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Energy consumption of a laboratory jaw crusher during normal and high strength concrete recycling

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ABSTRACT

This paper presents the measurement and analysis of energy consumption of a laboratory jaw crusher during concrete recycling. A method was developed to estimate the power requirements of a lab-scale jaw crusher. The impact of material properties on the crusher performance is studied. Eight concrete strength classes (C20/25–C80/95) were considered in the approach. Concrete specimens were cured for 28 days; at which time, concrete properties were obtained through tests such as bulk density, compressive strength, tensile strength, rebound number and ultrasonic pulse velocity. The impact of different aperture size (5 mm and 25 mm) on the energy consumption was also studied. From the experimental results, it is demonstrated that there is a strong dependance of energy consumption on the compressive strength of concrete. Energy of crushing for specimens with a 90 MPa compressive strength was four times higher than the energy needed to crush specimens with a 28 MPa compressive strength. Furthermore, the crushing requires three times more energy when the smaller aperture size is used to process concrete specimens. The results of this study can form a basis for a future large-scale field analysis and a detailed determination of the energy and economic efficiency of concrete recycling.

1. Introduction

Power consumption and therefore efficiency of crushing equipment are becoming increasingly important mainly due to the continuous and rapid increase of energy costs and efforts to minimise CO_2 emissions (Tromans, 2008; Legendre and Zevenhoven, 2014). In order to meet the Paris Climate Agreement goals, recycling should be maximized by 2050 because without recycling measures, the electricity demand of industry will increase by an additional 55 TWh in 2050 (Kullmann et al., 2022). None of the research so far had focused on experimental measurements of energy consumption for concrete crushing and recycling, even though construction and demolition waste is assessed to be 25–30 % of the total waste in Europe (Cai and Waldmann, 2019). At the same time, an energy consumption analysis is the very first step and it is essential for the development of energy-efficient technologies and scientific environmental assessment for production of recycled concrete aggregates (RCA).

RCA are mainly obtained from mixed streams of end-of-life concrete structures, but also from new and non-deteriorated concrete (Nedeljković et al., 2023). Given these streams of varying composition and inconsistent and varying quality of concrete (a material which can range from 20 to 150 MPa, with varying amounts of steel or fibre reinforcement), physical and compositional variations in RCA can be large, particularly in the finer fractions (Nedeljković et al., 2021). Over the past decade, extensive research has been carried out on the utilization of RCA and the effect of their properties on the properties of new concrete (Omary et al., 2016; Duan and Poon, 2014; Etxeberria et al., 2007; Ho et al., 2013; Jayasuriya et al., 2021; Kou and Poon, 2015; Limbachiya et al., 2000; Lotfi, 2016; Lotfi et al., 2014; Marinković et al., 2010; Nedeljković et al., 2022; Nedeljković et al., 2021; Pepe et al., 2020; Tošić et al., 2018; Pacheco and de Brito, 2021; Seara-Paz et al., 2022; Mylonas, 2021) to ensure the high quality of RCA. However, RCA can be used in high-end concrete applications at this moment up to 30 % based on the standard for concrete specifications (EN 206:, 2017). In order to increase future use of RCA; there are two routes: the use of advanced recycling techniques (Lotfi and Rem, 2016; Schenk, 2011)

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and, recycling after selective demolition (Nedeljković et al., 2023; Nedeljković et al., 2023).

Regarding energy consumption of RCA production, little is known, much less about the effects of input variables on the energy consumption during the concrete crushing process such as concrete mechanical and physical properties. Rough estimates of energy consumption from conventional and advanced recycling techniques were made in the absence of empirical data (Quattrone et al., 2014). According to the analysis of Quattrone et al., energy consumption of advanced recycling processes was 62 times higher than conventional recycling (Quattrone et al., 2014). Furthermore, Life Cycle Analyses (LCA) for RCA's assume the same energy consumption during recycling which is largely simplified and asks for consideration of RCA's origin (quality of parent concete). Therefore, a rational and empirically confirmed basis must be given for assessment of sustainable recycling and what is exactly its environmental impact. Understanding how energy is consumed in recycling will give LCA assessors a better understanding of how to evaluate the energy consumption. In order to improve the efficiency of a recycling technique it is first important to understand the actual crushing process (Legendre and Zevenhoven, 2014) and how material properties among other parameters can affect the crusher performance. After this, the crusher performance can be optimized (Legendre and Zevenhoven, 2014; Numbi et al., 2014).

Compressive strength of concrete is believed to have a large impact on the energy required for crushing concrete, based on the similar findings for crushing rocks (natural stone) (Korman et al., 2015). Rocks are taken as an example because of similarities with concrete (artificial rock). Laboratory studies showed that the crushability of rocks is directly associated with the rock strength and mineralogical composition (E., Özarslan, A., 2018; Miskovsky et al., 2004). Furthermore, the compressive strength is typically used to rank a rock's material hardness (Donovan, 2003). Tensile strength is also used since particles of brittle materials break in tension under compressive loads (Bearman et al., 1991). Olaleye (Olaleye, 2010) found that the rock compressive strength directly relates to the wear and energy consumption in jaw crushers. Similarly, Korman et al. (Korman et al., 2015) stated that the uniaxial compressive strength of rocks is a dominating factor for crushing energy consumption in jaw crushers. In the previous studies the specific crushing energy was determined indirectly based on the pendulum or falling weight tests. Additionally, Single Particle Breakage (SPB) test has been used to characterize the compressive breakage behaviour of rocks (Bengtsson et al., 2006; Bengtsson, 2021). The SPB can be applied to study the breakage on a more controlled level to achieve an individual breakage analysis. Furthermore, the SPB (or inter-particle breakage test (IPB)) is used for calibrating crusher models and for this particular research the correlation between one SPB test and a full scale jaw crusher test can not be done without further crusher modelling. Korman et al. (Korman et al., 2015) applied direct measurement of the power on the jaw crusher motor to evaluate the effect of mechanical properties of rocks on crushing energy of jaw crusher.

Considering all of the above, it is evident that a crucial step towards a more rational and efficient recycling of concrete is a better understanding of how input concrete properties, such as strength, influence the crushing process, in terms of energy consumption and the quality of the produced RCA. The main aim of this study was to measure the energy consumed during true crushing of concrete using measurement of the power on the jaw crusher motor. The investigated concrete compositions correspond to a real concrete composition in civil engineering. An energy consumption measurement system was developed and a series of experiments were conducted to analyze the energy consumption and its dependance on the input concrete properties. The average of the crushing energy needed for a given concrete composition was measured in this study. Furthermore, the goal of the study was to evaluate the combined effect of using a single crushing stage and the concrete compressive strength on the water absorption and Los Angeles coefficient of the produced RCA.

2. Experimental program

2.1. Materials

The cements used in concrete mixture designs (Table 1) were ordinary Portland cement, CEM I 52.5 R and ground granulated blast furnace slag cement CEM III/B 42.5 N with densities 3.15 g/cm^3 and 3.00 g/cm^3, respectively. As aggregates, river sand and gravel were used with a density of 2.65 g/cm^3. Superplasticizer (SP) SIKA VC 1550 con. 30 % based on polycarboxylether, was selected with a density of 1.06 g/ml. The dosage of SP was adjusted in order to obtain the target flow for each mixture. The water content was corrected relative to the water present in the SP. For the mix C80/95, a special type of cement, CEM III/A 52.5 R Variodur 40, and fly ash as a mineral addition with a density of 2.44 g/cm^3 were used in the mix design.

2.2. Concrete mixture designs and mixing

Table 1 presents an overview of the concrete mixture designs. Designs were adopted from the Dutch concrete practice, as commonly used mix designs in the Netherlands. Concretes had different water-to-cement ratio (w/c), this ratio excludes the water added for water absorption (WA) of aggregates. The type of aggregates and SP type were the same for all mixtures in order to exclude the effect of these parameters on the properties of the concretes and observe the influence of the strength, and thus water-to-cement ratio, on the energy consumption for crushing concrete.

A 40 L mixer was used for mixing concrete batches. The mix procedure was as follows: gravel, river sand and cement were dry-mixed for 1 min; thereafter, water was added and mixed for another 2 min. For mixtures with SP, SP was first added to a part of the water and then added to the mix. After mixing, the concrete was cast into cubic specimens 150 × 150 × 150 mm^3 compacted with a compaction table for 15 s. Subsequently, 24 h after casting, the specimens were demoulded and stored in the curing room at a temperature of 20 °C and a relative humidity of 99 % until the age of testing. For each concrete mix, 36 cubes were cast. Not all mixes were cast at the same time. The time difference between castings of mixtures was one week to make sure that all concrete mixes would be crushed at 28 days.

An age of 28 days is selected because of the assessment of several predesigned strength classes (at 28 days) on energy consumption for concrete crushing. The goal of the study was to crush concrete with target strength class, and that could be at any age while concrete has that target strength that we aimed for (25 MPa, 37 MPa, 45 MPa, 55 MPa, 67 MPa, 75 MPa, 85 MPa, 95 MPa).

2.3. Methods

2.3.1. Concrete properties

2.3.1.1. Hardened density. The density of hardened concrete mixtures at 28 days was tested according to NEN EN 12390–7:2019 (EN, 2019).

2.3.1.2. Compressive strength. The compressive strength of concrete was determined according to EN 12390–3:2019 (EN, 2019) and calculated as an average value of three specimens at 28 days. The standard deviations were also reported for each data set. Loading capacity of the compression machine (Matest^{TM}) was 5000 kN and the loading rate was maintained at 13.5 kN/s.

2.3.1.3. Tensile splitting strength. The tensile splitting strength of concrete was tested according to EN 12390–6:2009 (EN, 2009) and calculated as an average value of three specimens at 28 days. Then the standard deviations were calculated for each set of data.

Table 1
Concrete mixture designs.

	C20/25	C30/37	C35/45	C45/55	C55/67	C60/75	C70/85	C80/95
	Dry mass [kg/m^3]							
CEM III/B 42.5 N	250	286	357	249	231	220	100	
CEM I 52.5 R		32		134	231	240	400	
CEM III/A 52.5 R Variodur 40								435
Water	162.5	182	160	167	169	158	167	136
Sand [0/4 mm]	908	804	811	854	820	834	743	850
Gravel [4/16 mm]	1000	1034	1042	925	888	904	946	959
Fly ash								15
SP			1.428	1.648	2.446	2.760	3.000	4.599
Total cement content	250	318	357	383	462	460	500	450
Total agg. content	1908	1838	1853	1779	1708	1738	1689	1809
w/c	0.65	0.54	0.43	0.44	0.37	0.34	0.33	0.31

2.3.1.4. Determination of rebound number using a Schmidt hammer. The rebound numbers were determined according to EN 12504–2:2021 (EN, 2021) using proceq Silver Schmidt OS8200. The rebound number represents concrete surface hardness. Specimens, concrete cubes, were rigidly supported in the compressive test set up. A minimum of nine readings were recorded. No test points were within 25 mm of the cube edge and no two impacts were closer than 25 mm (<50 mm). The median of the 9 readings was taken as the representative rebound number for the tested concrete cube.

2.3.1.5. Determination of ultrasonic pulse velocity in concrete. The ultrasonic pulse velocity in concrete was tested according to EN 12504–4:2021 (EN, 2021) using proceq Ultrasonics Pulse Velocity Pundit PL200. Pulse velocity was measured by placing the two transducers on opposite faces of the concrete cube (direct transmission). Good acoustical contact was obtained by the use of a petroleum jelly and by pressing the transducer against the concrete surface. The pulse velocity was measured between moulded faces for cubes and it was expressed as a mean value of at least three measurements (spaced between top and bottom of the cube).

2.3.2. Properties of recycled concrete aggregates

2.3.2.1. Water absorption. The water absorption of coarse aggregates (4–16 mm) was tested according to EN 1097–6:2022 (EN, 2022). A sample of at least 10 kg was collected in agreement with the standard.

2.3.2.2. Los Angeles coefficient (LA). The resistance to fragmentation of coarse aggregates was tested based on Los Angeles test according to EN 1097–2:2020 (EN, 2020). The mass of the laboratory specimen was at least 10 kg with a particle size between 10 and 14 mm obtained after sieveing.

2.3.3. Crushing energy

Measurement of the electricity consumption during crushing was done on a laboratory jaw crusher Bauknecht, Fig. 1. Jaw crusher operates by compressing the feed material between a fixed and a moving jaw back and forth in an eccentric cyclic motion (Cleary and Sinnott, 2015). The feed size of the opening was 110 × 100 mm^2. Concrete cubes 150 × 150 mm^2 could not fit the opening of the jaw crusher. For this reason, 6 cubes from each concrete mixture were cut in 8 equal parts with one side dimension of 73 mm resulting in 48 cubes for crushing as shown in Fig. 2. Thus the specimens used for crushing were of the same size and of

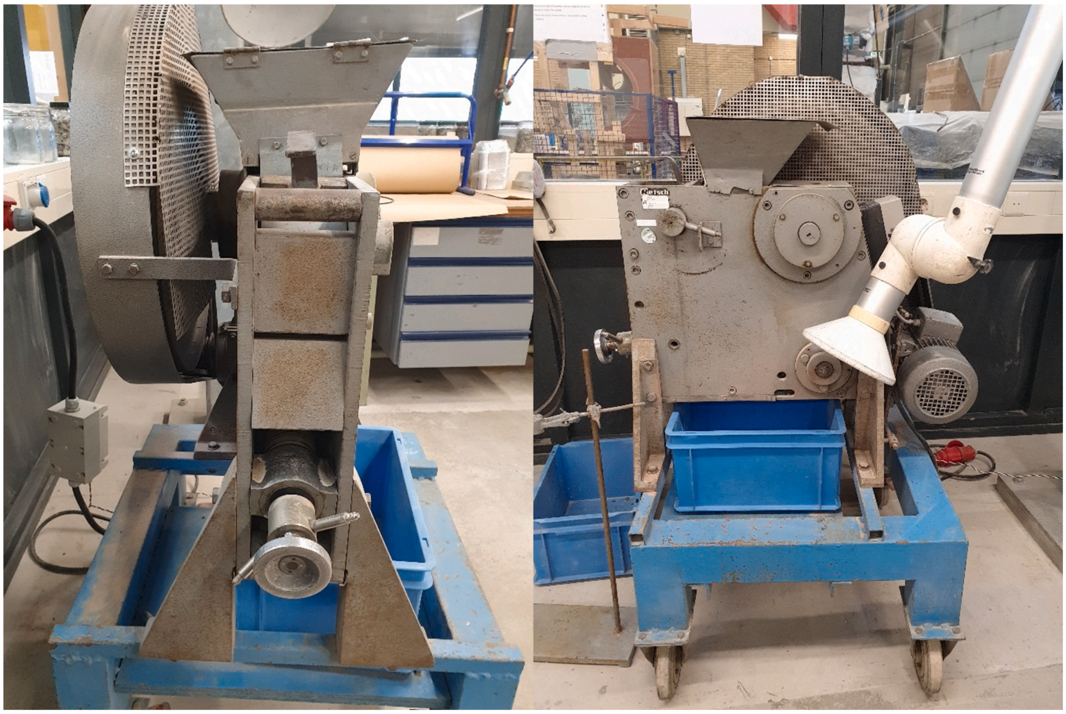

Fig. 1. Jaw crusher, front and lateral sides.

Fig. 2. Specimen preparation: concrete cubes before crushing, RCA after crushing batches C25 and C37.

the same weight. The mass of 48 specimens was, on average, 43.5 kg. After crushing, RCA were collected for further experiments, water absorption test and Los Angeles test, Fig. 2.

The technical characteristics of the jaw crusher are presented in Table 2. The granulation aperture size of the jaw crusher could be controlled in the range of 5 to 25 mm. The opening was set to a minimum value of 5 mm for the first batch (all concrete strength classes), and for the second batch, openings of 5 and 25 mm were used (only for concrete strength class C80/95).

The energy required for the crushing of individual specimens was obtained indirectly, by measuring electrical power. The 3-phase power meter measured the power used by the electric engine that drives the jaw crusher. For this purpose, the measuring device Thüringer Industrie Produkte (TIP) 41,600 energy consumption meter with maximum nominal voltage of 400 V (AC) and maximum current of 85 A was connected to the three phase conductors of the network. The system also contained a built-in current transformer that measured root-mean-square of instantaneous current values (rms) accurately in small time intervals. This is a special type of transformer in which the motor phase wire to be measured is led through the transformer. The rms value of the current is measured with a sample rate of 2000 measurements per second to measure rapid current changes. By using a current transformer, everything can be measured safely (galvanic isolation) without the meter being electrified.

The device measures the rms value of the current of one of the three phases (wires), which was enough considering that the motor is a three-phase motor and the current through the three phases is automatically balanced at all times. The electrical power (and also energy over time) is the voltage (230 V rms, constant) times the rms value of the current. The voltage was not measured because in the lab the voltage is very constant and by measuring the no-load power prior to a measurement, a correction is automatically applied if there is a small deviation.

The measuring system was connected to a computer where the data was collected using Mp3Prog software. The illustration of the system is shown in Fig. 3. The measured values were shown in the power – time graphs, and were recorded in the corresponding file.

For the calibration of the power meter system, the jaw crusher run for half an hour at no load (without concrete specimens) with the measurement in Mp3Prog. Before the measurement, the starting position on the large energy meter (3-phase AC, Fig. 3) was noted. After half an hour, the reading of the large energy meter was done again. The difference was the consumed energy. At that moment, the measurement in Mp3Prog was stopped. The calibration factors in Mp3Prog were 1.0 during this measurement and the system then gives a total measured energy. The calibration factor for the current measurement can then be determined by dividing the two values. After that, another check measurement was made to verify that it is correct.

Table 2
Operating details for the jaw crusher Bauknecht and powermeter TIP 41600.

Jaw crusher		Powermeter	
Nominal voltage (V)	380	Nominal voltage (V)	400
Nominal current (A)	3.7	Nominal current (A)	≤ 16
Frequency (Hz)	50	Frequency (Hz)	50
Inclination of moving jaw	35.9 deg		
Jaw speed (rpm)	1420		

Before commencing testing, the machine was running without any load in order to obtain stable state, Fig. 4. Stability is defined, for the tests, as the difference between the maximum and minimum idle power measured by sensors being no more than 2 Watt over a short period to make sure that the electricity supply is stable.

During testing the machine was filled with one cube at a time. The individual peaks in Fig. 5 represent the power consumed for crushing each cube. After crushing the cube, the power returned to the original level i.e. the idle power.

The energy used for crushing of the individual cubes equals to the total energy consumed minus the energy in the idle crusher from the moment of increasing load until the moment of the decrease of the power level to idle power. The principle is shown as a schematic in Fig. 6 where the energy consumed for the crushing is represented by the shaded area under the power-time curve. The mean value of idle power was used as a simplification to calculate the crushing energy. This was done to take into account small variations observed in the idle power measurements of the crusher (because of temperature effects and other effects). Crushing of one specimen requires more cycles of crushing i.e. approaching the moving jaw to fixed jaw (Fig. 3). Therefore, the total crushing energy E was calculated as a cumulative sum of area under the power-time curve with the use of numerical integration (Trapezoidal rule) after eliminating the mean idle power, as per Eq. (1):

$$E = \sum_{i=t_s}^{t_e} \frac{1}{2}\left[\left(P_i - P_{idle}\right) + \left(P_{i+1} - P_{idle}\right)\right] \bullet \left(t_{i+1} - t_i\right) \tag{1}$$

t_s is the starting time of crushing (s), t_e is the end time of crushing (s), P_i is the power at i-th point (Watt), t_i is the time at i-th measurement point (s) and P_{idle} is the average idle power (Watt).

3. Results

3.1. Crushing energy

The results for concrete properties are shown in Table 3. Cumulative crushing energy is plotted in Fig. 7 for different concrete strengths. It can

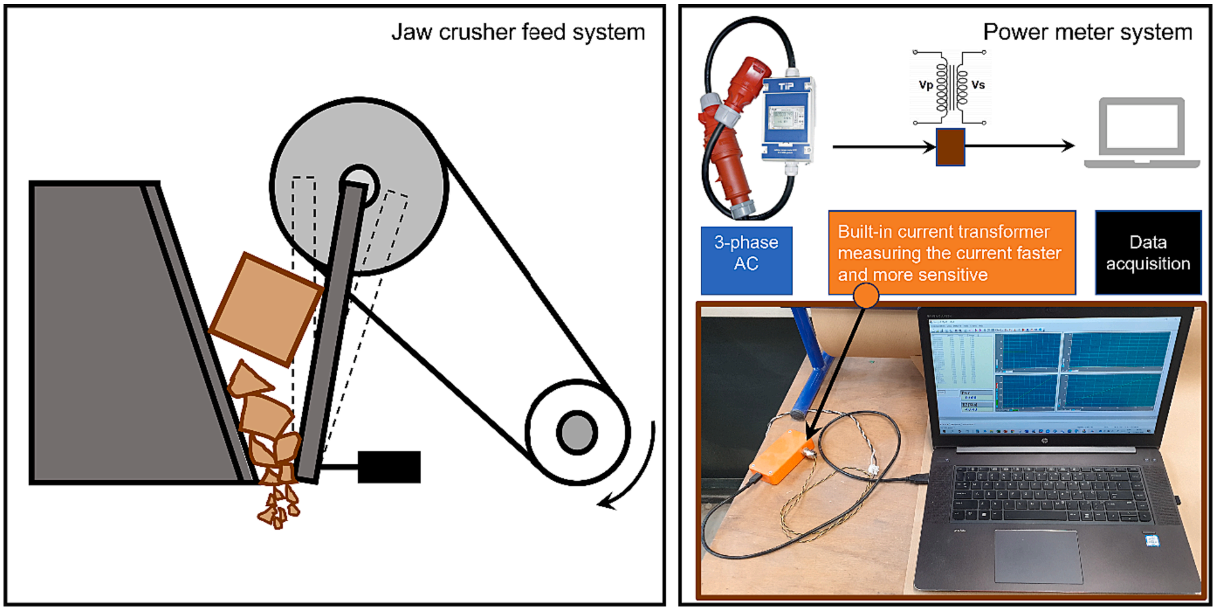

Fig. 3. Illustration of a jaw crusher showing a concrete specimen being crushed between fixed and reciprocating jaws (left), and experimental set-up for power meter system (right).

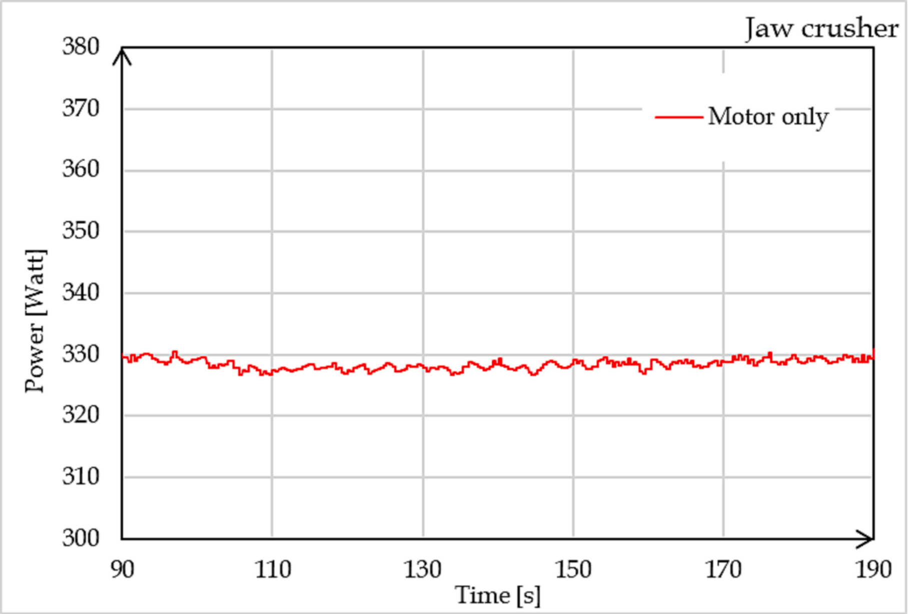

Fig. 4. Power during the steady state of the jaw crusher (no load).

be seen that the energy consumed for crushing the specimens (on the aperture size 25 mm), depends on the concrete compressive strength. Higher strength, 70 MPa and beyond, require higher energy for crushing compared to normal strength, i.e. below 70 MPa. The lowest energy consumption was obtained for concrete specimens with 28 MPa. The data obtained by indirect measurement of crushing energy for concrete specimens as described in this study are not available in literature. Korman et al. (Korman et al., 2015) measured power consumption of jaw crusher during crushing of rocks such as dolomite, limestone, spilite and diabase rocks and obtained similar trends, i.e higher the strength of the rock, higher the crushing energy. It is worthy to note that the crushing concrete specimens with 40 MPa took more time than concrete specimens with 55 MPa because of stucked specimens during their placement in the crusher.

A number of 48 major peaks corresponding to 48 samples, were consistently observed in power-time plots. A section of it is shown in Fig. 8 for concrete mixtures with 40 MPa and 90 MPa compressive strength for comparison. There are six major peaks. The relative sizes of the peaks are similar in general but can have variations in their exact proportions from specimen to specimen. The sizes (width and height) of these peaks are substantially smaller in concrete with 40 MPa than the corresponding peaks in concrete with 90 MPa. This is attributed to the denser cement matrix in high strength concrete, with a low w/c ratio. This is in line with finding that lowering the w/c ratio by 0.1 is more effective at minimizing threshold pore widths and total porosities than doubling the curing period for concrete (Cook and Hover, 1999). The observed fracture plane of the initial cubes in splitting test, where the crack occurred through the aggregates in concrete with 90 MPa,

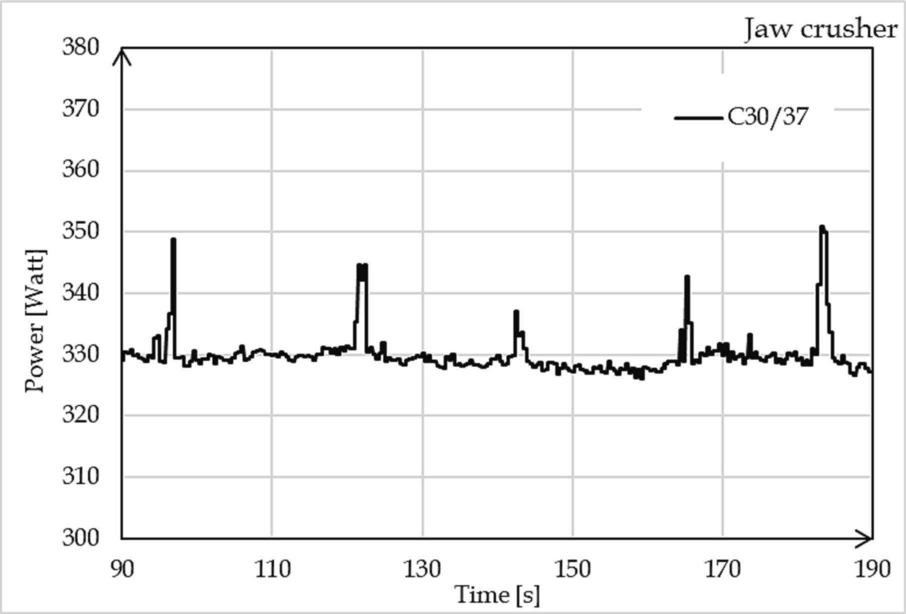

Fig. 5. Power consumption during crushing of individual specimens (concrete C30/37) as denoted by discrete peaks.

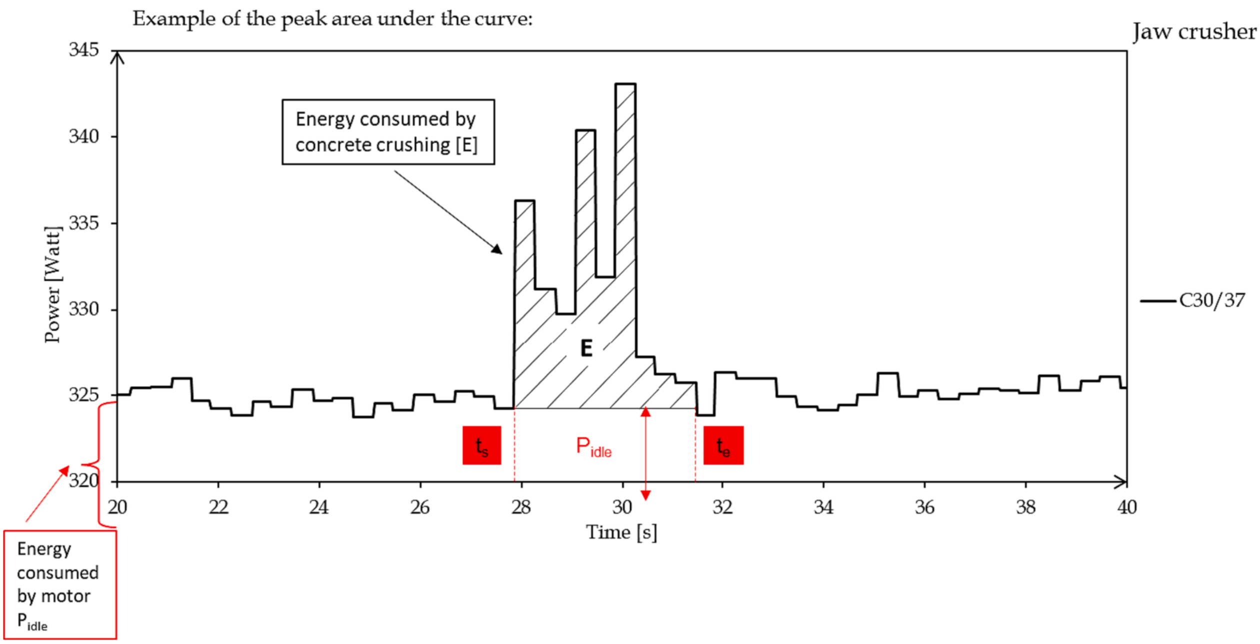

Fig. 6. Determination of cumulative energy used for concrete crushing.

Table 3
Concrete properties and crushing energy.

Target strength class	Type of gravel and sand	Bulk density [kg/m^3]28 days	Compressive strength [MPa]28 days	Tensilesplitting strength [MPa]28 days	Rebound number[-]28 days	UPV [m/s]	Cumulative concrete crushing energy [J]	Idle motor energy[J]
C20/25	Silicious	2344	28.1	3.0	31	4283	1314.82	297,000
C30/37		2353	39.6	4.3	38	4490	2680.56	
C35/45		2367	53	4.5	44	4601	2744.43	
C45/55		2376	61.4	4.3	55	4633	2981.16	
C55/67		2365	71	4.9	59	4647	3680.11	
C70/85		2376	80.1	5.6	63	4774	3857.62	
C80/95		2408	90	5.8	67	4828	4792.32	

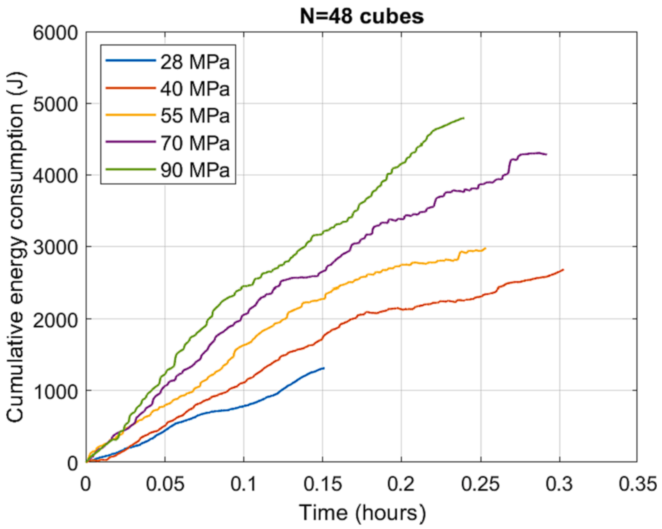

Fig. 7. Energy consumption for concrete crushing (the idle state is not included).

indicates stronger bond between aggregates and cement mortar than in concrete with 40 MPa (Fig. 9a,b). Fig. 9c,d shows also the shape of RCA sieved for Los Angeles test with a particle size between 10 and 14 mm obtained after dried sieveing. Shape of coarse RCA originating from two concrete strengths (40 MPa and 90 MPa) were different, angular aggregates were typical for crushed concrete with 90 MPa, whereas much less angular aggregates were obtained from crushed concrete with 40 MPa (Fig. 9c,d). This is in line with the more brittle nature of high strength concretes and stronger bond between aggregates and cement mortar.

While peaks for concrete crushing (C80/95) are within a range of 330 to 390 Watt, the contribution of the area of these peaks to area under the idle power (area under the 330 Watt) is very low, Fig. 10. In addition, the difference between the idle energy and concrete crushing energy values can be seen in Table 3. The idle energy was calculated as the integral idle energy during the actual concrete crushing excluding the pauses between the insertion of specimens. Based on this result, the motor energy consumption is much higher than the energy consumed for concrete crushing suggesting a very inefficient motor. This is logical since the laboratory jaw crusher is meant for crushing stronger materials, rocks and metals. In this regard, even high strength concrete, can be regarded as a soft material for such a powerful crusher. However, similar powerful crushers are also being used at the recycling plants, which motivates strongly to assess efficiency of such crushers especially for crushing concrete elements. Since the idle power depends on the crusher, a low power jaw crusher can be designed to crush concrete elements where the power requirements are lower as compared to rocks or metals. This could result in reducing the energy requirements and contribute towards improving the sustainability of the whole process.

3.2. *Effect of aperture size*

Feed gradation, crusher setting and crusher speed affect the energy consumption during rock crushing (Fladvad and Onnela, 2020). From a practical point of view, the question how energy consumption changes with reduction of aperture size on the jaw crusher in order to produce finer aggregates, while keeping all other crusher setings the same is relevant. Effect of aperture size on the energy consumption for crushing concrete with strength of 90 MPa is shown in Fig. 11. It can be seen that the crushing requires three times larger energy consumption when using smaller aperture size (5 vs. 25 mm) to process concrete specimens. This dependance of energy consumption on aperture size is largely important. If the energy consumption of a jaw crusher needs optimization then aperture size is the parameter to be under further investigation because the modification of aperture size on the jaw crusher leads to reduction of energy consumption. The results are also in line with findings in rocks comminition process. During the size reduction processes in a jaw crusher and rod mill for quartz ore (density 2800 kg/m^3) with density which is slightly higher than for normal concrete (2400 kg/m^3), crushing and grinding energy consumption decreases when coarser size fractions of the product are desired (Zeng and Forssberg, 1992).

3.3. *Properties of recycled concrete aggregates*

Table 4 shows results for LA and WA coefficients. Eight reference crushed natural aggregates types were selected for comparisons with eight classified RCA batches from this study and eight not-classified RCA batches produced from mixed concrete waste streams at several recycling plants in the Netherlands. To visualize the range for LA and WA, box-whisker plots for the various groups of aggregates are presented in Fig. 12.

The LA coefficient of natural aggregates ranged from 12 to 37, of classified RCA from 32 to 35.9, and of not classified RCA from 34 to 42. According to EN 12620:2002 + A1:2008 (EN, 2008); coarse aggregates for use in concrete mix should have a weight loss in the Los Angeles test

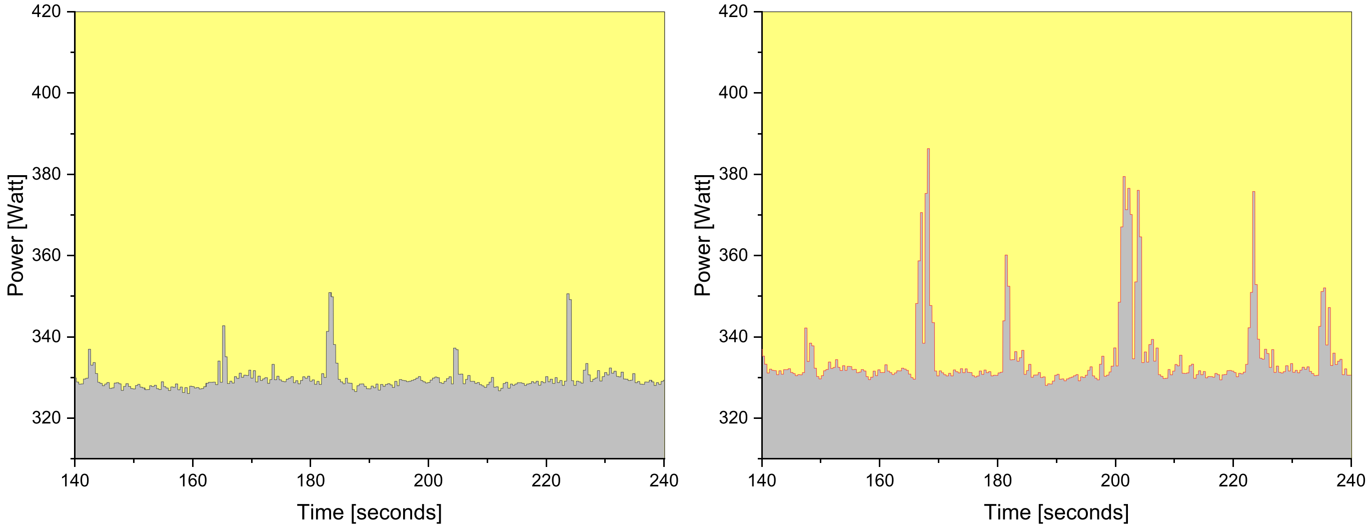

Fig. 8. Power-time graph for concretes with 28-days strength on left 40 MPa and on right 90 MPa.

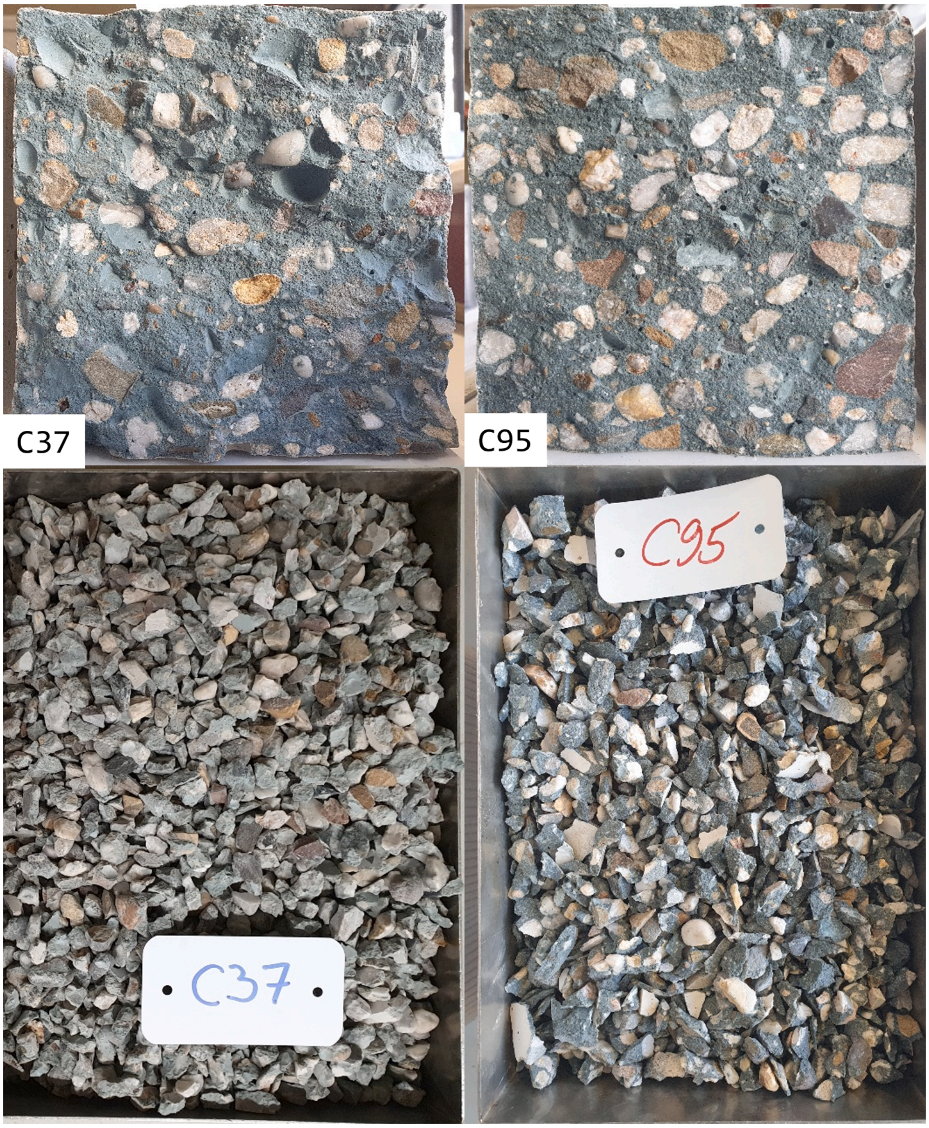

Fig. 9. Fracture in C30/37 and C80/95 specimens after tensile splitting strength test, and shape of RCA sieved for Los Angeles test with a particle size between 10 and 14 mm obtained after dried sieving.

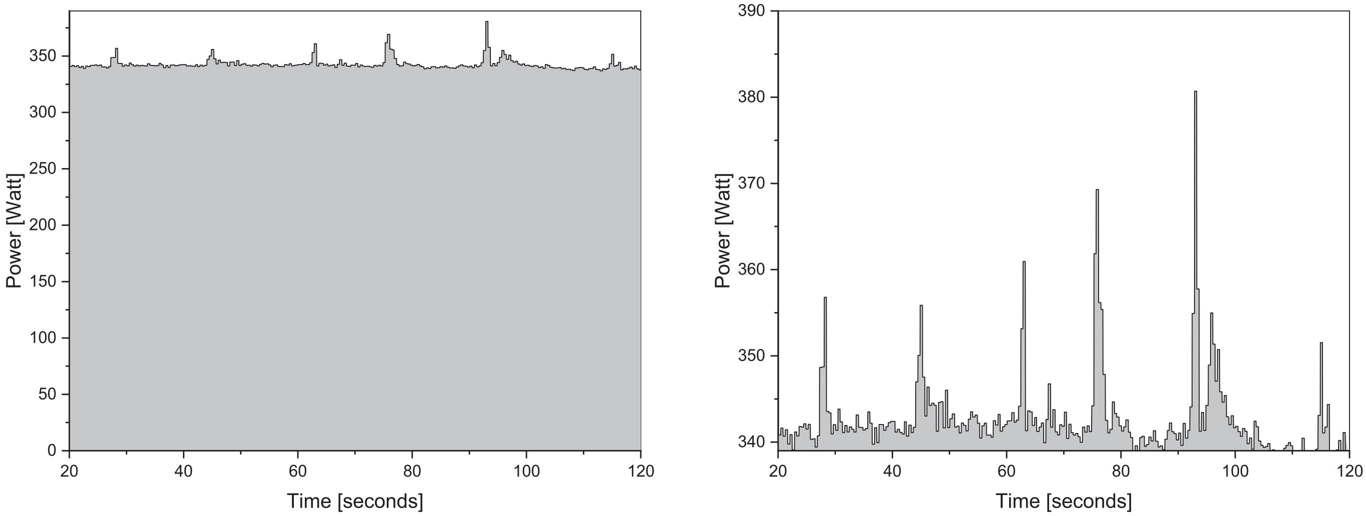

Fig. 10. (In)efficiency of the motor. The motor power is much higher than the power needed for concrete crushing.

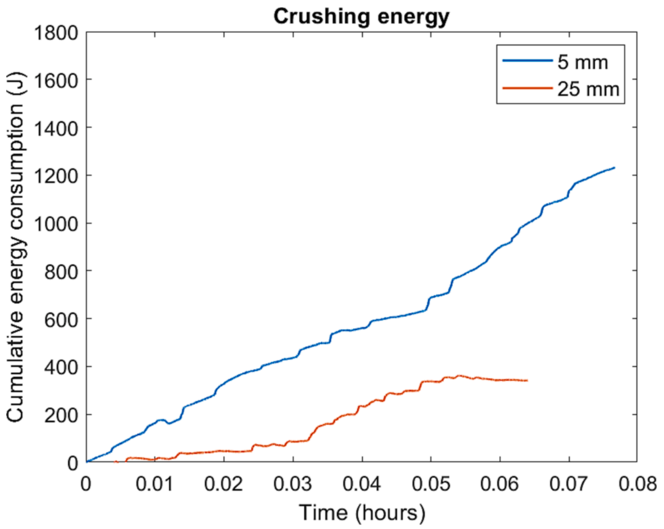

Fig. 11. Effect of aperture size (concrete C80/95) on the total energy consumption.

Table 4
LA and WA of reference aggregates, classified and not classified RCA.

Literature	Crushed coarse natural aggregates LA	WA	**This study**	Classified coarse RCA LA	WA	**Recycling plant**	Not-classified coarse RCA LA	WA
(Torgal and Castro-Gomes, 2006)	27	1.1	**C20/25**	34.5	3.8	**2022**	39	5.3
	24	2.1	**C30/37**	34.7	3.6	**2022**	42	5.1
	12	1.6	**C35/45**	32.3	3.3	**2019**	34	5.2
	22	1.0	**C45/55**	32	3.1	**2019**	37	5.6
	37	0.6	**C55/67**	34.2	3.0	**2019**	38	4.7
	18	2.2	**C70/85**	33.9	3.0	**2019**	34	4.9
	20	1.5	**C80/95**	33.0	2.9	**2018**	34	5.2
(Tunc and Alyamac, 2020)	25	0.9				**2017**	42	5.3

lower than 50 %. Accordingly, these three groups of aggregates (literature, this study, recycling plants) are in compliance with the standard in terms of abrasion strength, and they can be used as aggregates in concrete. Nevertheless, the higher the LA coefficient, the lower is the resistance of aggregates to fragmentation. For not classified RCA, higher LA coefficient might be caused due to weak physical interfaces between the cement mortar and aggregates in the parent concrete or due to presence of microcracks. Among aggregates, classified RCA were the least varying in terms of LA. This is due to the fact that the same type of the aggregates was used in all concrete mixtures for this study (river sand and gravel) and due to the good mechanical properties of this gravel material.

The average WA values varied from 1.3 for natural aggregates, 3.05 for classified RCA to 5.2 for not- classified RCA. WA values for natural aggregates were varied in a wide range in literature (ranging from 0.6 to 2.2). Regarding classified RCA, since the same type and amount of aggregates (volume) was used across the mixtures, the water absorption will strongly depend on the cement mortar quality. The water-to-cement ratio was ranging from 0.33 to 0.60 and the WA ranged from 2.9 to 3.8. This clearly indicates that 1 % higher WA is due to higher w/c ratio and consequently higher porosity in such concrete. It is expected that the w/c ratio would have greater impact on the WA of fine RCA since the finer aggregates contain more cement mortar and therefore, more dominant impact of w/c ratio.

4. Discussion

4.1. Compressive strength and crushing energy

Investigation was performed on the efficiency of energy use by comminution of several concrete strength classes with a lab-scale jaw crusher as a test case. The study showed that the lab-scale jaw crusher consumes significantly higher enegy in operation (idle state) than in the actual crushing of concrete. Such studies were not performed earlier for concrete crushing. Based on this study, it can be concluded that the lab-scale jaw crushers operate heavily below their capacities. Further, it can be also inferred that industrial jaw crushers which generally have higher crushing capacities will result in even more inefficient energy consumption as compared to the lab-scale jaw crushers. These results are also in line with previous research performed on granite rocks with industrial jaw crushers (Numbi et al., 2014). The traditional crushers used at concrete recycling plants are crushers for rocks, and they need to be largely optimized for concrete crushing. This is specifically important to be studied since the concrete recycling will be utilized to the maximum by 2050.

The statistical analysis of the results demonstrated the empirical dependence of crushing energy on mechanical properties of concrete classes. From the statistical analysis it can be concluded that the crushing energy depends mainly on the compressive strength (Table 5). Table 5 shows also that the UPV and tensile strength can be strongly correlated to the crushing energy values. It can be also seen that the hardness and bulk density can be correlated to the crushing energy, but the effect is minor.

Since the comminution for the jaw crusher is based on squeezing specimens in progressively narrowing space between opposed surfaces (Cleary and Sinnott, 2015), it is logical that the compressive strength has the greatest impact on crushing energy. Future studies are needed regarding the role of different types of crushers than jaw crusher concerning energy consumption for crushing. Furthermore, as the reducing size process for RCA depends on different performance characteristics of the crusher as well as various properties of the feeding material, future work has to properly combine these parameters to achieve a low energy consumption while maintaining a high product quality for a sustainable production process. Based on the results of the impact of aperture size on the energy consumption (Fig. 11), the most valuable step to reduce energy consumption is to properly design comminution with regard to the required aggregate size regardless of the applied technology to realize the crushing process.

The use of inefficient crushers may lead to many difficulties as the process quality may mainly depend on the quality of the crushers to feed the downstream process with product in an acceptable reduced size (Svensson and Steer, 1990).

4.2. Classification of recycled concrete aggregates

With this study it is shown that strength of concrete is a primary property for concrete quality assessment to assist selective demolition of concrete structures, since energy consumption for crushing is strongly dependent on it. Furthermore, water absorption of RCA is shown to be also dependent on concrete strength.

Selective demolition (and recycling in this study) leads to the homogeneity in the properties and high-quality of RCA due to known properties of the parent concrete. An earlier study proposed classification of fine RCA considering density and also relation of density to the amount of adhered mortar (AM < 10 % (Class A), 10 % < AM < 35 %

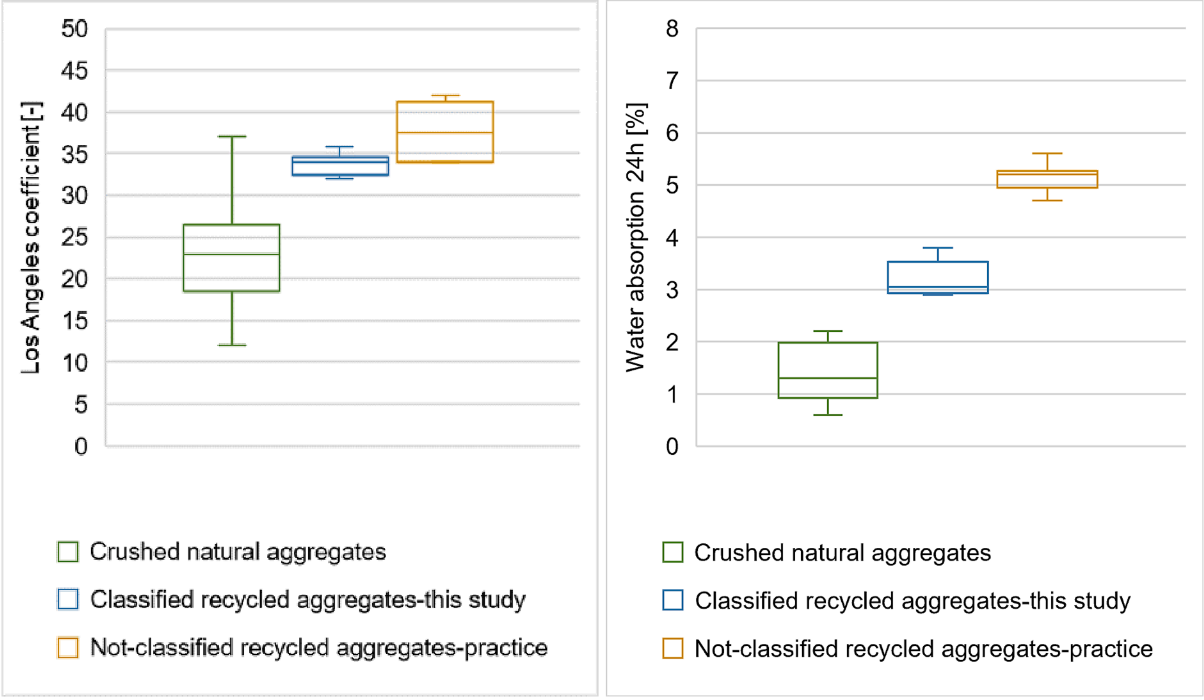

Fig. 12. The box-whisker plots of the LA coefficient left and WA right for coarse aggregates. The bar within the rectangle indicates the median value.

Table 5
Dependence of crushing energy on mechanical properties of concretes.

Mechanical properties	Regression equation	CoD
Compressive strength	$Ec = 48.448f_c + 219.48$	$R^2 = 0.933$
Bulk density	$Ec = 47.7D - 109900$	$R^2 = 0.786$
Tensile strength	$Ec = 1015f_{ct} - 1672.7$	$R^2 = 0.904$
Hardness (Schmidt)	$Ec = 76.618H - 760.43$	$R^2 = 0.886$
UPV	$Ec = 5.817v - 23658$	$R^2 = 0.919$

(class B), 35 % < AM < 55 % (Class C), AM > 55 % (Class D)). This classification has been the very first step in the quality assessment of fine RCA from unknown parent concrete after recycling (Rangel et al., 2019). In this study, classification of coarse RCA is proposed (Fig. 13) which can be used only if the strength of the parent concrete is known. Classification criteria are 24 h water absorption of coarse RCA, their parent concrete strength and energy of parent concrete crushing.

Currently, RCA are the least homogeneous in mechanical, chemical, and composition properties, since they originate from many different concrete waste sources. Their water absorption is higher than 4.7 % (Table 4) and it is, therefore, challenging to achieve good hardened properties of new concrete with such aggregates (Mylonas, 2021).

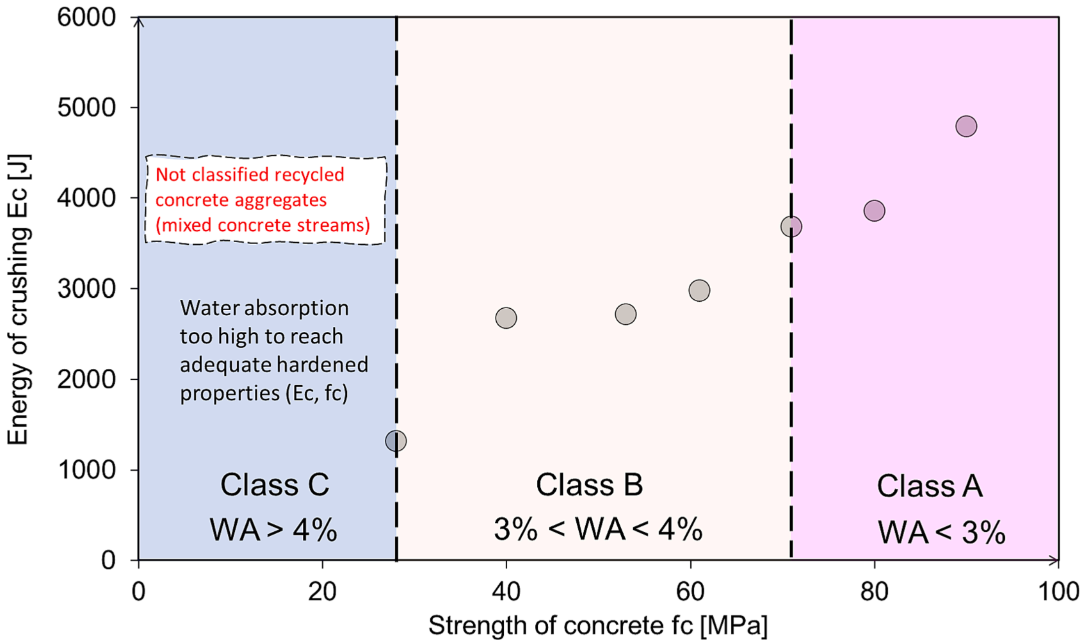

Fig. 13. Classification of coarse RCA as a function of their 24 h water absorption, their parent concrete strength and energy of parent concrete crushing.

Consequently, their quality belongs to class C, as illustrated in Fig. 13. Based on this study, and in relation to WA and energy consumption, two more classes are defined, class A and class B for coarse RCA with WA lower than 3 % and between 3 % and 4 %, also in line with results for crushing energy. It is important to note that for all three properties (strength, WA and energy of crushing) a significant amount of material was used to make classification precise. Only for crushing energy, the amount of material used was 43.5 kg and for WA, on average 10 kg of aggregates was used per batch. By evaluating fundamental parameters such as the compressive strength of parent concrete and WA of RCA, it is shown that selective demolition is largely important and much effort should be invested into non destructive quality evaluation of concrete structures before demolition.

5. Conclusions

In this investigation, the aim was to assess the influence of different concrete properties on the energy consumption for concrete crushing and on the properties of RCA in the context of selective demolition. The major findings are:

(1) A measuring system was developed which enables an indirect measurement of power of the laboratory jaw crusher electromotor. The crushing energy was determined based on the difference of the energy used in crushing specimens and energy used by the idle jaw crusher.
(2) To the authors knowledge; this is the first time that the energy consumption for concrete comminution with the jaw crusher has been tested and the first time that the compressive strength has been shown to exert such an important influence on energy consumption. The energy used for crushing is higher for higher strength concrete classes than for normal strength concrete classes. This justifies the use of strength testing prior to selective demolition of concrete structures. The UPV and tensile strength can also significantly correlate to the crushing energy. This can be advantageous to estimate the crushing energy non-destructively thereby, simplifying the selective recycling process significantly. The hardness and bulk density showed to have a minor impact on the crushing energy.
(3) The crushing requires significantly higher energy consumption when using smaller aperture size (5 mm instead of 25 mm) to process concrete specimens.
(4) The LA coefficients of coarse RCA are very similar for all the types of crushed concretes; this is due to the use of the same type of aggregates in all concrete mixtures and to the good mechanical performance of the original gravel material.
(5) The WA of coarse RCA is shown to be dependent on the strength of the parent concrete. It should be used, together with compressive strength of parent concrete as a parameter for classification of RCA from low to high quality. The low water absorption of coarse RCA can be obtained also by an ordinary jaw crusher if the input concrete is recycled from one source and it has higher strength than 70 MPa.
(6) Based on selective demolition, energy consumption in recycling can be controlled because of known material input properties. Furthermore, selective demolition (and recycling in this study) leads to the homogeneity in the properties and high-quality of RCA due to known properties of the parent concrete. The concrete compressive strength can assist recyclers in the selection of appropriate concrete crushing equipment and contribute to a sustainable production process.
(7) Future studies are needed regarding the role of different crusher types than jaw crusher concerning energy consumption for concrete recycling. Furthermore, recycling of other concrete types than in this study, such as fiber reinforced concrete, light and heavy weight concretes, should be considered.
(8) The study did not evaluate the use of other energy sources on performance of lab-scale jaw crusher. In spite of its limitations, the study certainly adds to our understanding of the energy efficiency of a jaw crusher when electricity is used as the power source for concrete crushing. Regardless the source of energy it is usually the case that more energy would be used than it is needed. Future studies are needed to address performance of other energy sources (a variety of carbon fuels).

CRediT authorship contribution statement

Marija Nedeljković: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Ameya Kamat:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Patrick Holthuizen:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Nikola Tošić:** Funding acquisition, Writing – original draft, Writing – review & editing. **Erik Schlangen:** Funding acquisition, Project administration, Writing – review & editing. **Sonja Fennis:** Funding acquisition, Writing – review & editing.

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.

Data availability

All data are presented in the manuscript.

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