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Energy and CO_2 from high performance recycled aggregate production

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ABSTRACT

The use of recycled concrete aggregates (RCA) in applications other than road sub-layers is limited by two factors: the high porosity of RCA in comparison with natural aggregates, and the restrictions set forth in standards and building codes. Research efforts aimed at alleviating these restrictions are focused on improving the quality of coarse RCAs by reducing the amount of adhered cement pastes, which is the weakest element in this system and influences the rheological behaviour.

This paper presents an analysis of the environmental impacts of the recent mechanical and thermo-mechanical processing techniques which produce high performance RCA by reducing the volume of adhered cement paste. Based on published data, processing scenarios were established. These scenarios permit making rough estimates of energy consumption, CO_2 emissions, fines generation and product quality. Using these data and the available emission factors from several countries, an objective comparison was made between these innovating processes and conventional recycling.

The production of fines increases from 40% up to as much as 70% as the volume of adhered cement paste on the RCA is reduced. Fuel fed thermo-mechanical process energy consumption, per tonne of recycled aggregate, varies between 36 and 62 times higher than conventional recycling processes. Mechanical processing, combined with microwave heating, increases energy consumption from 3 to a little more than 4 times conventional recycling. Consequently, CO_2 emissions released by conventional coarse aggregate production go from 1.5 to 4.5 $kgCO_2/t$, to around 200 $kgCO_2/t$, for that of fossil fuel fed thermo-mechanical treatments.

Mechanical and mechanical/microwave treatments appear to have the greatest environmental potential. Notwithstanding, the further development of markets for fines is crucial for reducing environmental loads.

1. Introduction

In many countries Construction and Demolition Waste (C&DW) is to a large extent, already being recycled in order to reduce the environmental burdens associated to construction life cycles. In Europe, for example, the proportion of recycled CDW ranges from 10% to 90%. The EU Waste Framework Directive (European Parliament, 2008), in force since 2010, has set the average quota for CDW recycling at 70% by 2020. Within the European Union some countries have already reached that objective, but for others this figure is utopia. Although the legislation in many countries allows using recycled aggregate in structural applications, worldwide about 90% of recycled aggregates are used in road or road-like applications (Vázquez, 2013). So, in order to close the cycle and use the recycled concrete aggregate in structural applications, researchers are trying to recycle those waste materials with their original quality by improving their performance and increasing value. That means reducing the weak phases that limit the applications of recycled concrete aggregate (De Juan and Gutiérrez, 2009), or more simply, removing the adhered cement paste. The hardened/adhered cement paste which envelops the natural stony particles is responsible for increasing porosity, decreasing the density of RCAs (Gómez-Soberón, 2002; Angulo et al., 2010) and influencing the properties of recycled aggregate concrete in the fresh and hardened state (Etxeberria et al., 2007a,b; Martínez et al., 2013; Matias et al., 2013; Andreu and Miren, 2014).

In efforts to upcycle rubble and produce high quality recycled concrete aggregates various processing techniques have been developed. Mechanical and thermo-mechanical treatments are techniques applied to remove the cement paste attached to the natural grains/stones (Kasai, 2006; Mulder et al., 2007; Sui and

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Mueller, 2012). The resulting product, rich in particles similar to natural aggregates in characteristics and behaviour, makes applying those recycled aggregates easier and more reliable in concrete applications. However, there is still a lack of knowledge concerning the environmental impacts linked to these treatments, e.g. energy consumption and CO_2 emissions.

In this study a rough estimate of the impacts of the energy utilized in recycling techniques and CO_2 emissions will be presented. It should give an indication of the "price" that will have to be paid to reclaim those materials. In spite of a lack of data which emerged during the literature review, the intended goal is to provide an order of magnitude of the above mentioned problem, by analysis and estimation.

2. Recycling aggregate processing

Fig. 1 gives a visual description of the processes discussed in the paper.

2.1. Ordinary recycling process

The production of recycled concrete aggregates (RCA) is quite similar to the production of crushed natural aggregates (Hansen, 1992).

The waste is fed into a grizzly feeder for a first size selection and the passing material is crushed, usually by a jaw crusher. Metallic scraps are separated and, depending on the plant circuit (closed or open), particles larger than the 20 mm can be crushed again. Grain size classification closes the process; recycled coarse (>4.8 mm) and fine (≤4.8 mm) aggregates are stockpiled.

The actual yield varies (Hansen, 1992); the percentage of fine fraction is in a range of 40–60% and today is scarcely used as back-filling, road or cement raw mixes for making cement clinker (Martins et al., 2013).

2.2. Production of high-quality RCA: mechanical treatments

Some mechanical treatments permit to produce RCAs with similar characteristics of natural aggregates making them more attractive to produce structural concrete.

Yonezawa and Yanagibashi (Yonezawa et al., 2001; Yanagibashi, 2002) present a novel rotation mill for producing high quality RCA. After a primary size reduction, the input material, is fed into the eccentric mill. It is crunched, rolled and tumbled by friction between the inner turning rotor and the internal wall of the drum, which partially removes the mortar.

Sakazume et al. apud Kasai (Kasai, 2006) describe the use of a screw abrading crusher where comminution is done by friction. After a primary crushing, necessary for RCAs' size reduction, coarse aggregates are fed into a circular tube which forces continuous contact between the aggregate particles.

Nagataki (Nagataki et al., 2004) describes a crushing process (by compression and impact) of four stages for obtaining RCAs with a low content of hardened cement paste. The recycling technology of this process consists of crushing the concrete waste in combination with a jaw crusher and an impact crusher and processing the crushed material twice with an even more efficient jaw crusher where a grinding effect can be expected to further minimize the attached cement paste.

Table 1 summarizes literature data concerning the treatments described above.

2.3. Production of high-quality RCA: thermo-mechanical treatments

Instead of multi-mechanical abrading steps, a high quality recycled aggregates can be produced by a combination of thermal and mechanical treatments.

When submitted to high temperatures hydrated cement paste decomposes, loses mechanical strength and is easily removed. For example, at 550 °C, the loss ranges from 55% to 70% of the original value (Georgali and Tsakiridis, 2005). C-S-H and aluminates lose most water between 70 and 400 °C (Alonso and Fernandez, 2004; Alarcon-Ruiz et al., 2005). Portlandite between 450 and 550 °C (Noumowe, 1995; Taylor, 1997; Baroghel-Bouny et al., 2002; Alonso and Fernandez, 2004). Calcium carbonate only decomposes at temperatures above 700 °C (Noumowe, 1995; Grattan-Bellew, 1996; Taylor, 1997).

Some cracking due to mechanical stress may also be observed. Entrapped water vapour from humidity and the bonded water can generate internal steam pressure. The combined drying and loss of water causes shrinkage, coarsening of pores' structure and produces more micro cracks (Piasta et al., 1984).

Quartz phases in the aggregates can suffer allotropic transformation from quartz-α to quartz-β at temperatures above 500 °C (Szoke, 2006), expanding in volume and producing more cracking. Rapid cooling reverses stress conditions, and the surface is put into a state of tension. Under these conditions brittle materials may experience fracture as a consequence of non-uniform dimensional changes termed thermal shock (Hasselman, 1969; Callister and Rethwisch, 2012).

Table 2 summarizes literature's data concerning the thermo-mechanical treatments.

Mulder (Mulder et al., 2007) describes a combination of mechanical and thermal treatments to generate recycled concrete aggregates with a very low content of cement paste. Pieces of crushed concrete (size ≤ 100 mm) are thermally treated at 700 °C; unfortunately, no information is given regarding how long the thermal treatment should last. Nonetheless, the adhesive properties of the cement paste are broken down and the constituents can be separated by simple sieving and air classifying (for powders). These secondary aggregates retain only about 2% cement paste, in volume.

Shima (Shima et al., 2005) presents a similar technology known as the heating and rubbing method. Rough-crushed concrete rubble (size ≤ 40 mm) is heated in a vertical kerosene furnace for 40–60 min at a temperature of about 300 °C, then crushed and rubbed in a tube mill or a tumbling ball mill. Due to the temperature restriction of the process and the resulting partial decomposition, milling is necessary to remove most of the cement paste. The heating generates cracks in the cement paste, and some of the adhered mortar separates from the surface of the aggregate. Thus, the remaining mortar must be milled, transforming the porous cement paste into powders. A pilot plant was constructed with capacity production of 5 t/h (Kasai, 2006).

To reduce energy consumption, Akbarnezhad (Akbarnezhad, 2010; Akbarnezhad et al., 2011) presents a heating treatment carried out using a microwave oven. Basically, the crushed aggregate is heated for 2 min in an industrial microwave oven built for this purpose; the heated aggregates are subsequently rubbed by a machine used to perform the Los Angeles Test.

3. Methodology

A rough estimate of the environmental impact of the processes, considering the energy consumption per metric tonne of processed material, has been calculated. The data extracted from literature was complemented with data from mining equipment technical

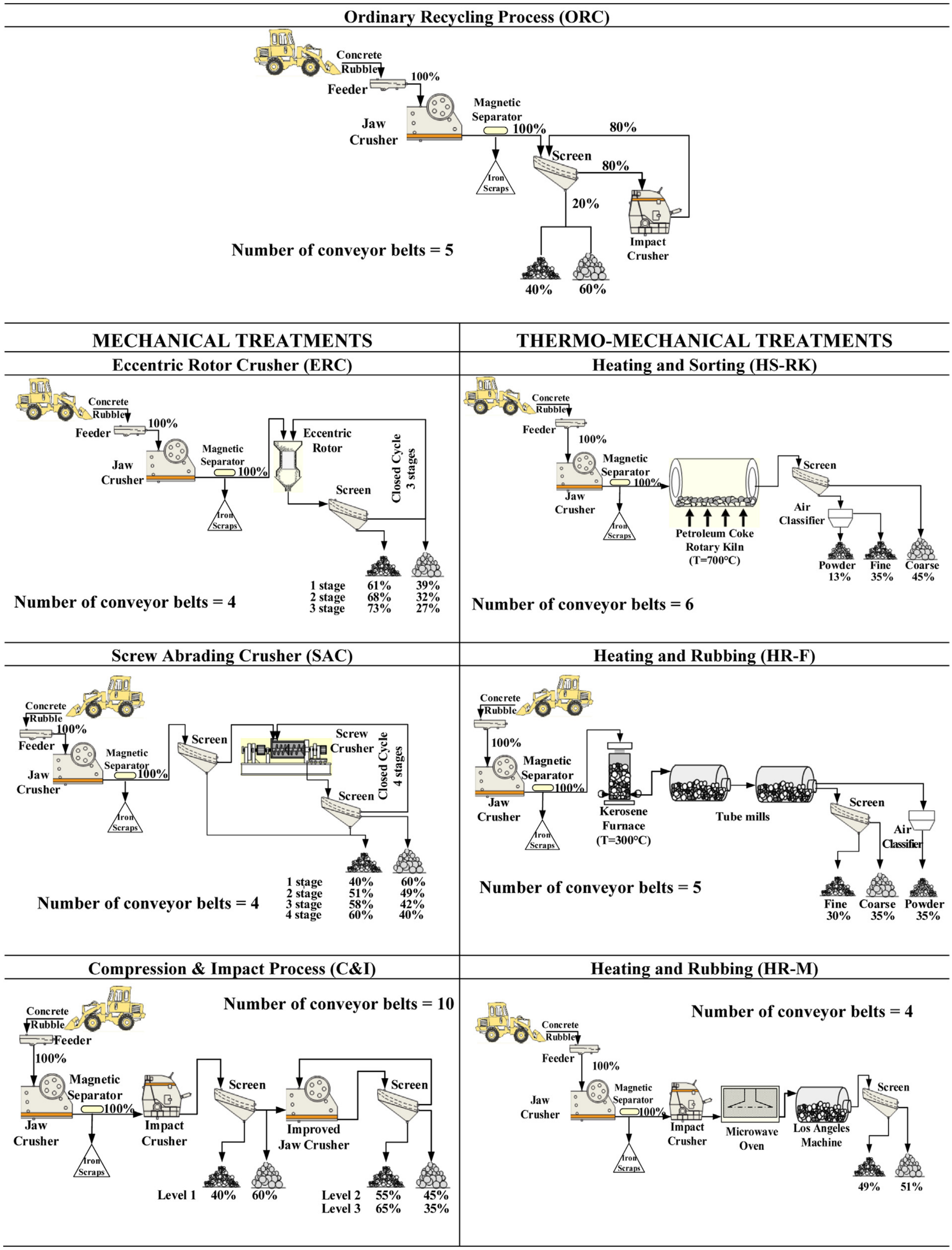

Fig. 1. Schematic representation, mass flow data and information of all analyzed processes. Symbols adapted from Metso Minerals datasheet.

data sheets. The considered system boundary is the processing plant from the feeding of the first processing machine to the stockpiling of aggregates. Impacts associated to the transportation of wastes to the processing plant and recycled aggregates from processing plant to consumers, have not taken into account because they suffer no influence from the process.

3.1. Processing scenario

A simple scenario is considered: the primary crusher can handle about 45 metric tonnes of concrete rubble per hour, whereas the production capacity of the other machines corresponds with the considered process' mass flow and with minimum technical

Table 1
Mechanical treatments of coarse RCA.

Technology treatment	Stages/levels of processing	Size of input material [mm]	Production capacity [t/h]	Density [g/cm^3]	Water absorption [% kg/kg]	Adhered mortar [% kg/kg]	Recovery as coarse aggregate [% kg/kg]
Eccentric rotor crusher (Yonezawa et al., 2001; Yanagibashi, 2002)	0[a]	≤40	30–60	2.22^{OD}	5.61	–	–
	1			2.58^{OD}	2.1		39
	2			2.65^{OD}	1.6		32
	3			2.67^{OD}	1		27
Screw abrading crusher (Nawa, 2005; Kasai, 2006)	1	≤40	5–10	2.47^{OD}	3.19	11.0	53.5
	2			2.51^{OD}	2.53	7.8	46.8
	3			2.53^{OD}	1.85	6.4	45.1
	4			2.55^{OD}	1.55	4.0	43.7
Compression and impact[b] (Nagataki et al., 2004)	1 – A	≤300	–	2.42^{SSD}	4.88	52.3	60
	3 – A			2.51^{SSD}	3.14	30.2	35
	1 – B			2.41^{SSD}	5.58	55.0	60
	3 – B			2.50^{SSD}	3.19	32.4	35
	1 – C			2.37^{SSD}	6.27	52.3	60
	3 – C			2.48^{SSD}	3.76	32.3	35

SSD, saturated surface density; *OD*, oven dry density.
[a] Original crushed concrete.
[b] Letters A (high quality), B (medium quality), C (low quality) identify the mix composition of original concrete and the quality of RCAs; numbers 1 and 3 the processing levels (Fig. 1).

specifications (Fig. 1 and Table 3). All machines are powered by electricity, except the loader shovel, and two of the three heating systems that are fossil fuel fed.

Table 3 summarizes the technical characteristics of the considered machines. A range of energy consumption has been calculated in accordance with minimum and maximum production capacity of the primary crusher.

3.2. Energy demand estimate

Electrical equipment energy requirement was calculated using Eq. (1):

$$\sum_i E_{el,i} = \sum_i \left(\frac{P_{m,i}}{\eta_{i,engine}} \right) n_{w,hi} \quad (1)$$

where $E_{el,i}$ is the electrical energy of the ith machine [kWh]; $P_{m,i}$ is the power of the ith engine installed in the ith machine of the plant [kW]; $\eta_{i,engine}$ is the efficiency of the ith electrical engine [–]; $n_{w,hi}$ is the number of working hours of the ith machine of the plant [h].

Energy consumption for combustion engine equipment was calculated using Eq. (2).

$$\sum_i E_{comb,i} = \sum_i (C_{hi} \cdot \rho_{hi} \cdot n_{w,hi}) \cdot H_{i,comb} \quad (2)$$

where $E_{comb,i}$ is the energy supplied to the ith engine by the combustion of the fuel [MJ]; C_{hi} is the per hour fuel consumption of the plant's ith engine [l/h]; ρ_{hi} is the density of the ith combustible [kg/l]; $n_{w,hi}$ is the number of working hours of the ith machine of the plant [h]; $H_{i,comb}$ is the net heating value of the combustible of the ith engine [MJ/kg].

Table 4 summarizes data concerning the efficiency of thermo-mechanical heating systems and the main characteristics of fossil fuels.

When estimating the energy consumption of fossil fuel fed heating systems (Eq. (3)), only the amount of heat necessary to increase the temperature of the recycled concrete aggregate from the ambient temperature (25 °C) to the operating temperature of the specific treatment was taken into consideration (see Table 2). This is the worst scenario and the influence of eventual temperature gradients will be discussed as sensitivity analysis. In accordance with Eq. (4), the calculated value has been divided by the efficiency of the heating system, e.g. rotary kiln, kerosene furnace.

The efficiency of the heating systems was taken from literature due to the lack of information concerning real values, e.g. geometry, materials, insulation systems, etc. Therefore, a variation range has been calculated considering different coefficients of efficiency equal to 0.25 and 0.75 (kerosene furnace), and to 0.5 and 0.8 (rotary kiln).

$$Q_{rca,i} = c_{rca} \cdot m_{rca} \cdot (\theta_{p,i} - \theta_{amb,i}) \quad (3)$$

where $Q_{rca,i}$ is the amount of heat necessary for increasing the temperature of recycled concrete aggregate [kJ]; c_{rca} is the specific heat of dry concrete, set as 0.9 kJ/kg °C [0.8÷1.3 kJ/kg °C] (Collepardi et al., 2009), ignoring the influence of humidity, which may increase; m_{rca} is the mass of recycled concrete aggregates [kg]; $\theta_{p,i}$ is the operating temperature of the ith treatment [°C]; $\theta_{amb,i}$ is the ambient temperature, set at 25 °C for recycled concrete aggregates [°C].

$$E_{th,i} = \frac{Q_{rca,i}}{\eta_{th,i}} \quad (4)$$

where $E_{th,i}$ is the energy requirement of the ith heating system [kJ]; $Q_{rca,i}$ is the amount of heat necessary for increasing the temperature of recycled concrete aggregate in the ith heating system [kJ]; $\eta_{th,i}$ is the efficiency of the ith heating system [–].

Eq. (5) allows estimating the amount of fuel to feed the heating system:

$$m_{comb,i} = \frac{E_{th,i}}{H_{comb,i}} \quad (5)$$

where $m_{comb,i}$ is the mass of the ith combustible [kg]; $E_{th,i}$ is the energy consumption of the ith heating system [MJ]; $H_{comb,i}$ is the net heating value of the combustible used in the ith heating system [MJ/kg].

The energy consumption of the whole process has been calculated as the sum of a single machine's energy consumption. The energy consumption per metric tonne has been chosen as the functional unit.

3.3. CO_2 emissions and primary energy estimate

CO_2 emissions and primary energy have been calculated by multiplying the energy requirement of every process by the CO_2 emission and conversion factors taken from the international database (Table 5). The analyzed processes do not reach temperatures above 700 °C and therefore are not able to decompose calcium

Table 2
Thermo-mechanical treatments of coarse RCA.

Technology treatment	Heating temperature and heating system	Size of input material [mm]	Production capacity [t/h]	Heating time [h]	Rubbing time [h]	After treatment		Mass balance [%]	Adhered mortar [% kg/kg]
						Density [g/cm^3]	Water absorption [% kg/kg]		
Heating and screening (Mulder et al., 2007)	700 °C Rotary kiln	≤100	–	–	–	–	–	45 coarse 35 fine 13 powder 7 vapour	2
Heating and rubbing (Shima et al., 2005; Kasai, 2006)	300 °C Vertical kerosene furnace	≤50	3–5	0.67–1	0.5–0.75	2.68^{OD}	0.8	35 coarse 30 fine 35 powder	–
Heating and rubbing[a] (microwave) (Akbarnezhad, 2010; Akbarnezhad et al., 2011)	140 °C Microwave 10 kW 2.45 GHz	≤30	0.65[b]	0.033	0.05[a]	2.46^{SD} (bulk) 2.43^{AD} (bulk)	2.8^{SD} 3.4^{AD}	51 coarse 49 fine 68 coarse 31 fine	24^{SD} 32^{AD}

AD, air dried; *SD*, saturated.
[a] Test results after 100 revolution with 10 steel balls in the Los Angeles equipment (31–33 rpm), estimate 193–181 s.
[b] Value estimated.

Table 3
Characteristics of equipment considered for the estimation of energy consumption in the absence of data. Electrical engines have been considered.

	Shovel loader	Grizzly feeder	Jaw crusher	Impact crusher	Improved jaw crusher	Cone crusher	Ball mill	LA machine	Magnetic separator	Vibrating screen	Air separator	Conveyor belt
Output power [kW]	–	2 × 2.2	30	75–110	30	75	30	0.75	1.5	6	7 .5	2.2
Production capacity [t/h]	–	40–100	20–55	60–100	20–55	50–60	25	–	–	20–80	–	–
Efficiency η [–]	–	0.8	0.9	0.93	0.9	0.93	0.9	0.7	0.77	0.847	0 .86	0.797
Fuel consumption [l/h]	9.1	–	–	–	–	–	–	–	–	–	–	–
Shovel capacity [m^3]	2	–	–	–	–	–	–	–	–	–	–	–

Loader shovel data from Liebherr-Werk Bischofshofen GmbH (2011).
Technical data of machines from Coeng Srl (2012), Metso Corp. (2012), Sturtevant Inc. (2012).
Efficiency of electrical equipment from Lafert Group (2012).
The cone crusher, with closed chamber, has been considered to simulate ERC (eccentric rotor crusher) and SAC (screw abrading crusher).

Table 4
Efficiency values of heating systems for thermo-mechanical treatments and main characteristics of fuels.

Heating system	Efficiency η [–]	Fuel	Density[a] [kg/l]	Net heating value[a] [MJ/kg]
–	–	Diesel fuel	0.825	43.3
Kerosene furnace	0.5[b]	Kerosene	0.795	43.5
Rotary kiln	0.55[c]	Petroleum coke	–	34.2

[a] Guadagni (2003).
[b] AAVV (2004).
[c] Trinks (2003).

Table 5
Emission and conversion factors.

	Country	Electricity	Diesel	Kerosene	Pet coke
CO_2 emission factor	Brazil EU-27 USA	0.087 $kgCO_2$/kWh 0.347 $kgCO_2$/kWh 0.522 $kgCO_2$/kWh	2.67 $kgCO_2$/l	2.52 $kgCO_2$/l	3.17 $kgCO_2$/kg
Primary energy conversion factor	Brazil EU USA	3.25 MJ/kWh 4.26 MJ/kWh 10.95 MJ/kWh	44.25 GJ/t	43.33 GJ/t	34.12 GJ/t

CO_2 emission factors for electricity and fossil fuels come from International Energy Agency (2012) and Greenhouse Gas Protocol (2013), respectively.
The primary energy conversion factors for electricity have been calculated dividing the primary energy consumption [MJ] by the net electricity production [kWh]. These data come from Empresa de Pesquisa Energetica (2013) for Brazil, Eurostat (2012) for Europe and US Energy Information Administration (2012) for the United States of America.
For fossil fuels has been considered the amount of energy to produce 1 metric tonne of fuel.

carbonate (Taylor, 1997). It has been shown that recycled concrete aggregates carbonate faster than concrete. This effect will be more important for the ordinary recycled aggregate, which has higher quantities of adhered cement paste (Engelsen et al., 2005; Pade and Guimaraes, 2007; Thiery et al., 2013). Because the carbonation rate depends on material source and exposure conditions, it has not been considered.

Table 5 summarizes the factors used to estimate the above mentioned quantities. To allow a more global comparison, Brazil, the USA and the EU-27 were considered in our analysis.

3.4. *Allocation*

The processing treatments discussed here have been developed to improve the quality of the coarse aggregate fraction. However, most of the reviewed literature did not recommend any commercial application for fines, for which production is high. Only a few references (Poon and Chan, 2006; Shui et al., 2008; Pelufo et al., 2011; Soutsos et al., 2011) do propose possible applications, without however, demonstrating the industrial suitability of the fines for such applications. The European Union Directive 2008/98/EC (European Parliament, 2008) asserts that a waste has to be considered as a by-product to have impacts allocated. It meets this condition if there is a market for it, without requiring any further processing other than normal industrial practice. This is not yet the case for recycled aggregate fines. However, even if an application were found, allocation by mass is not certain, despite its potential as binder (Shui et al., 2008). In the present study, two allocation scenarios are envisioned. One considers allocating environmental burdens to all processed material (fine and coarse fraction) and the other allocates environmental burdens to recycled concrete coarse aggregates, which easily replace natural aggregates in concrete production. In many practical applications however, the actual allocation will be somewhere in between these two extremes.

4. Results and discussion

The production of recycled coarse aggregate implies generating large amounts of fines – a minimum fraction of 35–40%. As Fig. 2 shows, the generation of fines increases with a reduction in porosity of the recycled coarse aggregate, which is an increase in quality. Some recycling processes generate water absorptions around 1% at the expense of transforming 68–75% of the incoming concrete rubble into fines. Only the HS-RK process is able to deliver 55% of fines with less than 1% water absorption, but at a high-energy cost (Table 6).

This is evidence that focusing only on producing high quality coarse aggregates is not the final solution for closing the loop of the concrete life cycle. This would require developing recycling technology that optimizes the commercial application not only of the coarse aggregate but also of all fine fractions, from fillers to sand to reactive powder (Sakai and Noguchi, 2012).

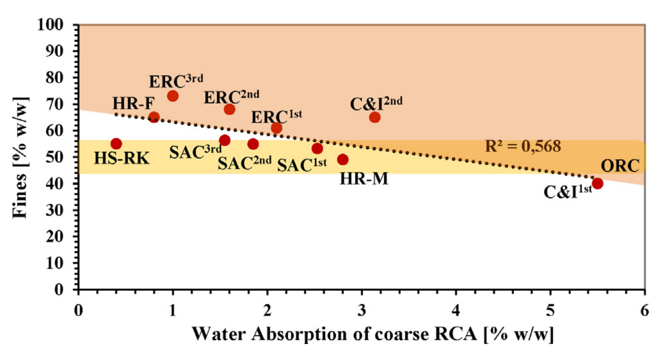

Fig. 2. Fine fraction production vs water absorption of coarse RCAs. The coloured area represents the recovery ratio of the high quality coarse fraction. The horizontal line centred on 50% shows the typical content of natural coarse aggregate in concrete. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Table 6
Energy consumption for the recycling treatments to produce high quality recycled aggregates [MJ/t].

	Process	Allocation to processed material	Allocation to commercial coarse aggregates
Mechanical	ORC	22.19	36.99
	ERC	34.20	126.67
	C&I	39.76	113.60
	SAC	63.54	158.84
Thermo-mechanical	HR-M	23.02	45.13
	HR-F	484.68	1384.81
	HS-RK	1055.99	2346.65

ORC (ordinary recycling process); ERC (eccentric rotor crusher); SAC (screw abrading crusher); C&I (compression and impact); HR-M (heating and rubbing – microwave); HR-F (heating and rubbing – furnace); HS-RK (heating and sorting – rotary kiln).

The energy requirement, estimated for the processes presented in item 2, are grouped considering allocation to the total amount of processed material and to the commercial coarse fraction (Table 6).

Fig. 3 shows the plotted estimated energy requirement vs RCA's water absorption, and presents the range of variation for each treatment. Energy consumption is allocated to the total amount of processed material. For RCAs produced by ORC, the water absorption value was adopted from literature (Hansen, 1992; De Brito et al., 2011; Vieira et al., 2011; Alaejos et al., 2013; Matias et al., 2013).

Considering the minimum values for the fossil fuel fed thermo-mechanical treatments, note that the energy requirements result in one order of magnitude higher than that of all the other processes. Moreover, contrary to thermal produced aggregates, those produced by mechanical processes may present similar porosity. It is very promising that there seems to be no direct correlation between the processing energy and porosity.

When the energy consumption is allocated to the produced commercial coarse fraction, in accordance with the mass flows presented in item 2, the difference between thermal and mechanical treatments increases up to two orders of magnitude (Fig. 4) without affecting the general trend.

The results in Figs. 3 and 4 show that there is no linear relationship between energy consumption and the water absorption of recycled material. Moreover, among the mechanical processes, the one with the highest energy consumption does not produce the aggregate with the lowest water absorption. Thus, it appears that the technology of the system strictly affects the quality of the produced material.

Fig. 5 shows comparisons of the analyzed mechanical treatments. The recovery ratio of coarse RCAs (a) and water absorption (b) are plotted vs stages of processing.

The figures clearly show that abrasion methods are more effective than compression and impact. Further, at the same processing level, abrasion methods produce recycled coarse aggregates with water absorption values lower than those produced by compression and impact treatments. Screw abrading crushing shows, at the second and third processing level, a recovery ratio higher than that of compression and impact methods.

Looking at thermal treatments, the one that seems promising is the microwave beneficiation technique. The energy consumption is on the same level with mechanical treatments, and the porosity is in between those of ERC and SAC operating at the 2nd stage of processing (Fig. 5). Although the microwave beneficiation treatment guarantees acceptable RCA water absorption values, it is a sophisticated technology requiring further development before proving feasible for large capacity production.

The results of the above mentioned differences are self-evident in Fig. 6 where the relative increase of energy consumption in function of allocation is presented.

Tables 7 and 8 summarize the CO_2 emissions related to the analyzed processes. Data, referring to the two allocation scenarios, have been grouped per energy source and geographic area.

Fig. 7 shows the overall estimated CO_2 emissions per metric tonne of RCA allocated on the total amount of processed material (a) and on the commercial coarse fraction (b).

Fig. 8 presents the variation in terms of CO_2 emissions of the different treatments as performed in the considered geographical areas. In order to simplify the comparison, ORC has been established as the baseline, as it is performed in Brazil, with the emissions allocated to the overall processed material and to the commercial coarse RCA fraction.

Results presented in the figure show how much the fossil fuels affect the emission values. On one hand, no significant difference can be noticed for HR-F or HS-RK when performed in different geographical areas; on the other, all treatments powered by electricity show significant variations in function of the quality of the energy source.

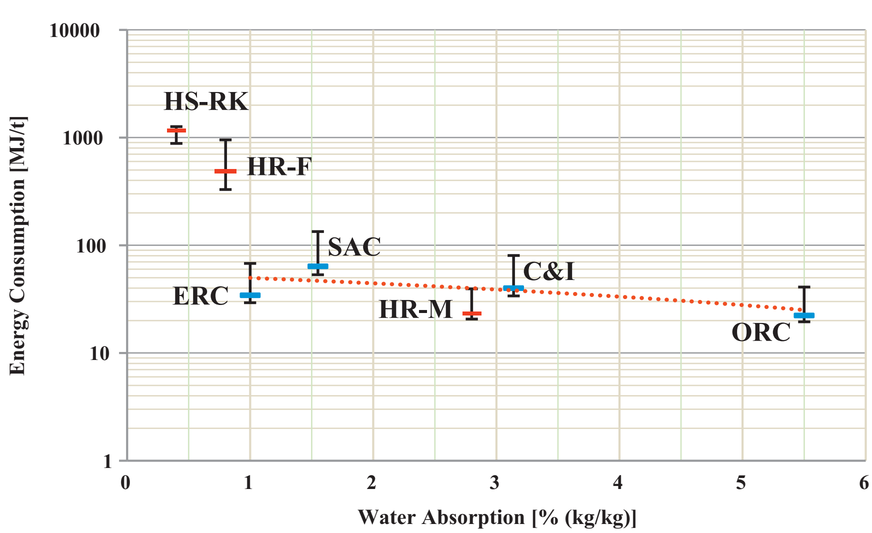

Fig. 3. Energy consumption per metric tonne (allocated to fine and coarse fraction) vs water absorption of RCAs subjected to advanced processes. ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

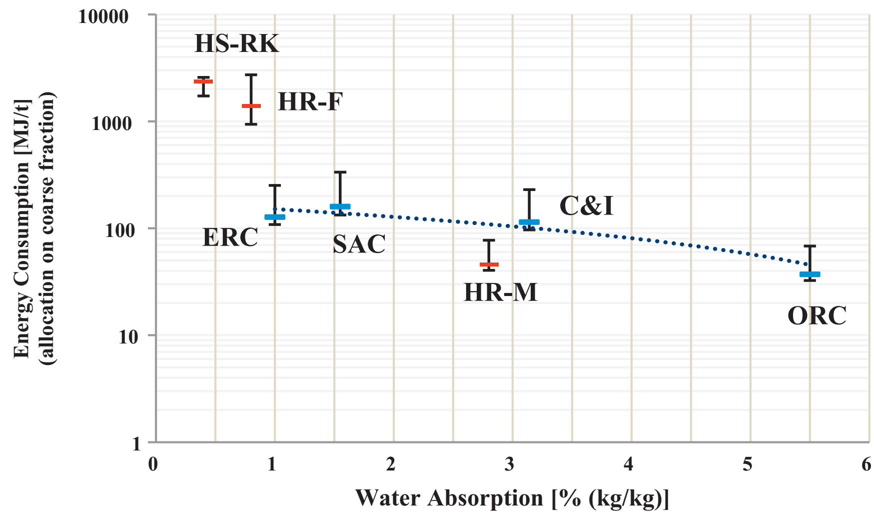

Fig. 4. Energy consumption per metric tonne (allocated to commercial coarse fraction) vs water absorption of RCAs subjected to advanced processes. ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

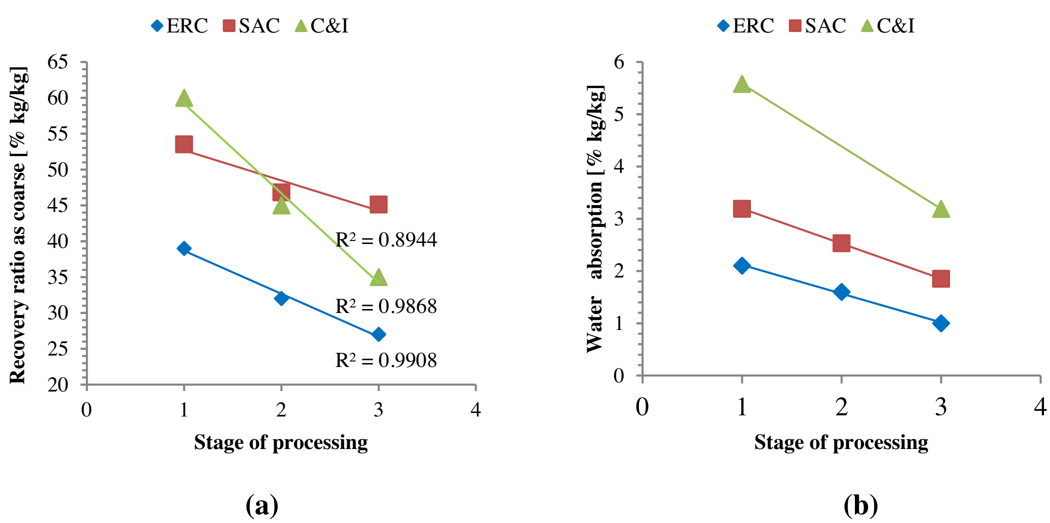

Fig. 5. Recovery ratio of coarse fraction vs stage of processing (a) and water absorption vs stage of processing (b). ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher).

Table 7
CO_2 emissions for the recycling treatments to produce high quality recycled aggregates [$kgCO_2/t_{rca}$]. Allocation on processed material.

Country	Energy source	ORC	ERC	C&I	SAC	HR-M	HR-F	HS-RK
Brazil	Diesel	0.541	0.541	0.541	0.541	0.541	0.541	0.541
	Electricity	0.362	0.652	0.786	1.361	0.382	0.241	0.135
	Kerosene	–	–	–	–	–	68.564	–
	PET coke	–	–	–	–	–	–	96.632
USA	Diesel	0.541	0.541	0.541	0.541	0.541	0.541	0.541
	Electricity	2.171	3.912	4.718	8.165	2.290	1.444	0.810
	Kerosene	–	–	–	–	–	68.564	–
	PET coke	–	–	–	–	–	–	96.632
EU-27	Diesel	0.541	0.541	0.541	0.541	0.541	0.541	0.541
	Electricity	1.443	2.600	3.136	5.428	1.522	0.960	0.538
	Kerosene	–	–	–	–	–	68.564	–
	PET coke	–	–	–	–	–	–	96.632

ORC (ordinary recycling process); ERC (eccentric rotor crusher); SAC (screw abrading crusher); C&I (compression and impact); HR-M (heating and rubbing – microwave); HR-F (heating and rubbing – furnace); HS-RK (heating and sorting – rotary kiln).

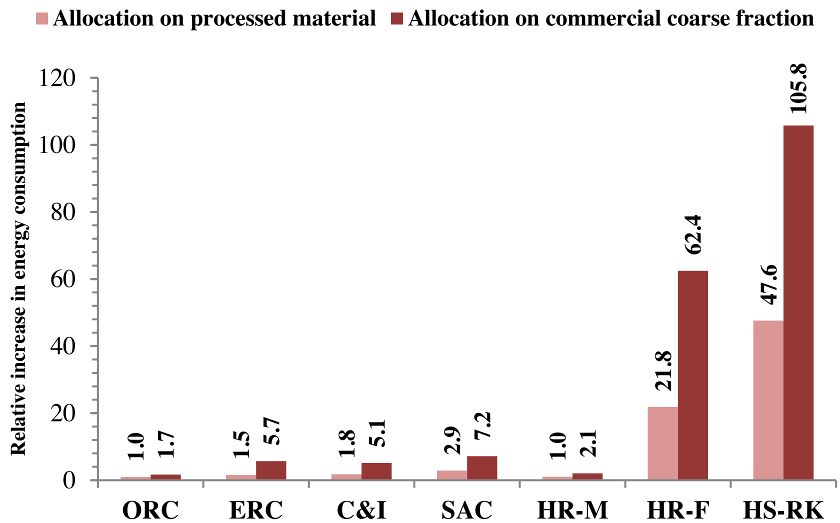

Fig. 6. Increment of energy consumption in function of the allocation; the ordinary recycling process has been set as baseline. ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

The estimated values of primary energy, relating to the analyzed treatment as performed in the considered geographical areas, are presented in Tables 9 and 10. Data are grouped per energy source and geographical area, and two allocation scenarios have been considered. Here also, allocation plays a prominent role.

Fig. 9 shows results in function of the energy requirement allocation: (a) on the overall amount of processed material; (b) on the amount of commercial coarse RCAs.

The comparison among the different treatments and the two allocation scenarios, as performed in the considered geographical areas, is presented in Fig. 10. ORC as performed in Brazil, with the primary energy allocated to the overall amount of processed material, has been set as the baseline.

Looking at the results, it is quite clear that the recycled aggregate produced by means of fossil fuel fed thermal treatments suffers a huge impact in both allocation scenarios. Even if the fine fraction (≤75 μm) is used as filler, in attempting to reduce the impact, the thermo mechanical systems are orders of magnitude higher than the mechanical ones (Sakai and Noguchi, 2012). Moreover, in order to produce a material with the right size, a part of the available fine fraction should be milled to increase the embodied energy of the final product.

The quality of the energy sources and the efficiency of power plants, in particular those producing electricity, affect process impacts. Thus, "local peculiarities" affect CO_2 emissions and primary energy consumption, which influences environmental impacts.

Construction and demolition waste recycling should not be considered only in terms of energy and CO_2 emissions. Recycling further reduces the depletion of raw materials, lessens environmental burdens due to transportation, and helps preserve landscape and landfill areas (Knoeri et al., 2013).

The presented data do not justify the need a priori to develop technologies designed only to produce high quality coarse aggregates as that might mean greater CO_2 emissions, a higher consumption of energy and/or fines generation. Considering that more than 50% is fines and there is no market for that fraction, most of the processed material might end up as a high-energy waste. From this point of view, developing recycling processes that optimize the productive use of the fine fraction is a top priority.

In addition, looking at the problem from a different point of view, it is necessary to take into account the real potential of that coarse fraction in terms of available quantity. As shown, the recoverable natural coarse fraction from concrete rubble is about 50% and that tends to decrease due to crushing. Considering

Table 8
CO_2 emissions for the recycling treatments to produce high quality recycled aggregates [$kgCO_2/t_{rca}$]. Allocation on commercial coarse material.

Country	Energy source	ORC	ERC	C&I	SAC	HR-M	HR-F	HS-RK
Brazil	Diesel	0.902	2.004	1.546	1.353	1.061	1.546	1.203
	Electricity	0.603	2.415	2.246	3.402	0.748	0.688	0.300
	Kerosene	–	–	–	–	–	195.897	–
	PET coke	–	–	–	–	–	–	214.737
USA	Diesel	0.902	2.004	1.546	1.353	1.061	1.546	1.203
	Electricity	3.618	14.488	13.479	20.413	4.490	4.126	1.800
	Kerosene	–	–	–	–	–	195.897	–
	PET coke	–	–	–	–	–	–	214.737
EU-27	Diesel	0.902	2.004	1.546	1.353	1.061	1.546	1.203
	Electricity	2.405	9.631	8.960	13.570	2.985	2.743	1.196
	Kerosene	–	–	–	–	–	195.897	–
	PET coke	–	–	–	–	–	–	214.737

ORC (ordinary recycling process); ERC (eccentric rotor crusher); SAC (screw abrading crusher); C&I (compression and impact); HR-M (heating and rubbing – microwave); HR-F (heating and rubbing – furnace); HS-RK (heating and sorting – rotary kiln).

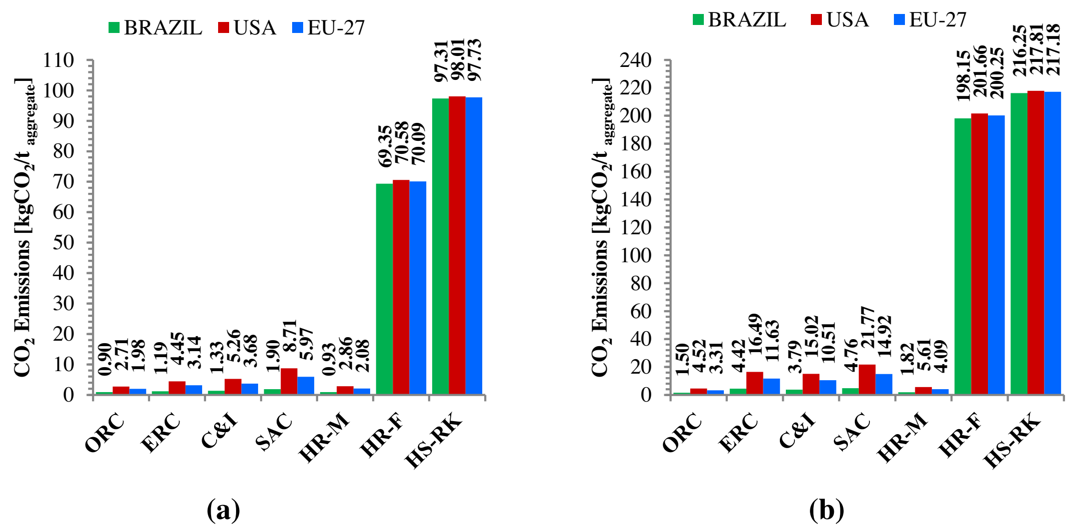

Fig. 7. Estimated amount of CO_2 emissions per metric tonne of processed material (a) and per metric tonne of commercial coarse RCA (b) produced by the assessed recycling processes. ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

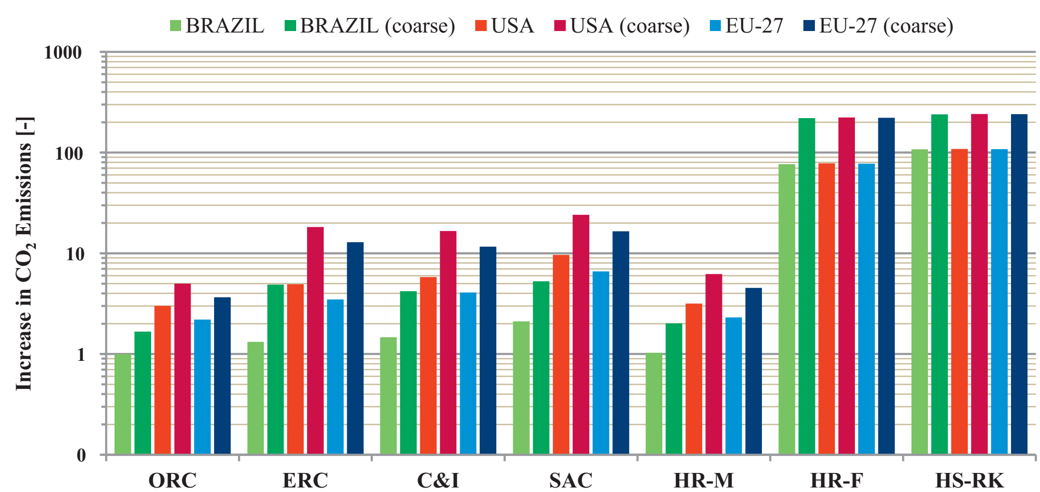

Fig. 8. Variation of CO_2 emissions in function of the geographic area and of the allocation ("coarse" means allocation to commercial coarse fraction). ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

Table 9
Primary energy for the recycling treatments to produce high quality recycled aggregates [MJ/t_{rca}]. Allocation on processed material.

Country	Energy source	ORC	ERC	C&I	SAC	HR-M	HR-F	HS-RK
Brazil	Diesel	7.4	7.4	7.4	7.4	7.4	7.4	7.4
	Electricity	13.5	24.4	29.4	50.8	14.5	9.2	5.2
	Kerosene	–	–	–	–	–	937.2	–
	PET coke	–	–	–	–	–	–	1040.7
USA	Diesel	7.4	7.4	7.4	7.4	7.4	7.4	7.4
	Electricity	45.5	82.1	99.0	171.3	48.7	31.0	17.7
	Kerosene	–	–	–	–	–	937.2	–
	PET coke	–	–	–	–	–	–	1040.7
EU-27	Diesel	7.4	7.4	7.4	7.4	7.4	7.4	7.4
	Electricity	17.7	31.9	38.5	66.6	18.9	12.0	6.9
	Kerosene	–	–	–	–	–	937.2	–
	PET coke	–	–	–	–	–	–	1040.7

ORC (ordinary recycling process); ERC (eccentric rotor crusher); SAC (screw abrading crusher); C&I (compression and impact); HR-M (heating and rubbing – microwave); HR-F (heating and rubbing – furnace); HS-RK (heating and sorting – rotary kiln).

Table 10
Primary energy for the recycling treatments to produce high quality recycled aggregates [MJ/t_{rca}]. Allocation on commercial coarse material.

Country	Energy source	ORC	ERC	C&I	SAC	HR-M	HR-F	HS-RK
Brazil	Diesel	12.3	27.3	21.1	18.5	14.5	21.1	16.4
	Electricity	22.5	90.2	83.9	127.1	28.3	26.3	11.6
	Kerosene	–	–	–	–	–	2677.8	–
	PET Coke	–	–	–	–	–	–	2312.8
USA	Diesel	12.3	27.3	21.1	18.5	14.5	21.1	16.4
	Electricity	75.9	303.9	282.7	428.2	95.5	88.5	39.2
	Kerosene	–	–	–	–	–	2677.8	–
	PET Coke	–	–	–	–	–	–	2312.8
EU-27	Diesel	12.3	27.3	21.1	18.5	14.5	21.1	16.4
	Electricity	29.5	118.2	110.0	166.6	37.2	34.4	15.3
	Kerosene	–	–	–	–	–	2677.8	–
	PET Coke	–	–	–	–	–	–	2312.8

ORC (ordinary recycling process); ERC (eccentric rotor crusher); SAC (screw abrading crusher); C&I (compression and impact); HR-M (heating and rubbing – microwave); HR-F (heating and rubbing – furnace); HS-RK (heating and sorting – rotary kiln).

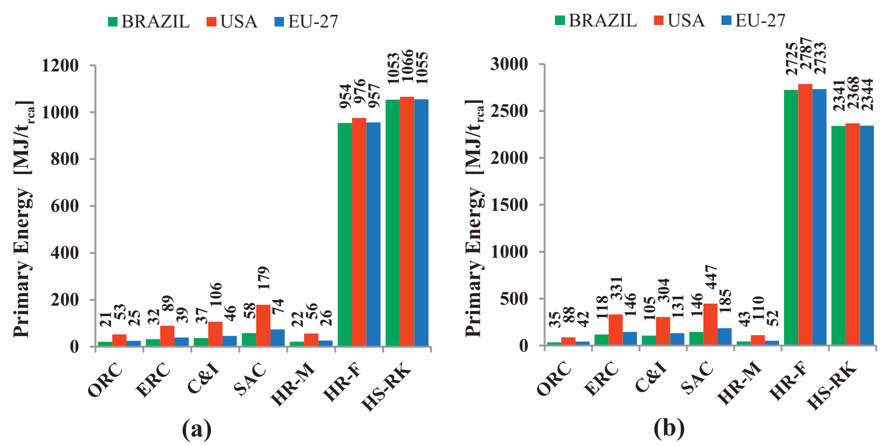

Fig. 9. Primary energy per metric tonne of processed RCA (a) and per metric tonne of commercial coarse RCA (b). ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

the amount of concrete produced worldwide, the contribution that this high quality recycled coarse fraction can make as a raw material replacement, is low.

Moreover, the simplest recycling technology (plain crushing) generates more coarse aggregates than that from original concrete, and the entire product, including fines, can easily be sold as a road base application. As an alternative, a swap between recycled concrete aggregate users and road contractors might be a solution to make full use of that recycled material. Considering that the real need is to close the cycle of the total economy involving concrete, this simplest recycling route seems to be the most effective, at least when there is no application for the fines.

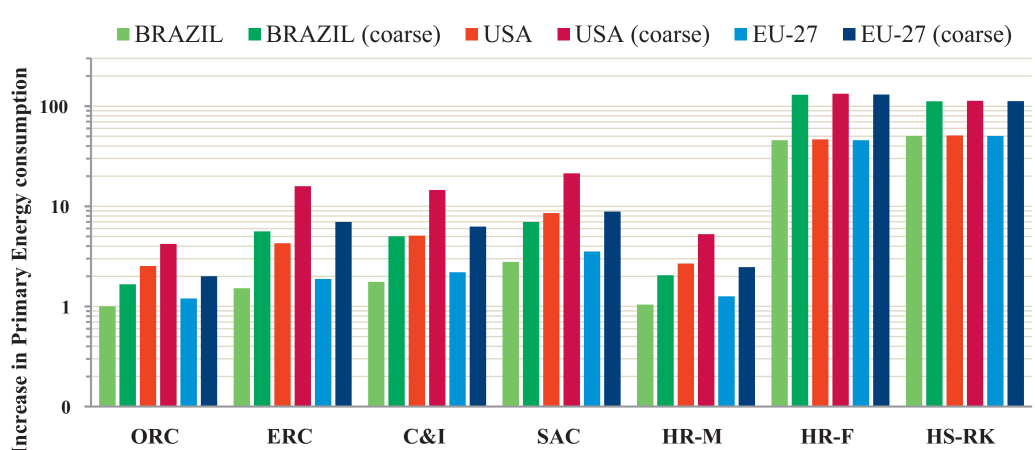

Fig. 10. Variation of primary energy requirement in function of the geographical area and of the allocation ("coarse" means allocation to commercial coarse fraction). ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting).

Finally, the data suggest that it might be worthwhile to question the concept of down cycling, as sometimes closing the loop within the same material does not minimize the environmental impact.

5. Conclusions

High quality coarse recycled concrete aggregate production, by means of mechanical and thermo-mechanical treatments, has been analyzed and compared with conventional recycling processes. The purpose was to estimate and compare the environmental impacts in terms of energy consumption and CO_2 emissions. Due to a scarcity of data, only rough estimations were possible; however, the following conclusions were drawn.

The lower the cement paste content, the higher the fine fraction, which reduces production yield, unless a high amount of thermal energy is used. Without a market for the fines, all environmental loads have to be fully allocated to the coarse fraction. This means an increase in energy consumption and CO_2 emissions. This fact alone could imply a twofold increase in the environmental loads, since the mass of fine fraction can increase from 40%, for common coarse RCA with 5–6% water absorption, to 70% for the mechanically processed coarse RCA with 1% water absorption.

With the exception of microwave heating, the energy consumption per tonne of coarse aggregate produced by the fuel fed thermo-mechanical process is between 36 and 62 times higher than that of the conventional recycling process. On the other hand, mechanical processing increases energy consumption from 3 to a little more than 4 times higher than conventional recycling. Microwave, plus mechanical treatment has an energy demand little higher than simple mechanical processing, but the available data is very limited. Energy consumption can therefore vary from 37 MJ/t for conventional coarse aggregate up to 1400–2300 MJ/t for fuel based thermal treatments.

CO_2 emissions resulting from recycling are mostly related to energy consumption, but are also dependent on the emission factors. These factors depend on the source of fuel and how the electricity is generated, which leads to a great disparity in emission factors from region to region. Conventional recycling implies CO_2 emissions between 1.5 and 4.5 $kgCO_2$/t coarse aggregate produced, depending on the region. This is about the same level as that produced by microwave treatment. Mechanical treatment emissions are somewhat higher; varying from 3.8 to 21.7 $kgCO_2$/t. Fossil fuel fed thermal processing emission rates are around 200 $kgCO_2$/t.

Therefore, the production of low cement paste content, high-performance recycled aggregate is viable from an environmental point of view in places where natural aggregates are very scarce, and probably require long transportation distances. The environmental load associated to this process can be reduced by developing markets for fines.

From an environmental point of view, the mechanical process and the mechanical/microwave heating process seems to have the greatest potential. And, the mechanical abrasion treatments appear to be more effective than those of compression and impact.

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