cycle assessment in terms of aggregate quality, cost and energy use. Selective fragmentation (Shigeishi, 2017) using electric pulses discharge or microwave heating (Bru, Touzé, Bourgeois, Lippiatt, and Ménard, 2014; Menard et al., 2013) was also examined as an option to recycle concrete wastes. These methods are applied to weaken concrete samples and claims to enhance selective liberation of cement paste from aggregates surface. Compared to microwave heating, electric pulses treatment seems to be more efficient and robust, but the fact that it is applied underwater limits the recovery of cement paste component. This may suggest the need for additional energy for sludge treatment. This method is still at lab scale and at the moment it appears to be complex to upgrade at industrial scale. In any case, with the amount of C&DW being generated nowadays, it is obvious that the need for robust and cheap industrial scale technologies for recycling and sorting concrete wastes into valuable resources is crucial.

Our contribution, therefore, aims to address the following issues: Firstly, quality issues of recycled aggregates raised by many researchers; Secondly, problems associated with resources scarcity; Thirdly, emission issues related to transport of raw materials; by developing innovative industrial scale technologies such as ADR and HAS, also interchangeably called as C2CA (concrete to cement and aggregates) technologies. The method generally starts by exposing the crushed EoL concrete into ADR, a mechanical sorter and impactor, and later through HAS, where the clean recycled aggregates, and hydrated cement fines are produced. Compared to other recycling technologies, C2CA technologies are easier to implement and upscale, moreover, it delivers quality aggregates at competitive price. We believe that these set of technologies will bring a complete solution to improve the quality of recycled aggregates compared to the traditional recycling route, where the wet state of crushed aggregates often pose problems for their sieving operation.

In this paper the working principles of two innovative technologies to completely recycle EoL concrete, namely ADR and HAS, are briefly discussed. The combination of these two technologies is used to treat the crushed EoL concrete into three major product streams: the coarse recycled aggregates (4–12 mm), fine recycled aggregates (0.25–4 mm) and ultrafine fraction (< 0.25 mm). While ADR technology is a mechanical system of sorting crushed wet concrete wastes according to their particle size, HAS (Heating Air classification System) uses a combination of thermal and air classification methods to separate and activate the hydrated cement paste. The production process of aggregates, the quality of both the coarse recycled aggregates (4–12 mm) and fine recycled aggregates (0.25–4 mm) is subject of this study. The use of coarse and fine recycled aggregates by entirely replacing natural coarse and fine aggregates in a concrete mix is also examined.

2. Materials and methods

2.1. Processing recycled aggregates from C&DW

Processing aggregates from C&DW begins by selectively demolishing a building to separate the different waste materials according to their type and composition (Coelho and De Brito, 2011). Once other materials have been selectively dismantled, the End-of-Life (EoL) concrete is torn down with the help of machinery. The crushing processing of EoL concrete has already been described elsewhere in the literature (Nagataki, Gokce, Saeki, and Hisada, 2004; Kahn et al., 2018). As a common practice, combinations of jaw and impact crushers are used; nevertheless, their ability to liberate cement paste from aggregate surface is debatable. Once EoL concrete waste is crushed, it is important to mention that the crushed concrete waste is in a moist state due to the fact that water is sprayed during the demolition process to avoid/reduce dust. Consequently, the crushed concrete waste in this specific study has an average moisture content of 5–8%. The crushing cycle is designed to generate aggregates of particle size of 0–12 mm, which are immediately fed into ADR. Fig. 1 describes an outline for the entire process of recycling EoL concrete using ADR and HAS.

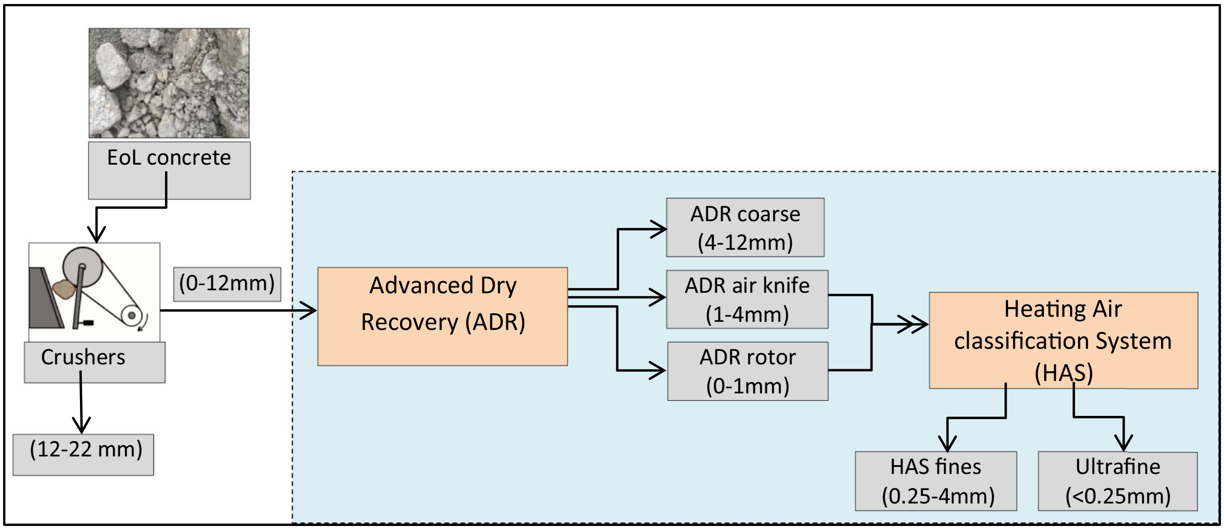

Fig. 1. A sketch of processing EoL concrete by using ADR and HAS technologies.

2.1.1. Advanced Dry Recovery (ADR)

ADR technology is a mechanical system for extracting the fine fraction from moist crushed concrete aggregates. It uses kinetic energy to break the water bond formed by moisture with fine particles (De Vries, 2017). ADR has two major units: The rotor and air sifter. The spinning rotor breaks water bonds between grains, after which small and big grains are separated via ballistic separation into various size and composition. The cut point determines the quality and composition of classification. The ADR sorts out the input crushed concrete waste (0–12 mm) into three product streams: these are, the coarse product (4–12 mm), the fine product (1–4 mm), hereafter called airknife; and another fine product (< 1 mm), hereafter called rotor. The air knife product is separated from the coarse fraction by using an air sifter; hence, lighter contaminants like wood and plastics are also part of this product. In general, the major products of ADR are the coarse aggregates (4–12 mm) and the fine fraction products (0–4 mm). Unlike conventional sieving methods, ADR technology has proved the possibility of sorting crushed aggregated into different product streams in relatively wet state. ADR has been patented by researchers at Delft university of technology (International publication number: WO 2012/015299 A1). The current design of ADR, shown in Fig. 2 has a capacity of 50 tons per hour.

While the coarse fraction (4–12 mm) can be directly used in a new concrete mix, the fine fraction (0–4 mm) must be further processed to extract the old cement paste from the sand.

The most essential features of ADR technology are its mobility, flexibility and affordability in terms of technology (energy efficiency and simplicity compared to the conventional technologies developed earlier). The name ‘Dry’ implies the process does not use water as compared to conventional aggregate washing plants. The innovative features of ADR are its ability to classify C&DW aggregates independently of their moisture content (this reduces process complexity and avoids problems associated with dust or sludge). As shown in Fig. 2(B), ADR is installed on a 13.2 m trailer so that it can be easily transported by a truck to a demolition site to process aggregates on site. The flexibility of ADR is due to the possibility to tune some process variables (belt speed and air velocity at sifter) which makes it adaptable towards different input materials such as limestone concrete wastes, lightweight concrete wastes and bottom ashes.

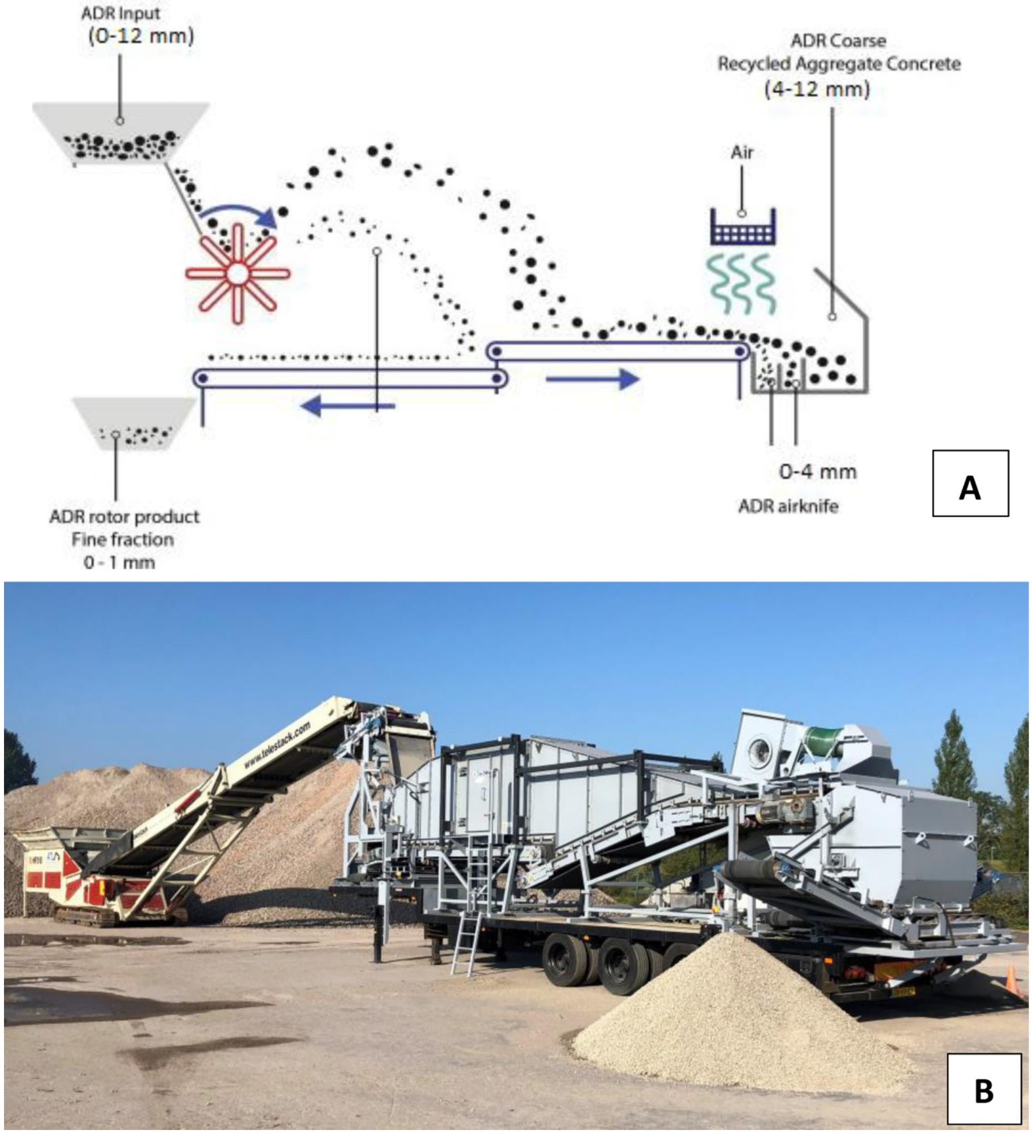

Fig. 2. A sketch of ADR working principles (A) and ADR installation on site (B).

2.1.2. *Heating air and classification system (HAS)*

The HAS setup is complementary to the ADR technology. The input material for the HAS technology is a mix of the airknife product (1–4 mm) and the rotor product (0–1 mm) that comes from ADR. The HAS technology is designed to further expose the fine fraction aggregates into a hot gas so as to dry the fine aggregates and to get rid of undesirable tiny C&DW contaminants, mainly wood and plastic shards. The entire process involves the interaction of particle-gas system in a fluidized-type reactor, where air is used to carry the heat and at the same time classify fine aggregates based on their particle size. The use of heating is to dry the material and somehow activate the ultrafine particles which are mainly composed of hydrated cement. The contact between the hot air and the aggregates is maximized at the cascade of tubes which are embedded in the vertical structure of the HAS setup. Cascades are positioned at the upper and lower section of the HAS, as shown in Fig. 3. The use of cascades is twofold: first to facilitate an efficient heat and mass transfer between aggregates and the hot gas, and second, to enable the spalling of aggregates while jumping from cascade to cascade after being exposed to higher temperatures. While the ultrafine particles are swept up by the air flow, the heavier particles settle down into the bin of the HAS where the clean fine fraction is collected. The current design of HAS holds a capacity of 3 tons per hour.

The system is made of several components such as the burner, vibrator motors, compressor, cyclone and rotary sluice. The burner uses diesel to generate hot gas at temperatures up to 700 °C. This heat is dragged into the system to dry the fine aggregates. The compressor is used to draw air, circulate the warm air from the cyclone and blow part of the vapour saturated air into the atmosphere. Vibrators are used to ensure the down flow of fine aggregates through the staggered arrangement of tubes inside the HAS chamber. The Cyclone is a vortex separation system used to separate the ultrafine particles (extracted from the feed) from the air stream. While the solid particles hit the wall of cyclone and decelerate to fall into the base, the warm air will pass upwards to the recirculation. A patent has been filed for the technology and for the method of recycling cement paste from EoL concrete waste by TU Delft.[1]

The classification of the particles occurs in the separation zone, where the particles interact with the air flow (Shapiro and Galperin, 2005). There are four basic separation zones in most of the air classification systems. These are; gravitational-counterflow, gravitational-crossflow, centrifugal-counterflow and centrifugal-crossflow zones. The HAS technology comprises the principles of gravitational-

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[1] Patent application no. : N2020846

counterflow zone and centrifugal counterflow zone, where the classifier is designed around a rising air flow inside a vertical chamber. The aggregate particles fall from top of the chamber and the drag force acts in the opposite direction to gravity. Consequently, classification occurs where the drag force is larger than gravity. Coarse particles will continue downwards while fines will be carried out by air flow, where they are dominated by centrifugal counterflow zone inside the cyclone. The major drawback of this system may be the low separation efficiency because coarse particles may block fines from rising with the air stream.

Unlike conventional air classifiers, the unique feature in the HAS technology is the presence of horizontally staggered tubes inside the vertical chamber. The function of these tubes is to increase the residence time of aggregates for efficient heat/mass transfer between wet fine aggregates and the hot gas. It is believed that the complex interaction between particle-particle, particle-heat, and particle-horizontal bars give rise to some important phenomena like spalling. The thermal stresses generated by rapid heating and the increase in pore pressures due to thermal shock contributes to spalling.

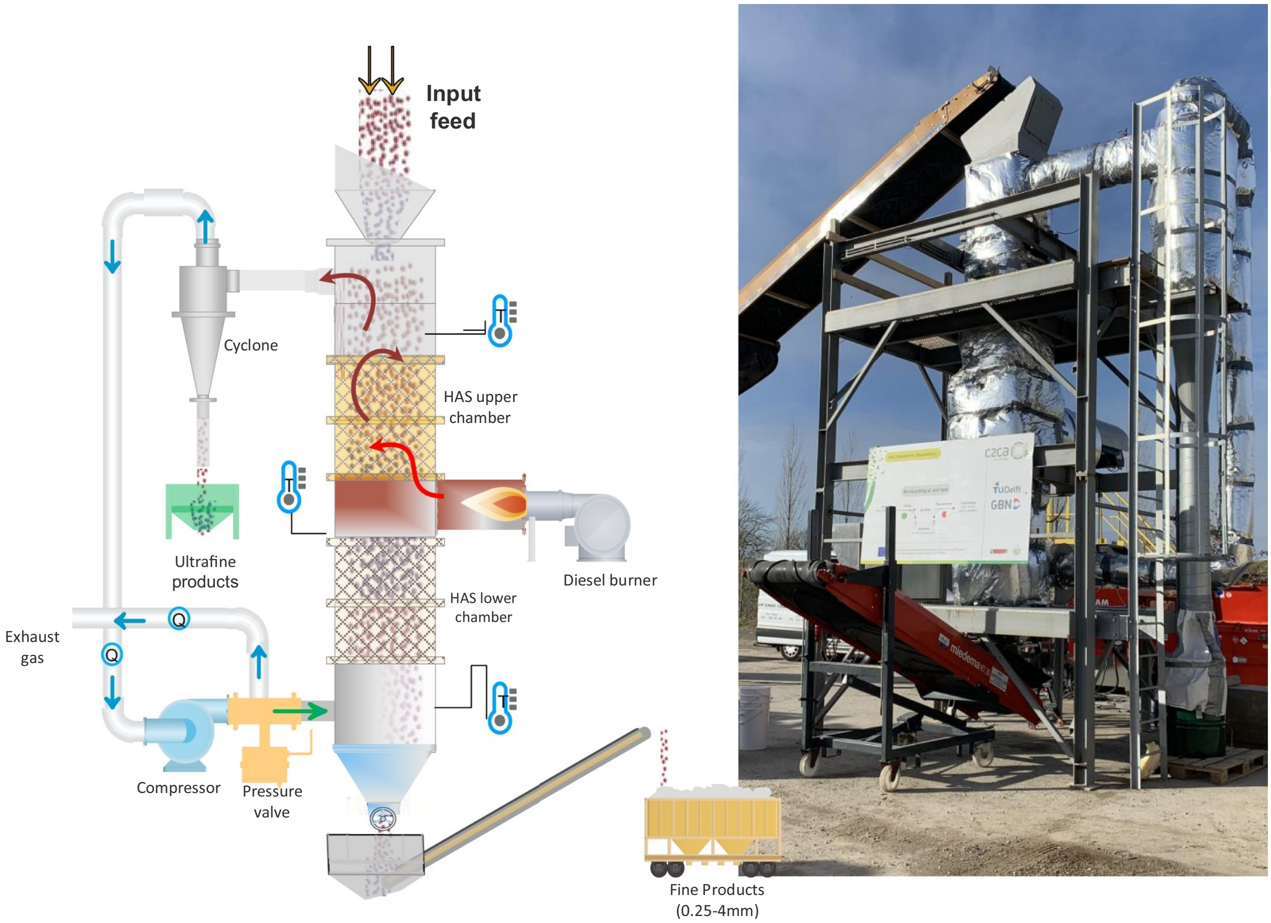

Fig. 3. A sketch of heating air classification system (HAS) for recycling concrete fines, where the measurement points are indicated as Q for flow and T for temperature (Left). 3 t/h HAS facility at site in Hoorn, Netherlands (Right).

3. Experiments

3.1. Moisture and particle size distribution of ADR aggregates

The moisture content is an important parameter to evaluate the water content of aggregates from different product streams. The moisture content in this case appears to have direct relation to the particle size of product streams. Three types of EoL concrete wastes have been collected from different sources. Lightweight concrete wastes and limestone concrete wastes were collected from Spain, while normal (siliceous) concrete wastes are collected from the Netherlands. The aggregates from each ADR output stream were collected during each test program. The moisture content was determined for each aggregate fraction by drying at 105 ± 5 °C for 24 h (NEN-EN-1097-5). The particle size distribution of aggregates from each ADR product stream was also performed by taking a representative sample from each product stream and sieving each product after being dried at 105 ± 5 °C for 24 h, according to the European standard EN 933-1. The significance of this test is not only to understand the particle size distribution of products but also to roughly evaluate the efficiency of ADR in separating the coarse and fine fractions.

3.2. Property of recycled coarse and fine aggregates

The property of recycled aggregates produced by ADR and HAS technologies were evaluated to assess their conformity for concrete production. The water of absorption and the specific density of aggregates were determined based on European standard EN 1097-6 where a pycnometer is used for accurate measurements for both coarse and fine recycled aggregates. The Los Angeles abrasion loss was determined using the European standard EN 1097-2. The amount of mortar attached to the surface of aggregates was determined based on acid dissolution method reported elsewhere in the literature (Tam, Tam, and Le, 2007). The particle size and the composition of the HAS ultrafines were also analysed according to EN-1097-5 and using x-ray fluorescence (XRF), respectively.

3.3. Performance of recycled aggregates in concrete

At this level, the performance of ADR coarse and HAS fine products has been investigated by totally replacing natural coarse aggregates (NCA) and natural fine aggregates (NFA) with recycled coarse aggregates (RCA) and recycled fine aggregates (RFA). The first sample belongs to reference recipe (C-Ref) which is composed of natural coarse and natural fine aggregates. In the second sample, the coarse natural aggregates are completely substituted with recycled coarse aggregates (C-100–0). In the third recipe (C-100-100), both natural coarse and natural fine aggregates are fully replaced with RCA and RFA. Table 1 indicates a mix composition optimized for aggregates produced by ADR and HAS technology.

Table 1

Mix composition of both reference and recycled concrete for 1 m^3.

Components		C-Ref	C-100-0	C-100-100
Cement (kg)	CEM III/A 42.5R	335	335	335
Filler (kg)	Limestone	145	145	145
Fine aggregates (kg)	NFA (0–4 mm)	750.0	682.0	0.0
	RFA (0–4 mm)	0.0	0.0	567
Coarse aggregates (kg)	NCA (4–12 mm)	907	0.0	0.0
	RCA (4–12 mm)	0.0	882	881
Water (kg)		161	161	161
Superplasticizer (% cement)		0.65	0.75	1.3

3.3.1. Test techniques

The concrete specimens were designed to have resistance class of C35/45 and an exposition class of XC4 (corrosion induced by carbonation) with slump range S4. Table 1 shows the composition of the concrete mix design. During this specific test, normal weight recycled aggregates (siliceous recycled aggregates) originated from construction and demolition activities in the Netherlands are used. The PSD of the reference mix (C-Ref) was adjusted based on the PSD of the recycled aggregates. The coarse and fine recycled aggregates were mixed based on the two-step mixing approach (Tam and Tam, 2008). Then, the remaining components like cement, fillers and superplasticizer were introduced into the mixer together with the remaining amount of mixing water. Other than the calculated amount of water, additional water (WA24) has been slowly added into the mix to comply with the designed slump S4. After proper mixing, three concrete specimens were casted into cubes (150 × 150 × 150 mm) for compressive strength tests at each age.

3.3.2. Fresh and hardened concrete tests

The density and slump tests were performed to examine fresh concrete properties for each concrete mix. Slump or workability of the fresh concrete mix was determined according to EN–12350-2. The density of fresh concrete mix was determined based on EN-12350-6. The compressive strengths of the cubes were tested at the ages of 2, 4, 7, 28 and 90 days, according to EN 12390-3; 2009. The average compressive strengths of three cubes for each sample were taken at each testing age.

4. Result and discussion

4.1. ADR and HAS technologies

It is possible to produce clean recycled aggregates and hydrated cement paste (HCP) from EoL concrete wastes at small scale research laboratories but the envisaged techniques may not be feasible, sustainable or cheap. The development of both ADR and HAS technologies to leverage EoL concrete waste into high quality recycled coarse and fine aggregates, comes at competitive price. The mobility (transportability) of these technologies enables to locate them either close to precast concrete manufacturing plants or right at the demolition site. This is an added value to the technologies, where transport movements due to construction activities could be significantly reduced. The possibility to process crushed EoL concrete wastes in their moist state is another unique advantage of these technologies. In general, the importance of these technologies is not only in maximizing resource conservation and efficient resource utilization but also reduction of transport related emission of greenhouse gases such as CO_2 and NOx.

Compared with the amount of EoL concrete waste generated today, these technologies have some limitations: firstly, limitations related to capacity. At the moment, the capacity of ADR is 50 t/h and that of HAS is 3 t/h. This indicates their capacity is not compatible. In order to do so, the capacity of HAS need to be upgraded to at least 15 t/h (assuming the fine fraction is about 30% of the crushed concrete). Secondly, the source of heat in the heating air classification system (HAS) is diesel, which has negative impact to the environment (although less environmental impact compared to clinker production). Nonetheless, the future design of HAS will be based on biofuel related sources of energy.

4.2. Sorting efficiency of the ADR

The efficiency of ADR is evaluated based on the particle size distribution of the input material. Separation is characterized by the cut size diameter d50, where particles above d50 are part of the coarse fraction. There are two important locations where the cut size is determined in the ADR. The first is at the rotor where the cut size can be adjusted by tuning the rotor speed and the belt position; and the second is at the air sifter. When adjusted properly ADR can be used to sort out different materials based on their particle size. Based on the current adjustment, the efficiency the ADR system is examined by taking a representative sample from each product stream and sieving the samples after being dried. Comparing the amount of coarse (4–12 mm), Airknife (0–4 mm) and rotor (0–1 mm) aggregates retained on their particular sieve to the total amount of materials expected at its respective output stream roughly gives the efficiency of ADR for sorting particles according to their size. Table 2 summarizes the efficiency of ADR at the output streams for different concrete wastes crushed under identical conditions.

From Table 2, it is shown that 4–12 mm siliceous aggregates comprise 90% (by wt.) of the coarse ADR product while particles 0–1 mm comprise 71% (by wt.) of the ADR rotor product. Thus, it is evident that ADR is robust in separating the coarse fraction from other fractions and contaminants. Consequently, the coarse fraction (4–12 mm) is directly used in making recycled concrete. The lower efficiency observed for LCW materials could be due to the sticky nature of these materials when moist.

Table 2

The efficiency of ADR for different output streams compared to the input composition.

Type of waste	Efficiency (%)		
	ADR coarse (4–12 mm)	ADR Airknife (0–4 mm)	ADR rotor (0–1 mm)
Siliceous concrete wastes (SCW)	90.0	90.0	71.0
Lightweight concrete wastes (LWCW)	93.0	72.7	75.3
Limestone concrete wastes (LCW)	89.0	70.5	65.0

4.3. Moisture and particle size distribution of ADR aggregates

The moisture content of each product stream has been determined according to the Dutch standard NEN-EN-1097-5, where a representative sample of ADR output aggregates from the coarse stream, airknife stream and rotor stream are dried in an oven at 105 °C and weighed after being cooled. Table 3 shows the moisture content of each product stream.

Due to the porous nature of the cement paste, most moisture is accommodated in the finer fraction of ADR product. The higher amount of moisture on the finer fraction is indicative of the fact that most of the hydrated cement paste is concentrated at the airknife and rotor products. So, the concentration of old cement in the ADR rotor product is at least 2 to 2.5 times higher than in the ADR coarse.

The particle size distribution of each ADR product stream has been determined according to the European standard EN 933-1. Based on the

Table 3
The moisture content of different concrete wastes from CDW of different origin.

Type of waste	Moisture content (%)			Source
	ADR coarse (4–12 mm)	ADR Airknife (0–4 mm)	ADR rotor (0–1 mm)	
Siliceous concrete wastes (SCW)	5	8.5	13.1	Netherlands
Lightweight concrete wastes (LWCW)	4.5	7.7	9	Spain
Limestone concrete wastes (LCW)	6	9.2	11	Spain

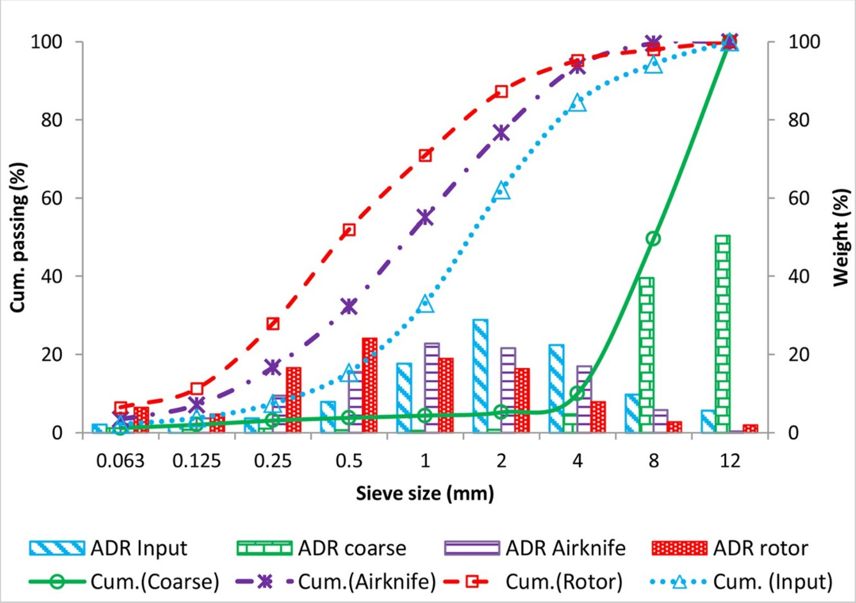

Fig. 4. Particle size distribution of ADR input and output siliceous concrete wastes.

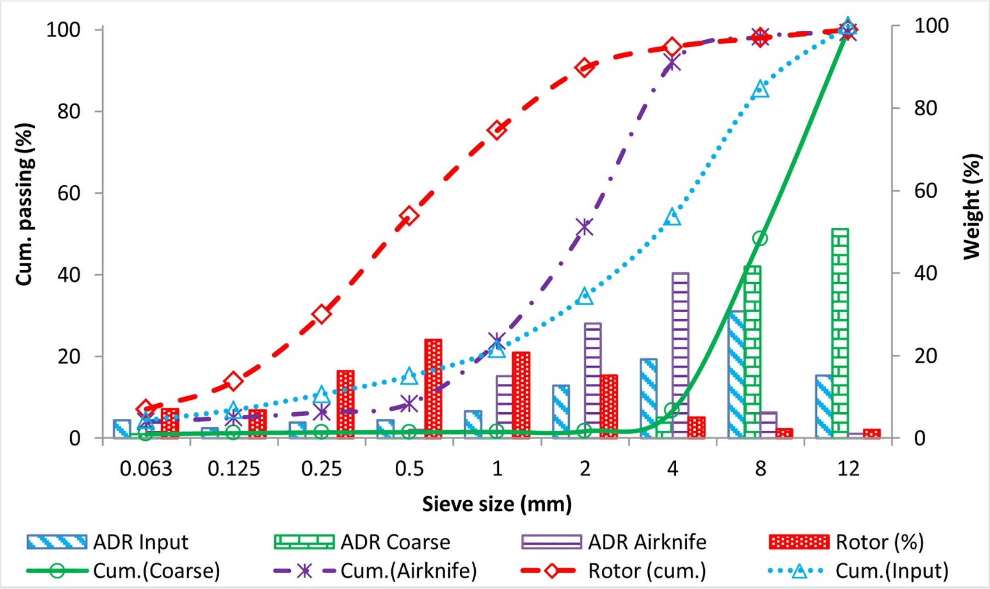

Fig. 5. Particle size distribution of ADR input and output light weight concrete wastes.

Particle size distribution of the ADR input and output streams, it can be seen each aggregate fraction is well sorted out by its particle size. Figs. 4 and 5 summarize the particle size distribution of ADR inputs and outputs for siliceous and lightweight materials, respectively. The particle size distribution graphs for both siliceous and light weight concrete wastes clearly witness that the ADR input aggregates have been classified into clean coarse aggregates (4–12 mm) and fine fraction aggregates (ADR Airknife and ADR rotor). It is shown that the amount of ultrafines passing 63 μm sieve is below 1.5% of coarse aggregate weight, which ensures the suitability of the coarse aggregates (4–12 mm) for concrete production.

4.4. Quality of recycled coarse aggregates from ADR

Coarse aggregates are the primary products of ADR. The fine aggregates and ultrafine particles are the major products of HAS. The quality of the coarse and fine recycled aggregates is assessed based on the tests described at the experimental part. Table 4 summarizes the quality parameters for both ADR coarse and HAS fine aggregates.

The higher value of water absorption for fine fractions is due to the presence of cement paste adhered to aggregate surface, as smaller fraction aggregates present higher mortar content (Evangelista, Guedes, De Brito, Ferro, and Pereira, 2015). The presence of cracks generated during crushing (Djerbi Tegguer, 2012) and also the presence of pores created in the cement hydration process are another reason for the high water absorption of recycled aggregates compared to natural aggregates (De Vries, 2017; Pan, Huang, Kuo, and Lin, 2008). These results are consistent with the literature (Omary, Ghorbel, and Wardeh, 2016; Silva, De Brito, and Dhir, 2014). Likewise, the porous nature of the old cement paste adhered to the surface of aggregates is attributed to the lower density of recycled aggregates. The increased amount of water absorption for HAS fines is not only due to adhered mortar but also these fines are exposed to heating inside the HAS setup which implies these fine aggregates are totally dry.

Table 4
The density, water absorption and LA abrasion test result for recycled coarse and fine aggregates.

Quality Variables	Method	ADR coarse (4–12 mm)	HAS fines (0.25–4 mm)
Specific gravity	NEN-EN 1097-6	2.23	2.13
Apparent specific gravity	NEN-EN 1097-6	2.45	2.35
Water absorption (%)	NEN-EN 1097-6	4.16	9.65
L.A. Abrasion loss (%)	NEN-EN 1097-2	26	–

The Los Angeles (LA) test is an empirical measure for resistance to fragmentation of aggregates. The fragmentation of aggregates is caused by the impact of steel balls when mixed and rotated in a horizontal drum for a specific number of revolutions. The generation of fine particles is examined by measuring the amount of particles smaller than 1.6 mm sieve. The LA abrasion test for ADR coarse products was performed according to NEN-EN 1097-2, as shown in Table 4, and found within the acceptable range (LA $\leq$ 30 for natural aggregates and LA $\leq$ 40 for recycled aggregates) (Reza and Wilde, 2017). Different authors have attempted to correlate water of absorption, specific gravity and LA Abrasion loss. For recycled aggregates, it has been noticed a decrease in density is accompanied by an increase in water of absorption and LA Abrasion loss (Omary et al., 2016), which is not different in our case.

4.5. Quality of recycled fine aggregates and ultrafine particles from HAS

As it is known from the previous research studies, the majority of the hydrated cement powder is concentrated in the fine fraction (0–4 mm) of recycled aggregates (Evangelista et al., 2015). In this method, the fine fraction of recycled concrete (0–4 mm) is used as an input to the HAS setup and then exposed to a flowing hot gas. While the fine powder (ultrafine particles < 0.25 mm) are classified and dragged by the circulating hot air into cyclone, the fine fraction (0.25mm-4 mm) is collected at the downstream of the HAS setup. At the end there are two product streams from HAS: Recycled fine fraction (0.25–4 mm) and recycled ultrafines (< 0.25 mm).

Since the presence of the attached cement paste on the surface of aggregates is often considered the reason for the poor quality of recycled concrete aggregates (RCAs), the amount of hydrated cement paste for the major products of the technology has been experimentally estimated. Thus, the amount of hydrated cement paste has been determined by dissolving a specified amount of RCA samples in HCl solution and computing the mass loss (Tam et al., 2007; Akbarnezhad, Ong, Zhang, and Tam, 2013). When the HCP/mortar is exposed to HCl solution, most of the oxides of cement react with the acid to give their respective salts which are soluble. The major reactions are summarized as:

$$CaO + 2HCl \rightarrow CaCl_2 \cdot H_2O \tag{1}$$

$$Fe_2O_3 + 6HCl \rightarrow 2FeCl_3 \cdot 3H_2O \tag{2}$$

$$Al_2O_3 + 6HCl \rightarrow 2AlCl_3 \cdot 3H_2O \tag{3}$$

Since the aggregates are made of gravel, they are least attacked by the acid. Thus, the amount of mass loss roughly gives an estimation of adhered cement paste along with aggregates. The presence of cement paste along with HAS fine recycled aggregates may be the main reason for high water of absorption and low density of recycled aggregates observed previously in Table 4. Based on the acid dissolution test, Table 5 summarizes the amount of hydrated cement paste attached to the surface of recycled aggregates. The amount of hydrated cement paste deduced from these experiments is consistent with other literature values (Florea and Brouwers, 2013).

The presence of higher amounts of hydrated cement paste with HAS ultrafines suggests that cement rich particles are concentrated at the ultrafine fraction, revealing the role of HAS technology in recovering and concentrating hydrated cement paste in one of the product streams. Thus, the benefit of HAS technology is twofold: firstly, it helps to optimize the property of fine aggregates (0.25–4 mm), as most of HCP is sufficiently separated and secondly, the cement rich ultrafines are can be potentially used as cement replacement, a subject interesting from the environmental and economic point of view. However, the impact and potential of ultrafines will not be included in this study.

Table 5
The amount of hydrated cement paste (HCP) in each product.

Type of RCA product	Amount of HCP (wt.%)
ADR coarse recycled aggregates (4–12 mm)	18
HAS fine recycled aggregates (0.25–4 mm)	10.3
HAS recycled ultrafines (< 0.25 mm)	48.7

4.5.1. Particle size distribution of HAS outputs

Fig. 6 shows the particle size distribution of HAS input and output materials. As shown in the figure, the input material initially had a significant amount of fines. After being processed by the HAS, the input material has been classified into two products; the fine aggregates (0.25–4 mm) and the ultrafines (< 0.25 mm). The classification of products by the HAS setup can be clearly seen in Fig. 6.

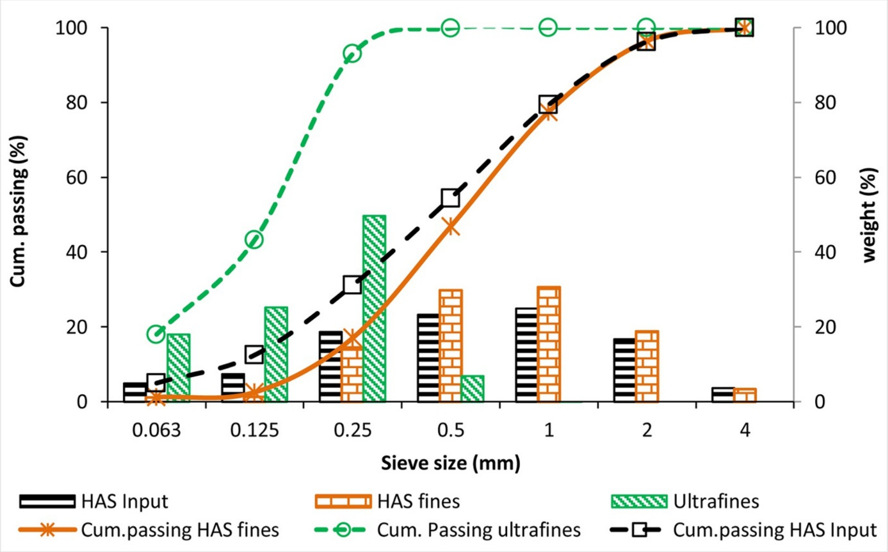

Fig. 6. Particle size distribution of HAS input and output materials.

The amount of ultrafines (< 0.25 mm) along with the HAS input and HAS output samples (HAS fines and ultrafines) has been compared. It was found that more ultrafines were collected compared to the amount the input material initially had (based on the particle size distribution of input material). This suggests the role of spalling in generating additional ultrafine particles that are fractured from surface due to the differential thermal stresses between the sand and cement paste and/or due to the pore pressure developed inside the porous hydrated cement. Nevertheless, this will be justified in the future work with more controlled tests.

The composition of the ultrafine products was examined by using XRF analysis. The test was carried out by taking a representative sample of ultrafine products from HAS cyclone. Table 6 shows the major oxide composition of ultrafine products. The amount of SiO_2 and CaO in ultrafines indicates that most of the hydrated cement paste has been concentrated with these ultrafines, which is also supported with acid dissolution test. Compared to CaO, the amount of SiO_2 in the ultrafines is a slightly overstated. This may be due to an extra amount of SiO_2 generated during the crushing process. The Loss on Ignition (LOI) is determined by heating the ultrafine product at 950 °C. The high amount of LOI indicates the presence of hydrated cement paste and other carbonates along with the product. In order to completely dehydrate and activate the ultrafine product, the working temperature of the HAS setup may need to be increased. This would question the environmental and economic sustainability of the product. However, this option will be studied further in the future.

Table 6
XRF analysis on oxide composition of ultrafine products.

Oxide	Concentration (%)
SiO_2	53.02
CaO	24.26
Al_2O_3	7.29
Fe_2O_3	3.1
MgO	1.72
SO_3	1.03
K_2O	0.96
TiO_2	0.34
MnO	0.16
Cl	0.002
LOI	8.12

4.6. *The performance of recycled concrete*

In this study the mechanical property of concrete made of recycled aggregates and natural aggregates has been compared. This comparison is only based on their compressive strength, simply to evaluate the quality of recycled aggregated produced by the aforementioned technologies. Accordingly, recycled concrete mixes are designed to incorporate as much recycled aggregates as possible. In this study, all natural coarse and fine aggregates are replaced with recycled coarse and recycled fine aggregates to examine the overall performance of recycled aggregates. The compressive strength of these samples is examined and details are described below.

4.6.1. *Fresh and hardened concrete properties*

In this experiment the slump was controlled to assume S4 requirement. In order to do so, sufficient amount of water has been added to each concrete mix step by step. Generally, as the amount of recycled aggregates increased, the workability decreases. As shown in the mix design in Table 1, recycled aggregates consume more water in 24 h (WA24) compared to natural aggregates. To compensate the minimum slump requirement more water has been added to the concrete made of recycled aggregates. To avoid an excessive amount of water, plasticizers are used to adjust the workability. Therefore, the amount of plasticizers required slightly increases as the amount of recycled aggregates increase.

Fig. 7 shows the average compressive strength results for concrete obtained after different days of curing. The compressive strengths of all mixtures increased with age. The concrete mixture containing 100% coarse recycled aggregates (C-100-0), display almost comparable compressive strength until 28 curing days compared to the reference (C-Ref), with little increase at 28 days and little decrease in value at 90 days of curing. Despite the differences in strengths, all concrete mixtures developed consistent rate of strength gain up to 90 days and eventually shown adequate strengths enough for structural purposes. The fact that all concrete specimen displays higher compressive strength than expected could be due the use of slag cement CEM III/A 42.5 N which could easily meet the criteria of class 52.5 after 28 days of hardening.

Table 7
Fresh and hardened concrete properties.

Type of test	Standard test method	C-Ref	C-100-0	C-100-100
Consistency (mm)	EN 12350-2	180	195	190
Fresh concrete density (kg/m3)	EN 12350-6	2295	2254	2194
Hardened concrete density after 28 days (kg/m3)	EN 12390-7	2197	2099	1990
Water absorption after 24 h, WA_{24} (kg/m3)	PN-B 06250	23	57	95
Water absorption after 28 days (wt.%)	PN-B 06250	5.4	8.6	10.8

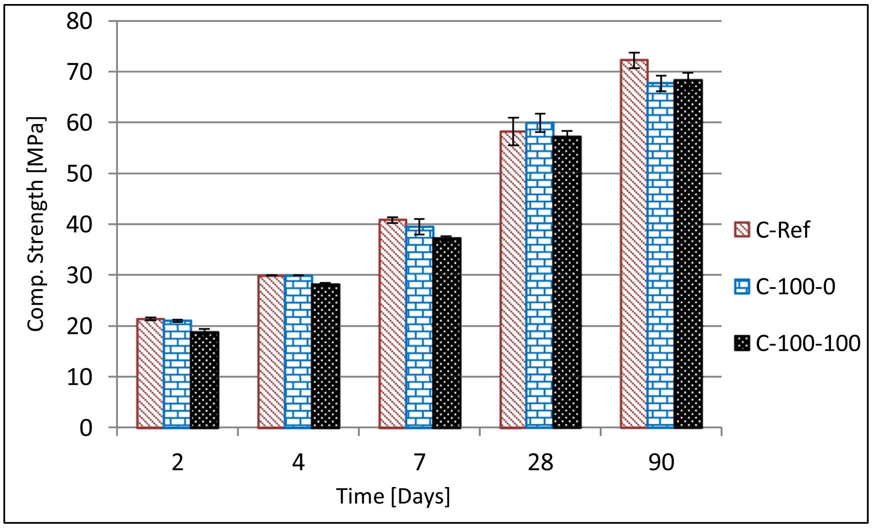

Fig. 7. Compressive strength of recycled concrete and reference concretes.

Based on the compressive strength tests, it can be seen that after 2 days of hardening up to 12% difference in compressive strength was noticed between C-Ref and C-100-100. This difference, however, decreases with curing time. After 7 days of hardening, the difference in compressive strength drops to approximately 8%. After 28 days the compressive strength of C-100-0 slightly surpasses the reference concrete (C-Ref). After 90 days, C-100-100 has shown a little decrease in compressive strength which is 68.2 MPa compared to the reference concrete (C-Ref) which has compressive strength of 72.2 MPa. This difference could be considered insignificant.

The 3rd concrete mix (C-100-100) is entirely made of recycled fine and coarse aggregates. Considering all components of the concrete mix, C-100-100 has got an overall substitution rate of 75% by weight or 79.7% by volume. This means 75% (by wt.) of the concrete (C-100-100) is composed of recycled aggregates compared to C-100-0 which is only 43% (by wt.). This concrete is therefore the most sustainable and the most circular among other concrete mixes in this study.

Indeed, there is a discrepancy in research results about the amount of RCA used in a concrete mixture. Depending on the extent of substitution, the performance of concrete made with recycled aggregates fluctuates. While some researchers report better compressive strength at 100% replacement of the coarse aggregate (Malešev et al., 2010), others insist not to use beyond 30% replacement of coarse aggregates (Tam, Gao, and Tam, 2005; Verian, Whiting, Olek, Jain, and Snyder, 2013; Verian, Ashraf, and Cao, 2018). Contrarily, the substitution of fine recycled aggregates has been strongly discouraged. Due to the fact that recycled fine aggregates exhibit low specific gravity and high water absorption, there has been less interest in these materials. According to a study by Braga (Braga, De Brito, and Veiga, 2012), incorporation of recycled concrete fines up to 15% offers some advantages in performance. On the other hand, the detrimental effects of recycled concrete fines on the final compressive and tensile strength of the concrete have been reported (Khoshkenari, Shafigh, Moghimi, and Mahmud, 2014; Zhao, Remond, Damidot, and Xu, 2015). Despite all kinds of research outputs on recycling concrete, it is evident that the quality of recycled aggregates is dependent on the way of collecting, crushing, sorting EoL concretes and ultimately detaching the cement paste from aggregate surface. Nevertheless, this study revealed the positive effect of using both coarse and fine aggregates produced by ADR and HAS technology on the compressive strength of recycled concrete.

There are many reasons why recycled concretes display comparable mechanical properties to the reference concrete. Some to mention, the elimination of the friable and porous aggregates into micro defect-free recycled aggregates of high integrity due to recycling process (crushing and grinding processes) (Nagataki et al., 2004), the presence of high amount of permeable pores which still have a positive influence on the mechanical property of the recycled concrete, and the elastic compatibility between the recycled aggregate and the surrounding cement paste (Bremner and Holm, 1986). Thus, it is undeniable that the quality of recycled aggregates depends on the way EoL concrete wastes are handled and recycled/processed.

Designing and applying such a circular concrete mix in the construction sector facilitates the transformation of the existing linear economy into a circular economy. According to the circularity gap report (Wit, Verstraeten-Jochemsen, Hoogzaad, and Kubbinga, 2019), the circularity of the built environment in Europe is estimated at 12%, higher than the global figure of 9%. The development of such technology further reinforces the effort towards circularity. To sum up, the combination of ADR and HAS provides a prospective future towards the importance of recycling and reusing recycled aggregates to fully close the materials' loop and to effectively implement circular economy in the construction sector.

5. Conclusion

A complete and innovative approach to recycling EoL concrete wastes have been introduced in this study. The approach is based on sorting crushed recycled aggregates into different fractions by preserving the integrity of aggregates and at the same time liberating hydrated cement paste from aggregates surface. Further treatment of fine aggregates (0–4 mm) through the HAS enables to dry out fine aggregates thereby separating it into fine aggregates (0.25–4 mm) and hydrated cement paste rich ultrafines (< 0.25 mm). These sets of technologies are patented and currently operational under C2CA technologies. The existence of these technologies is a step closer to assuring efficient resources utilization and closing the materials loop in the construction sector. The major conclusions drawn from this study are:

- The development of ADR and HAS technologies at industrial scale not only ensure a stable supply of clean coarse recycled aggregates and fine aggregates (recycled sand) to the construction sector but also lower CO_2 related emissions in the industry due to the use of HCP rich ultrafines as substitution to cement or cement precursors.
- The mobility (transportability) of these technologies offers an additional advantage in reducing traffic-related emissions, as the processed recycled aggregates are intended to move minimally between the production site and ready-mix or precast plants.
- Three major products presented by these technologies are: The coarse aggregates (4–12 mm), fine aggregates (0.25–4 mm) and HCP rich ultrafines (< 0.25 mm). The quality of these aggregates is shown to be reasonable except their high water absorption and low density, compared to natural aggregates.
- Full incorporating these aggregates (coarse and fine) in a concrete mix displayed 68.2 MPa in compressive strength. This is a property that can be considered almost comparable to the reference concrete (72 MPa in compressive strength).
- The performance of the most circular concrete, which comprises 79.7% of recycled aggregates by volume, has been examined and found to have promising performance for concrete structural applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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