



Using a modified jaw crusher for improved concrete recycling: energy consumption and separation efficiency

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ABSTRACT

Closing the material loop of the concrete industry will reduce material consumption, waste generation, and lower CO₂ emissions. Although the use of recycled concrete aggregates (RCA) in new concrete mixtures has been demonstrated, little research has been published on techniques improving the liberation of hydrated cement paste (HCP) during concrete recycling. Using a modified crusher designed for HCP liberation, this paper investigates the impact of material feed, crushing frequency, and width of the closed-side settings on the material output and energy consumption. It was shown that factors increasing friction and abrasion promote HCP liberation and generate cleaner aggregates, but also increase the energy consumption compared to a conventional jaw crusher. When accounting for the increase in surface area, the energy consumption of the modified crusher and the conventional jaw crusher became comparable.

1. Introduction

With an annual waste production of 2.2 billion tonnes, the construction industry is responsible for 40% of the global solid waste generation, of which ~21% is concrete rubble (Gálvez-Martos and Istrate, 2020; Soto-Paz et al., 2023). As the concrete sector is further accountable for 8% of the global CO₂ emissions, it faces increasing pressure to reduce its environmental footprint. Improving the circularity of cement and concrete could reduce emissions by up to 50% while providing economic benefits (Goddin et al., 2019; Liu et al., 2024). However, current global recycling rates vary between 20 and 99%, where most recycling is limited by the quality of the recycled concrete aggregates (RCA), leading to low-end applications (Gálvez-Martos et al., 2018; Villoria-Sáez et al., 2020).

The reduced quality of the RCA can be ascribed to the presence of residual hydrated cement paste (HCP), which decreases the strength and increases the water absorption, making its removal essential in the recycling of RCA (Sri Ravindrarajah et al., 1987; B. Zhang et al., 2022; C. Zhang et al., 2022). Separation of the HCP further enables the development of reactive fillers by carbonating the main component of the HCP: the calcium-silicate-hydrate (C-S-H) gel (Skocek et al., 2020; Teune et al., 2023). In this process, CO₂ mineralizes with the calcium in the HCP to form CaCO₃, while generating pozzolanic silica. Improved separation of the HCP from RCA could thus enhance recycling rates,

reduce cement consumption, and lower CO₂ emissions.

Although the benefits are clear, the development of new mechanical separation technologies reported in scientific literature is limited. To the best of the authors' knowledge, the last two reported developments included the Smart Crusher in 2013 and the advanced dry recovery technology in 2020 (Florea and Brouwers, 2013; Gebremariam et al., 2020; Zhang et al., 2019). The low energy efficiency of jaw crushers makes it difficult to model the crushing dynamics as a significant amount of energy is lost on sound and heat during the crushing, thereby complicating the development of new crushers (Legendre and Zevenhoven, 2014; Momber, 2003; Yan and Eaton, 1994). Moreover, parameters like crushing frequency, width of the closed-side setting (CSS), and material size affect both the crushing dynamics and the energy consumption, making it difficult to study the impact of only one parameter (Fladvad and Onnela, 2020; Gupta and Yan, 2016). Similarly, differences in concrete composition strongly impact the strength and fracture behavior, separation efficiency, and the energy consumption (Korman et al., 2015; Momber, 2002; Nedeljković et al., 2023; Olaleye, 2010; Refahi et al., 2010). Thus far, very limited systematic research exists that investigates the effect of these parameters on the crushing dynamics in the field of concrete recycling, and no research has been found that further explores the impact of these parameters on the liberation of HCP.

Yet, as HCP is the weakest component in concrete, selective crushing

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of the HCP should theoretically improve the energy efficiency, as less energy is required to crush HCP (Hearing, 1997; Jebli et al., 2018; Khalilpour et al., 2019). Previous work demonstrated that energy monitoring of a crusher provides information about the brittleness and strength of the crushed material, but no relation to the separation efficiency has been established thus far (Momber, 2002; Nedeljković et al., 2023).

In this research, the crushing parameters of a modified jaw crusher are studied to improve HCP liberation. The impact of the crushing frequency, width of the CSS, and scalping of the material feed in relation to the throughput, composition, and quantity of the HCP, and energy consumption is studied. This work thus provides an overview of the factors impacting concrete recycling efficiency and thereby creates a stepping-stone to improve future (concrete) recycling techniques.

2. Materials and methods

2.1. Crushing

The modified crusher (SC, Fig. 1) was based on the Smart Crusher and the patented model of D. Eerland, both designed to enhance the liberation of cement paste (Eerland, 2021; Florea and Brouwers, 2013; Schenk, 2014). The obstruction plate prevents the material from falling through, which allows a more parallel alignment of the jaws. Both the crushing frequency and the CSS width could be adjusted. For comparison, a laboratory jaw crusher (JC, Retsch BB-2), fitted with waved manganese steel jaws, was used. The experimental design is shown in Table 1, where the names refer to the crusher type (SC or JC), experiment number, material feed size (if scalped), CSS width, and the crushing frequency.

For each experiment, 40 kg of mixed concrete waste was manually added to ensure constant choke feeding. The energy consumption was measured using a Counttec EC332C mobile kWh-meter connected to a Squirrel 2040-4F logger, which registered the power consumption every 30 s, with a sensitivity of 1000 pulses per kWh.

Concrete mix M1 was supplied by Eindhoven University of Technology, and mix M2 was provided by the company CircularMineral. Both materials were industrially pre-crushed and stripped of rebar and other contaminants. The composition of M1 is provided in the supplementary information (S.I.) Fig. A1, and the particle size distribution is shown in Fig. 2 (Paragraph 3.1).

In Experiment 3, a CEM-I paste was used as reference material (SC3

CEMI 48/130). The paste was cured in water (180 d) and subsequently crushed, dried, and sieved to 64-32 mm.

2.2. Particle size distribution

The particle size distribution (PSD) was determined by dry sieving the material following EN 933-1 and EN 933-2 using a sieve tower (Retsch AS 450) with increasing mesh sizes from 63 μm to 64 mm (CEN, 2012, 1995). In this paper, aggregate sizes are reported using the lower sieve size; thus, “32 mm” refers to the 64-32 mm sieve fraction.

2.3. XRF

Materials were milled for 15 min at 300 rpm in a Fritsch Pulverisette 5 planetary ball mill fitted with zirconium oxide bowls, 20 mm balls. Powder samples ($<125 \mu\text{m}$) were heated to 1000 °C for 12 h before analysis, to determine the loss on ignition (LOI). Subsequently, 1 g of sample was mixed with 9 g of lithium tetraborate (67,00% $\text{Li}_2\text{B}_4\text{O}_7$ – 33,00% LiBO_2 , Malvern PANalytical), 300 μl of lithium iodide (5M, Merck), and fused in a borate fluxer oven (Claisse leNeo, 1065 °C for 29 min) to produce a bead. XRF analysis was performed using the standardless OMNIAN method (Epsilon 3, Malvern PANalytical, Netherlands)

2.4. Quantitative XRD

The samples were mixed with 10 wt% Si, milled for 15 min (McCrone micronizing mill, Retsch, Germany), and measured (D4, Bruker, Germany) (Co tube, $K_{\alpha 1}$ 1.7901 [Å], $K_{\alpha 2}$ 1.7929 [Å], step size 0.018 2 θ , range 10-90 2 θ). Mineral phases were identified with X'Pert HighScore Plus 2.2. (PANalytical) using the ICDD PDF-2 database, and quantified using the TOPAS software (version 4.2, Bruker).

3. Results and discussion

3.1. Experiment 1: CSS width and crushing frequency

3.1.1. PSD analysis

Using a reported preselected setting (SC1 48/130), the liberation of the HCP from the recycled concrete was studied by changing the width of the CSS and crushing frequency (Van De Wouw et al., 2016). The PSDs of each experiment are shown in Fig. 2. Using the 80% passing size of the

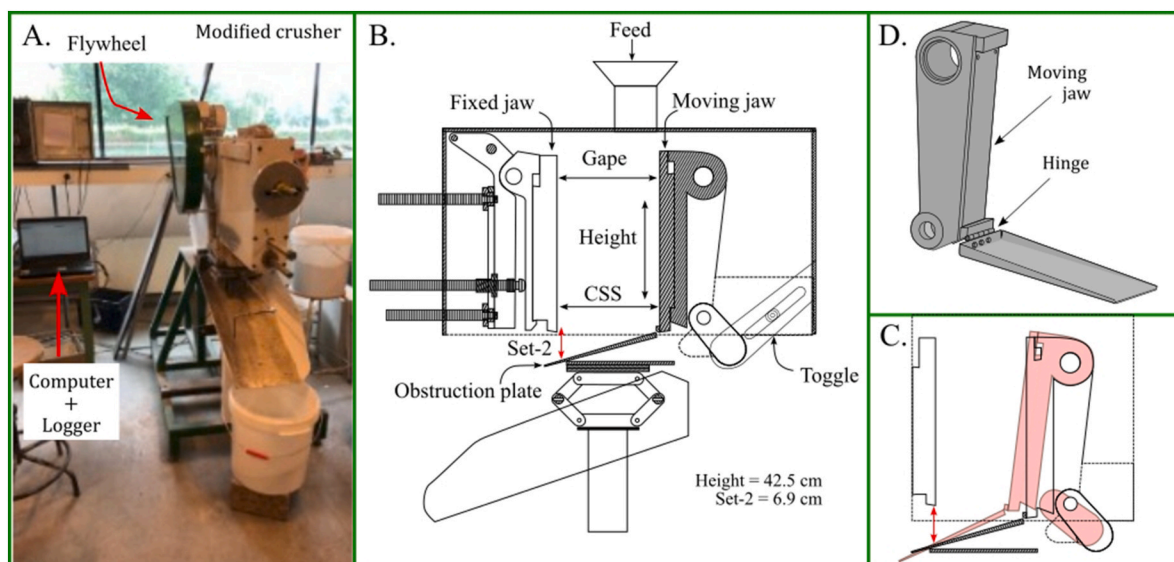
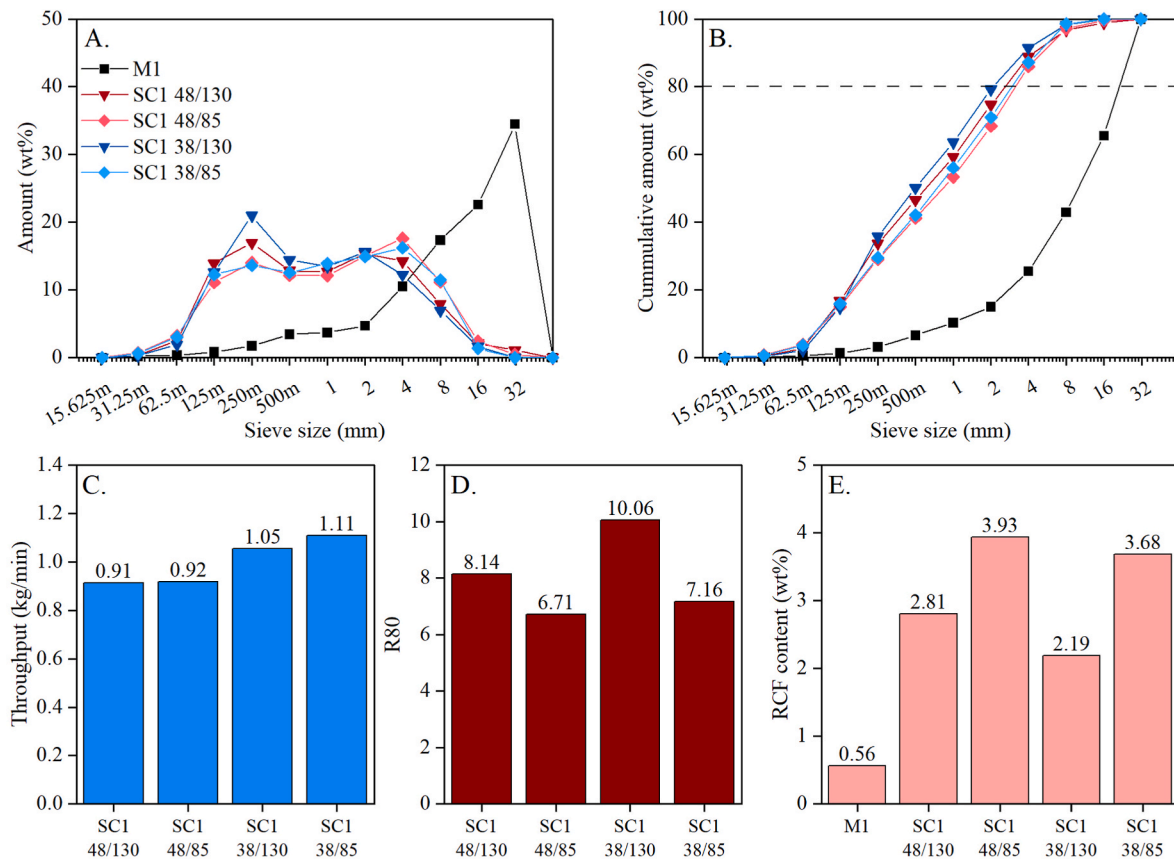


Fig. 1. Photo (A.) and schematic (B.) of the modified jaw crusher (C.) and its movement during crushing (red), and a technical drawing of the obstruction plate (D.).

Table 1

Experimental design. The fraction size indicates the size of the lower sieve size according to EN 933-1 and EN 933-2.

Experiment 1: CSS width versus speed					
	SC1 48/130		SC1 48/85		SC1 38/130
Gape - CSS (mm)	70 - 48		70 – 48		55 - 38
Speed (rpm)	130		85		130
Concrete mix	M1		M1		M1
Fraction (mm)	Complete range of M1		Complete range of M1		Complete range of M1
Experiment 2: Speed versus size of material feed					
	SC2 32 50/270	SC2 32 50/135	SC2 32-16 50/270	SC2 32-16 50/135	JC 32 50/270
Gape - CSS (mm)	73 - 50	73 – 50	73 – 50	73 – 50	100 - 50
Speed (rpm)	270	135	270	135	270
Concrete mix	M2	M2	M2	M2	M2
Fraction (mm)	100%	100%	50/50 wt%	50/50 wt%	100%
	32 mm	32 mm	32 + 16 mm	32 + 16 mm	32 mm
Experiment 3: Packing of the feed					
	SC3 32 48/130		SC3 32-8 48/130		SC3 32-8-2 48/130
Gape - CSS (mm)	70 - 48		70 – 48		70 – 48
Speed (rpm)	130		130		130
Concrete mix	M1		M1		CEM-I
Fraction (mm)	100%		50/50 wt%		33/33/33 wt%
	32 mm		32 + 8 mm		32 + 8 + 2 mm
					32 mm

**Fig. 2.** Frequency (A.) and cumulative (B.) particle size distribution of the material feed (M1) and the crushed output of Experiment 1 (Table 1), as well as the measured throughput (C.), calculated R_{80} according to Eq. (1) (D.), and RCF content (E.). The 80% passing is indicated with a dashed line in (B.).

feed and product (F_{80} and P_{80}), the R_{80} was calculated according to (Gupta and Yan, 2016):

$$R_{80} = \frac{F_{80}}{P_{80}} \quad (1)$$

As shown in Fig. 2, a reduction in crushing frequency causes a decrease in the amount of material below 500 μm , irrespective of the CSS width. Simultaneously, the R_{80} decreases with decreasing crushing frequency, which aligns with the work of Fladvad and Onnela (2020),

who found that a lower crusher frequency led to a material output with a steeper PSD curve. Interestingly, the throughput decreases slightly with increasing frequency, which suggests the material is prevented from falling through at this specific frequency (Johansson et al., 2017). Similarly, the more rapid horizontal and upward displacement of the obstruction plate (Fig. 1C.) could prevent the material from falling through.

Decreasing the CSS width leads to an increase in the amount of material below 250 µm at 130 rpm, but does not impact the PSD at 85 rpm. Simultaneously, the R_{80} increases from 8.14 to 10.06 at 130 rpm and remains relatively low (6.71 and 7.16) at 85 rpm. For both frequencies, the decrease in CSS width increases the throughput, which is likely caused by the stronger size reduction, which allows the material to be pushed out of the crusher more easily, aligning with previous works (Deniz, 2011, 2014).

Although the R_{80} value reflects the size reduction of the larger aggregates, it does not provide information about the quality of the separation. As shown in previous works, the recycled concrete fines (RCF) below 125 µm are rich in HCP and can be used to assess the separation quality, which was confirmed experimentally (S.I. Fig. A2) (Florea and Brouwers, 2013; Nedeljković et al., 2021). As shown in Fig. 2, the amount of RCF increases with increasing CSS width and decreasing crushing frequency, thus opposing the trend in R_{80} value. This suggests that RCFs are generated by frictional forces that abrade the more brittle HCP while preserving the larger aggregates.

3.1.2. Composition of the RCF

As HCP is calcium-rich, and most Dutch concrete is made with quartz-rich (i.e., silica-rich) alluvial aggregates, XRF analysis can be used to estimate the separation efficiency (Florea and Brouwers, 2013; Nedeljković et al., 2021). As shown in Table 2, the highest (27.93 wt%) and lowest (23.15 wt%) CaO content is found in the RCF of SC1 48/130 and SC1 38/130, respectively. Simultaneously, the SiO_2 content increases from 38.45 wt% to 50.40 wt%. At 85 rpm, both the CaO and SiO_2 content of the RCF remain constant irrespective of the CSS width.

As the largest differences in SiO_2 and CaO content were measured for the RCF generated at 130 rpm, both samples were analyzed with Q-XRD. As shown in Table 2, the decrease in CSS width increases the quartz content, which confirms that the increase in SiO_2 content is due to aggregate chipping. As a decrease in CSS width at 85 rpm did not impact the SiO_2 content, the increase in SiO_2 content at 130 rpm is likely due to aggregate chipping caused by the more frequent crushing impact. Based on the XRF and Q-XRD results, the HCP content was estimated according to:

Table 2

XRF and Q-XRD analysis of the RCF from Experiment 1. 'Other' phases include the calcium-free feldspar phases and magnetite. The HCP content is calculated according to Eq. (2) and Eq. (3).

		SC1 48/ 130	SC1 48/ 85	SC1 38/ 130	SC1 38/ 85
XRF (wt%)					
CaO		27.93	25.19	23.15	25.30
SiO_2		38.45	45.83	50.40	45.72
Other		15.26	13.20	11.90	12.07
LOI		18.35	15.78	14.55	16.91
XRD (wt%)					
Quartz	(SiO_2)	28.8 ± 0.4		41.5 ± 0.6	
Calcite + vaterite	(CaCO_3)	17.6 ± 0.6		14.6 ± 0.7	
Portlandite	(Ca(OH)_2)	1.8 ± 0.2		1.1 ± 0.2	
C_2S	($2\text{CaO} \cdot \text{SiO}_2$)	2.3 ± 0.5		2.4 ± 0.6	
Amorphous		37.7 ± 1.2		29.3 ± 1.6	
Other		11.9 ± 0.6		11.1 ± 0.8	
Wt% HCP		29.27		24.20	

$$\text{wt\% CaO}^{\text{HCP}} = \left((\text{wt\%}^{\text{XRF}} \text{CaO}) - \frac{\text{wt\%}^{\text{XRD}} \text{CaCO}_3 \cdot \text{Mm}_{\text{CaO}}}{\text{Mm}_{\text{CaCO}_3}} - \frac{\text{wt\%}^{\text{XRD}} \text{Ca(OH)}_2 \cdot \text{Mm}_{\text{CaO}}}{\text{Mm}_{\text{Ca(OH)}_2}} - \frac{\text{wt\%}^{\text{XRD}} \text{C}_2\text{S} \cdot 2\text{Mm}_{\text{CaO}}}{\text{Mm}_{\text{C}_2\text{S}}} \right) \quad (2)$$

$$\text{wt\% HCP} = (\text{wt\% CaO})^{\text{HCP}} + \frac{(\text{wt\% CaO})^{\text{HCP}} \cdot \text{mM}_{\text{SiO}_2}}{1.7 \cdot \text{mM}_{\text{CaO}}} + \frac{(\text{wt\% CaO})^{\text{HCP}} \cdot 2.6 \cdot \text{mM}_{\text{H}_2\text{O}}}{1.7 \cdot \text{mM}_{\text{CaO}}} \quad (3)$$

where Mm is the molar mass, $\text{wt\%}^{\text{XRD/XRF}}$ is the wt% according to the Q-XRD/XRF results, and a C-S-H gel composition of $(\text{CaO})_{1.7} \cdot \text{SiO}_2 \cdot (\text{H}_2\text{O})_{2.6}$ is assumed (Bergold et al., 2013). As shown in Table 2, the CaO content aligns well with the HCP content, thus confirming that the CaO content is a good indicator of the HCP removal.

3.1.3. Gates-Gaudin-Schuhmann and Rosin-Rammler modeling

Although the R_{80} is commonly used in the field of comminution, the R_{80} only includes the 80% passing size, and thus does not provide information on the PSD of the material. As PSD modeling can provide information on the crushing dynamics, the PSDs were modeled with the Gates-Gaudin-Schuhmann model:

$$R(d)^{\text{GGS}} = \left(\frac{d}{d_{\text{max}}} \right)^n \quad (4)$$

and the Rosin-Rammler model:

$$R(d)^{\text{RR}} = 1 - \exp \left[- \left(\frac{d}{d'} \right)^n \right] \quad (5)$$

where $R(d)$ is the cumulative passing percentage of sieve size d . Both models are commonly used to model the material output of jaw crushers (Gupta and Yan, 2016; Momber, 2002; Stamboliadis, 2002; Wills and Finch, 2016). Rearrangement of both formulas allows for the derivation of the linear formulas:

$$\log(R) = n^{\text{GGS}} \log(d) - n^{\text{GGS}} \log(d_{\text{max}}) \quad (6)$$

$$\ln[-\ln(1-R)] = n^{\text{RR}} \ln(d) - n^{\text{RR}} \ln(d') \quad (7)$$

where the distribution modulus (n), theoretical maximum passing size (d_{max}), and 63.2% passing size (d') can be derived by fitting a linear function in the (linear) middle part of the data (20-80% passing range of the PSD). This range best reflects the change in crushing mode, as the tails are often more prone to errors. The n^{GGS} reflects the fragmentation behavior, where a decrease in n^{GGS} value reflects a flattening of the PSD curve, meaning more fine material and less coarse material is retained. The n^{RR} reflects the spread of the particles, where an increase in n^{RR} reflects a narrowing of the PSD range, i.e., more uniform particles. For both models, a fitting range between 500 µm and 8 mm is used to derive the fitting parameters, as shown in Fig. 3 and tabulated in Table 3.

As shown in Table 3, the variation in n^{GGS} values (0.34-0.39) is larger than the variation in n^{RR} values (0.60-0.63), meaning that the slope of the PSDs varies more than the spread of the particle sizes. This aligns with the PSDs in Fig. 2, where the overall size range remains similar, but the amount of material below 500 µm and above 4 mm changes depending on the crushing conditions. Increasing the crushing frequency from 85 rpm to 130 rpm leads to a decrease of the n^{GGS} value from 0.39 to 0.34-0.35, meaning more fine material is liberated. Similarly, the n^{RR} value decreases slightly from 0.61 to 0.63 to 0.60-0.61 with increasing crushing frequency, reflecting an increase in the PSD spread.

Contrary to the crushing frequency, the increase in CSS width barely impacts the n^{GGS} values but instead increases the d_{max} value. This

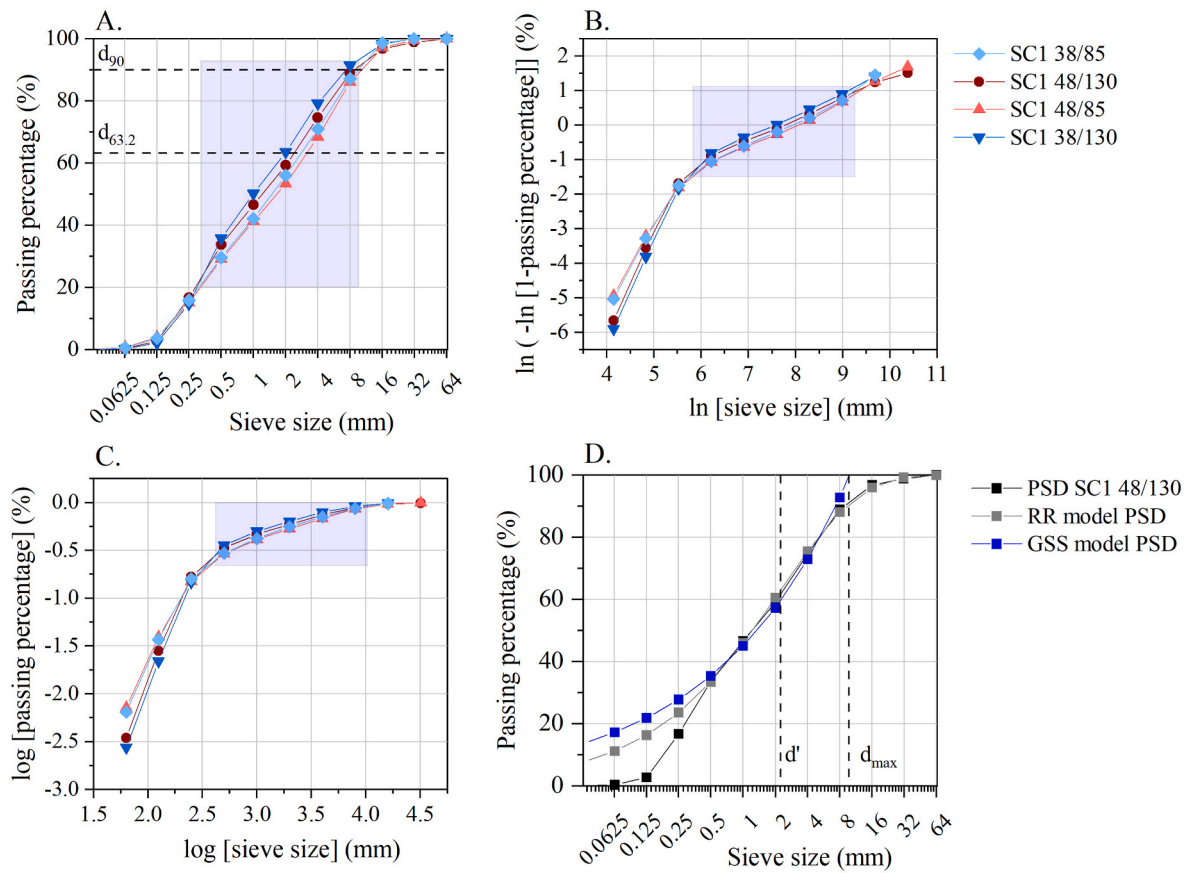


Fig. 3. A. Cumulative passing percentage of the material output of Experiment 1, B. Rosin-Rammler distribution of the material output, C. Gates-Gaudin-Schumann distribution of the material output, and D. modeled PSDs compared to the PSD of SC1 48/130. The blue highlight indicates the 20-80% passing range.

Table 3

Calculated parameters of the GGS and RR model according to Eqs. (4)–(7), and measured material properties as derived from the PSD measured in Fig. 3.

	SC1 48/ 130	SC1 48/ 85	SC1 38/ 130	SC1 38/ 85
n^{GGS}	0.35	0.39	0.34	0.39
GGS d_{max} (mm)	9.93	10.96	8.79	10.15
R^2 GGS model (range 0.5–8 mm)	0.988	0.993	0.978	0.988
n^{RR}	0.60	0.61	0.61	0.63
RR d' (mm)	2.26	2.92	1.88	2.68
R^2 RR model (range 0.5–8 mm)	0.998	0.995	0.999	0.998
Wt% RCF	2.81	3.93	2.19	3.68
d_{90} (mm)	8.90	10.33	7.42	9.55
$d_{63.2}$ (mm)	2.39	3.16	1.95	2.79

reflects a shift of the whole PSD to a larger particle size. Similarly, the d' -value increases and the n^{RR} value decreases slightly with increasing CSS width, meaning larger aggregates are liberated and the PSD spread increases.

As shown in Table 3, the d_{90} is lower compared to the d_{max} , as the d_{max} reflects the maximum passing size. Moreover, as the GGS model follows an exponential curve, the d_{max} can easily overshoot the actual d_{max} value. The discrepancy in value reflects the struggle of this model to capture the complex fragmentation behavior of the SC. The d' -values are slightly lower compared to the $d_{63.2}$ values, which indicates a tail towards the fine aggregates, as shown in Fig. 3D. Overall, the RR model describes the PSD slightly better compared to the GGS model.

Although the RCFs are not included in the RR and GGS model, it

appears that more RCF is generated when the d' and d_{max} are higher, and the n^{GGS} value increases, as shown in Table 3. This aligns with the hypothesis that HCP liberation increases by promoting abrasion without crushing the larger aggregates. It would therefore be expected that a wider spread (lower n^{RR}) would also reflect improved separation. Yet, as shown in Table 3, a lower n^{RR} value does not lead to more RCF, thus suggesting that the quality of the separation, in terms of RCF quantity, cannot be determined based on the GGS and RR parameters. This discrepancy is likely due to the fitting range of the RR and GGS model and is a fundamental limitation of these standard comminution models, making them less suitable to model abrasion-heavy recycling techniques.

3.2. Experiment 2: crushing frequency and material feed

As the settings of SC1 48/130 produced HCP-rich RCF, these settings were used to study the energy consumption and impact of material feed packing on the crushing output. Two material feed mixes were used: a coarse (100% 32 mm) and a mixed (50/50 wt% 32 mm + 16 mm) material feed. Additionally, the performance of the modified crusher was compared to that of a conventional lab jaw crusher.

3.2.1. PSD analysis

As shown in Fig. 4, the output material of the JC contains primarily aggregates larger than 8 mm (~75%), reflecting very limited crushing. Using the same settings (SC2 32 50/270), the SC produced fewer 16 mm-sized aggregates and more aggregates below 8 mm. Similarly, the JC produced 0.99 wt% of RCF, whereas the SC produced 3.46 wt% of RCF. Due to the absence of an obstruction plate in the JC, the aggregates fall through the crusher, leading to a higher throughput (5.96 kg/min)

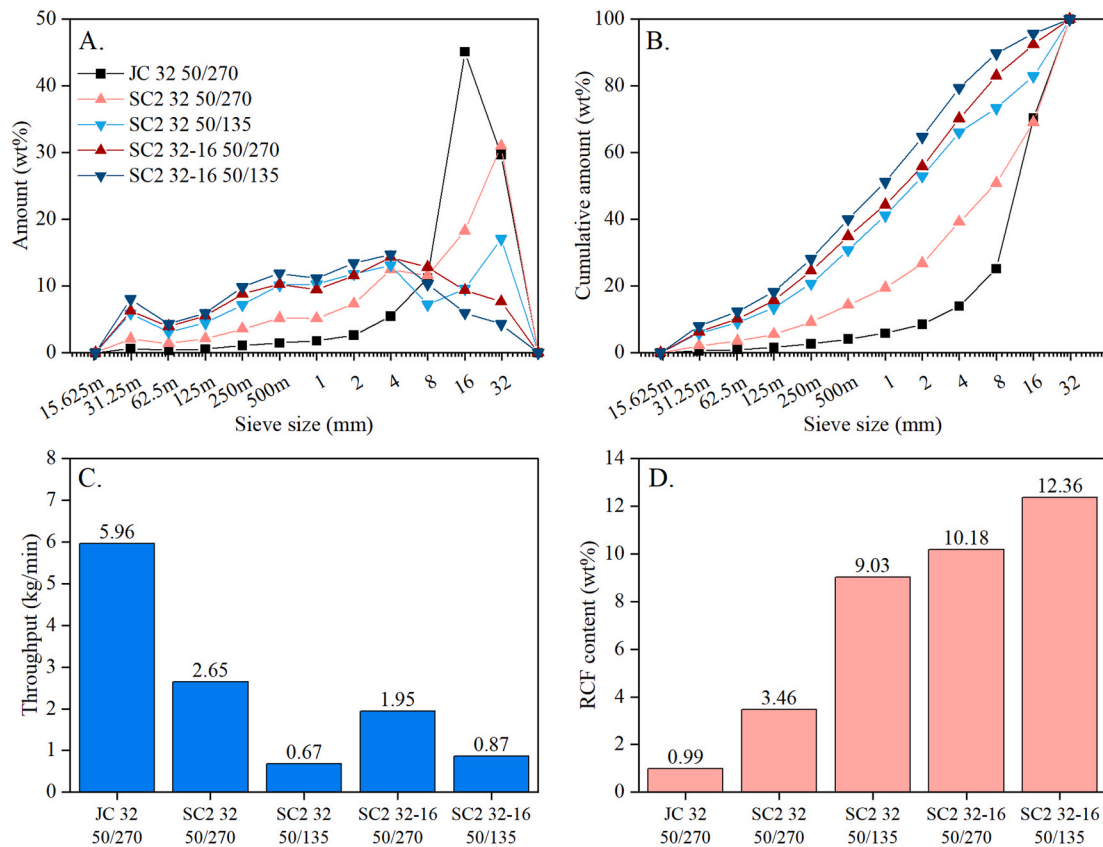


Fig. 4. Frequency (A.) and cumulative (B.) particle size distribution of the material output of Experiment 2 (Table 1), as well as the measured throughput (C.) and RCF content (D.).

compared to the SC (2.65 kg/min) and a reduced crushing probability (Gupta and Yan, 2016).

As shown in Fig. 4, increasing the crushing frequency of the SC from 135 rpm to 270 rpm increases the fraction of aggregates above 4 mm, and decreases the fraction below 4 mm. This effect is more pronounced for the coarse (32 mm) material feed compared to the mixed material feed (32 mm + 16 mm). Yet more RCF (10.18 wt% and 12.36 wt%) is generated with the mixed material feed compared to the coarse material feed (3.46 wt% and 9.03 wt%), irrespective of the crushing frequency. For both material feeds, the amount of RCF decreases as the crushing frequency increases, which aligns with the findings in Paragraph 3.1.

Contrary to Paragraph 3.1, increasing the crushing frequency increases the throughput of the SC. This could be related to the difference in packing density between the experiments, as a higher packing density can reduce the throughput as described by Rose and English (Gupta and Yan, 2016). This further explains the stronger increase in throughput of the coarse feed upon increasing the crushing frequency, compared to the mixed feed. Moreover, changing the material feed from coarse to mixed aggregates reduces the throughput at 270 rpm (2.65 kg/min to 1.95 kg/min) but increases the throughput at 135 rpm (0.67 kg/min to 0.86 kg/min).

Like the increase in throughput upon narrowing the CSS width in Paragraph 3.1, the increased packing could lead to more compression and thus forces the material out of the crusher at lower crushing frequencies. At 270 rpm, however, the increased packing likely prevents the material from leaving the crusher. This aligns with the findings of (Deniz, 2011, 2014), who showed that the throughput reduced as the material feed decreased in size, or as the crushing frequency was increased beyond the optimum frequency. Moreover, likely, the movement of the obstruction plate (Fig. 1C.) impacts the throughput as well, but more research is required.

As shown in Fig. 4, a reduction in throughput results in an increase in RCF content. The RCF content increases most when the material feed changes from coarse to mixed, whereas the throughput increases most as the crushing frequency increases. This means both the throughput and RCF quantity can be optimized by increasing both the packing density and crushing frequency.

To further study the changes in PSD of the JC and SC, the GGS and RR fitting parameters were calculated and tabulated in Table 4. As the fitting range of the GGS and RR model is between 8.0 and 0.5 mm, it is assumed that the fitting parameters are not significantly affected by the mixing of the material feed, unlike the R_{80} values.

As shown in Table 4, both the n^{GGS} and n^{RR} drop significantly when using the SC compared to the JC, indicating a change in crushing dynamics to more abrasion-based. For the SC, decreasing the crushing frequency decreases both the d' and d_{max} values for both material feeds. At 270 rpm, the d' and d_{max} values decrease from 58.28 mm to 23.15 mm to 19.32 mm and 5.63 mm, respectively, as the material feed

Table 4

Calculated parameters of the GGS and RR model according to Eqs. (4)–(7), derived from the PSD measured in Fig. 4.

	JC 32 50/270	SC2 32 50/ 270	SC2 32 50/ 135	SC2 32- 16 50/270	SC2 32- 16 50/135
n^{GGS}	0.64	0.49	0.41	0.37	0.37
GGS d_{max} (mm)	153.58	58.28	19.41	19.32	13.50
R^2 GGS model (range 0.5–8 mm)	0.996	0.995	0.986	0.991	0.988
n^{RR}	0.67	0.58	0.55	0.51	0.55
RR d' (mm)	133.96	28.15	6.68	5.63	3.58
R^2 RR model (range 0.5–8 mm)	0.996	0.996	0.997	0.998	0.998

changes from coarse to mixed, whereas the throughput decreases from 2.65 kg/min to 1.95 kg/min. Yet, at 135 rpm, the d' and $d_{\max}$ values decrease from 19.41 mm to 6.68 mm to 13.50 mm and 3.58 mm, respectively, yet the throughput increases from 0.67 kg/min to 0.87 kg/min. This suggests that there is an optimum material feed density and crushing frequency, which would allow for a high throughput and sufficient size reduction.

As shown in Table 4, changing the material feed from coarse to mixed aggregates leads to a decrease in n^{GGS} values from 0.41 to 0.49 to 0.37, irrespective of the crushing frequency. The change in n^{RR} value is, however, dependent on the crushing frequency: at 135 rpm, the n^{RR} value remains constant (0.55) upon changing the material feed from coarse to mixed, but it decreases from 0.58 to 0.51 at 270 rpm. An increased material feed packing thus increases the amount of fine material, but not necessarily the spread in particle sizes.

Increasing the crushing frequency for the coarse material feed results in an increase of both the n^{GGS} (0.41 to 0.49) and n^{RR} (0.55 to 0.58) values, meaning more coarse and uniform aggregates are liberated. For the mixed feed, the increase in crushing frequency lowers the n^{RR} value (0.55 to 0.51), whereas the n^{GGS} value remains constant (0.37), indicating an increase in the spread of particle sizes while preserving the ratio between large and fine fractions.

In Paragraph 3.1, it was hypothesized that HCP liberation through abrasion is characterized by a PSD rich in fines (low n^{GGS}) and with a wide size range (low n^{RR}). The lowest n^{GGS} and n^{RR} values are obtained for SC 32-16 50/270, which also has the second highest RCF content (10.18 wt%). This suggests that the parameters, in this case, do somewhat reflect the improved HCP liberation.

3.2.2. XRF analysis

To determine the quality of the RCF, XRF analysis was done. As shown in Table 5, the RCF generated by the JC has a lower calcium content (30.18%) compared to the SC (32.02%). Moreover, the total quantity of RCF is lower compared to SC2 32 50/270 (0.99 wt% versus 3.46 wt%). For the SC, the RCF generated from a mixed material had an identical composition, irrespective of the crushing frequency, suggesting similar fracture mechanics. For the coarse material feed, an increase in crushing frequency leads to an increase in CaO content (27.49 wt% to 32.02 wt%) while reducing the RCF quantity (9.03 wt% to 3.46 wt%).

Changing the material feed from coarse to mixed aggregates lowers the SiO₂ content from 45.16 wt% to 42.41 wt% at 135 rpm, and increases it from 39.30 wt% to 42.41 wt% at 270 rpm. As the increased packing density of the mixed material feed reduces the free space around the aggregates, more abrasion and compression forces are introduced. With increasing crushing frequency, the increased packing can lead to more compression of the material as the material cannot settle between strokes, which leads to chipping of the aggregates and thus an increase in SiO₂ content. At 135 rpm, the material is allowed more time to settle between strokes, and the increased packing density primarily promotes abrasion. This aligns with the findings of Paragraph 3.1, where a narrow CSS, i.e., more dense packing, and higher crushing frequency increased the RCF quantity as well as the SiO₂ content.

3.2.3. Aggregate shape analysis

As the crushing mechanism impacts the aggregate shape, all samples were analyzed using ImageJ, except for SC2 32-16 50/135, as there was

no variation detected among the other 3 SC samples (Gomes et al., 2015; Rajan and Singh, 2017; Ulsen et al., 2019). The circularity of the particles was calculated using:

$$\text{Circularity} = 4\pi \frac{[\text{Area}]}{[\text{Perimeter}]^2} \quad (8)$$

Where the ratio for a perfect circle is unity, meaning smoother particles will approach a value of 1, and rougher particles will approach 0. The flakiness was calculated using the aspect ratio (AR):

$$\text{AR} = \frac{[\text{Wide}]}{[\text{Narrow}]} \quad (9)$$

where [Wide] and [Narrow] are the dimensions of an ellipse fitted in the aggregate contours, and a higher AR value indicates more flaky aggregates.

As shown in Fig. 5, all aggregates generated with the SC are smoother (circularity of 0.82-0.84) and more rounded (AR of 1.31-1.42) compared to the aggregates from the JC (circularity of 0.74 and AR of 1.74). T-test analysis confirmed that the difference in shape characteristics between the JC and SC aggregates was significant, as all p-values were below 0.001. Both the increased circularity and AR indicate a more friction-based crushing mechanics (Rajan and Singh, 2017). In addition to a difference in angularity, the SC generates cleaner aggregates compared to the JC, as shown in Fig. 5C. This confirms that the modified crusher increases friction between the aggregates, abrading the HCP from the aggregates.

3.2.4. Surface area versus energy consumption

To assess how the energy consumption reflects the crushing efficiency of the SC, the fracture energy E_{fracture} in kJ/kg was calculated according to

$$E_{\text{fracture}} = \frac{(E_{\text{full}} - E_{\text{empty}}) \cdot t}{M} \quad (10)$$

where E_{full} and E_{empty} are the energy consumed (J/min) when the crusher is full and empty, respectively, t is the duration of the crushing experiment (min), and M is the total weight of crushed material in kg.

To account for the change in PSD, the fracture energy is scaled to the increase in surface area (ΔSA in m²/kg) (Gupta and Yan, 2016; Tee, 2007; Wills and Finch, 2016). The ΔSA is calculated by subtracting the SA of the material feed (lower-case m) from the SA of the output material (lower-case n), according to:

$$\Delta \text{Surface Area} = \sum_{i=1}^n \frac{M_n^k A_n}{\rho_n^k V_n} - \sum_{i=1}^m \frac{M_m^k A_m}{\rho_m^k V_m} \quad (11)$$

$$\frac{A_n}{V_n} = \frac{2\pi r^k \left(AR^n \cdot r^k \frac{\sin^{-1} \sqrt{q}}{\sqrt{q}} + r^k \right)}{\frac{4}{3} \pi \cdot AR^n \cdot r^k \cdot (r^k)^2} \quad (12)$$

$$q = 1 - \frac{(r^k)^2}{(AR^n \cdot r^k)^2} \quad (13)$$

Here, M^k is the wt% retained on sieve size k , ρ^k is the density of the fraction in kg/m³, $\frac{A}{V}$ is the surface-to-volume ratio of an ellipsoid, AR is the aspect ratio, and r^k is the geometric mean of the particles between sieve k and $2 \cdot k$ in meters. The particles are presumed to be prolate spheroids, where the AR of the material feed and JC are set at 1.73 and 1.36 for the SC samples. The density was fixed at 2.6 g/cm³, as pycnometer analysis revealed a maximum variation of ± 0.1 g/cm³. The fracture energy per m² was subsequently calculated as:

$$E_{\text{fracture}}^{125 \mu\text{m}} = \frac{E_{\text{fracture}}}{\Delta \text{Surface Area}} \quad (14)$$

Table 5
XRF analysis of the RCF from Experiment 2.

XRF (wt%)	JC 32 50/270	SC2 32 50/270	SC2 32 50/135	SC2 32-16 50/270	SC2 32-16 50/135
SiO ₂	41.98	39.30	45.16	42.41	42.41
CaO	30.18	32.02	27.49	29.03	29.30
Other	13.69	14.07	13.51	14.43	13.6
LOI	14.15	14.61	13.84	14.13	14.69

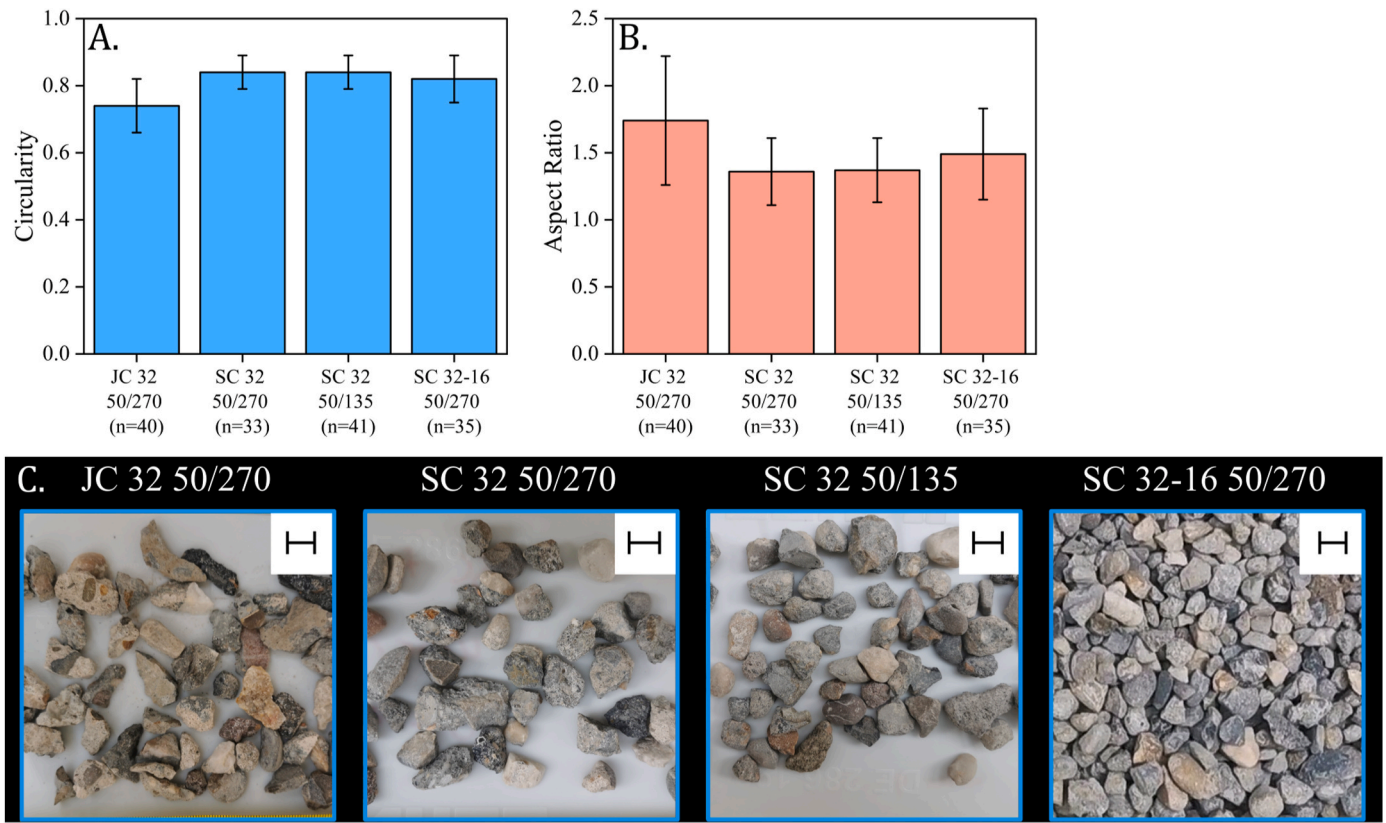


Fig. 5. Measured circularity (A.) and aspect ratio (B.) of the 16-8 mm aggregates (C.) after crushing. The parameters were calculated according to Eqs. (8) and (9) using ImageJ. The bar insert is equal to 1 cm.

Here, $E_{fracture}^{125\mu m}$ is the fracture energy ($J/m^2 \cdot min$) with a $125\mu m$ cut-off size, as the material below $125\mu m$ is classified as RCF.

As shown in Fig. 6, the fracture energies of the SC experiments (4.30–19.86 kJ/kg) are higher than the JC (1.50 kJ/kg), which is likely due to the lower throughput of the SC caused by the obstruction plate. The highest fracture energy per kg is measured for the mixed material feed at 135 rpm (19.86 kJ/kg) and the lowest for the coarse material feed crushed at 270 rpm (4.30 kJ/kg).

As shown in Fig. 6, changing the material feed from coarse to mixed aggregates increases the fracture energy by +2.10 kJ/kg at 135 rpm and by +8.62 kJ/kg at 270 rpm. This is paired with an increase in RCF content of +1.08 wt% at 135 rpm and +1.98 wt% at 270 rpm (Fig. 5). For both the coarse and mixed material feed, an increase in crushing frequency leads to a decrease in fracture energy of –12.46 kJ/kg and –6.78 kJ/kg, respectively, and a matching decrease in RCF content of

–6.57 wt% and –2.18 wt%. The increase in fracture energy with decreasing frequency and increased material feed packing suggests that more energy is consumed due to increased friction, which also reduces the throughput. Simultaneously, the RCF content is significantly higher for the experiments conducted at 135 rpm.

As shown in Fig. 6B., the fracture energy per m^2 of the JC ($3.79 kJ/m^2$) is slightly higher than the fracture energy of SC2 32 50/270, which shows that the material is crushed more efficiently with the SC. Scaling the fracture energy to the increase in SA further confirms that a significant amount of energy is lost on friction, as reflected by the higher fracture energy of the crushing experiments conducted at 135 rpm ($6.38 kJ/m^2$ and $5.81 kJ/m^2$) compared to 270 rpm ($3.52 kJ/m^2$ and $4.41 kJ/m^2$). Moreover, at 270 rpm, changing the material feed from coarse to mixed aggregates causes an increase in fracture energy from $3.52 kJ/m^2$ to $4.41 kJ/m^2$, which further suggests that more energy is

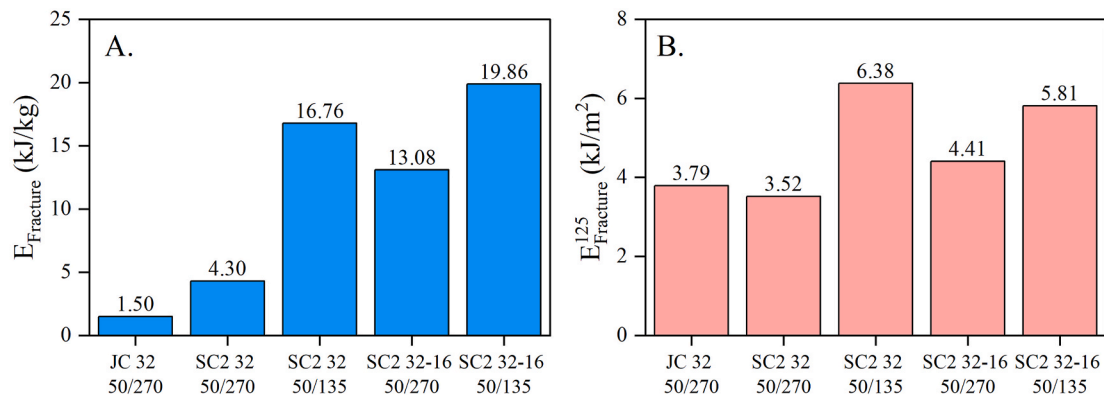


Fig. 6. The fracture energies per kg (A.) and per m^2 (B.) of Experiment 2 according to Eq. (10) and Eq. (14).

consumed due to the increase in frictional forces. Yet, at 135 rpm, the fracture energy decreases from 6.38 kJ/m^2 to 5.81 kJ/m^2 , while the throughput also increases from 0.67 kg/min to 0.86 kg/min as the material feed changes from coarse to mixed. This shows that the fracture energy is not solely impacted by the throughput.

As the fracture energy is related to the material hardness, an increase in fracture energy per m^2 could reflect crushing of the (stronger) quartz aggregates (Gupta and Yan, 2016; Wills and Finch, 2016). Comparison of the SiO_2 content (Table 5) to the fracture energy per m^2 shows an increase of both as the crushing frequency decreases for the coarse material feed. Yet, for the mixed material feed, the SiO_2 content remains constant as the crushing frequency increases, whereas the fracture energy decreases. Thus, the fracture energy does not solely reflect the selectivity of the crushing in terms of SiO_2 content.

The increased energy consumption of the SC will increase the RCA price. Presuming a theoretical best-case scenario, an average price of 0.15 €/kWh and an RCA price of 5.0 €/tonne would result in a $\sim 10\text{--}35\%$ price increase of the SC-generated RCA ($0.62\text{--}1.96 \text{ €/tonne}$) (Eurostat, 2025; Ma et al., 2022). This is a very rough approximation, as RCA prices vary widely per country (Ma et al., 2022). Moreover, machine-related costs are not accounted for, whereas the high friction and abrasion during the crushing will likely increase the wear of the machine, therefore increasing the machine-related costs.

3.3. Experiment 3: mixing of aggregates in the feed

As the packing density of the material feed significantly impacts the throughput and RCF quantity, three mixes with increasing packing density were studied, using the optimal settings according to Paragraph 3.1. Their performance was compared to the crushing of a pure hydrated cement paste.

3.3.1. PSD analysis and energy consumption

As shown in Fig. 7, the addition of 8 mm and 2 mm aggregates leads to an increase in the amount of material below $500 \mu\text{m}$. Yet, the RCF content barely increases, which could be related to the low HCP content of the aggregates in the material feed (S.I. Fig. A1). The increased packing of the material feed further leads to an increase in throughput. As the increase in throughput per dilution ($\sim 20\%$) is less than the dilution introduced by the 8 mm and 2 mm aggregates ($+50\%$ and $+33\%$ respectively), this shows that aggregates do not simply fall through the crusher, but participate in the crushing.

Comparison of the crushed HCP (SC3 CEM-I 32 48/130) to the recycled RCA (SC3 32 48/130) shows that the crushed HCP contains more aggregates with a size above 8 mm. This is due to the homogeneous strength of the HCP, which makes the material more prone to chipping instead of breakage, as this requires less energy (Gupta and Yan, 2016; Semsari Parapari et al., 2020). In concrete, fractures are more likely to progress through the brittle HCP. Moreover, the stronger aggregates can act as milling balls in the crushing process, which is further reflected by the higher throughput of the concrete (0.94 kg/min) compared to the HCP (0.58 kg/min).

As shown in Fig. 8, increasing the packing of the material feed increases both the fracture energy scaled per kg (15.36 kJ/kg to 34.23 kJ/kg) as well as the fracture energy scaled per m^2 (6.27 kJ/kg to 11.18 kJ/kg). This shows that the increased packing density leads to reduced energy efficiency, as more energy is lost on friction. Comparison of the fracture energy of the HCP (9.13 kJ/m^2) to the coarse concrete feed shows that the fracture energy of the concrete is lower (6.27 kJ/m^2), which is likely due to the more brittle nature of the interfacial transition zone between the HCP and the aggregates (Scrivener et al., 2004).

3.3.2. XRF analysis

To assess if the quality of the RCF improved with increased packing,

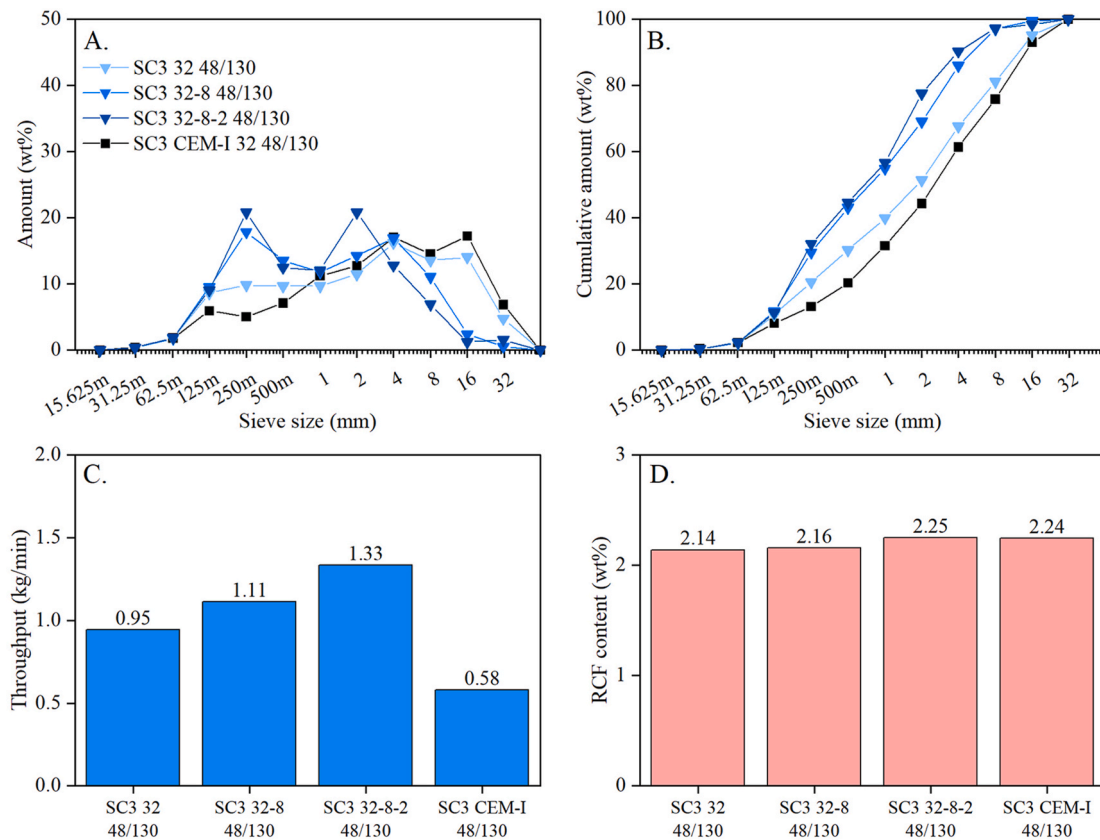


Fig. 7. Frequency (A.) and cumulative (B.) particle size distribution of the material output after crushing HCP (CEM-I) and mix M1 according to Experiment 3 (Table 1), as well as the measured throughput (C.) and RCF content (D.).

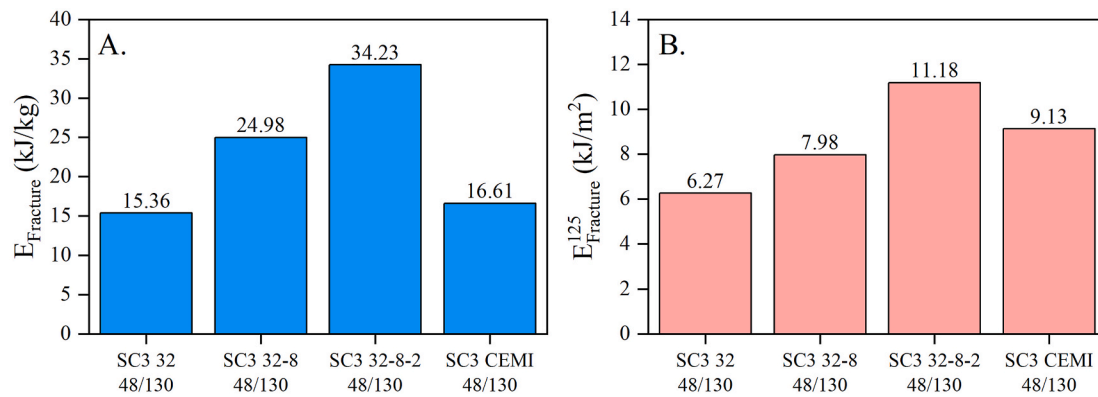


Fig. 8. The fracture energies per kg (A.) and per m² (B.) of Experiment 3 according to Eq. (10) and Eq. (14).

Table 6

XRF of the RCF and 32 mm aggregates of the material output generated during Experiment 3.

	SC3 32 48/130	SC3 32/8 48/130	SC3 32/8/2 48/130
RCF (wt%)	2.14	2.15	2.25
XRF (wt%) RCF			
CaO	25.71	25.75	25.32
SiO ₂	43.97	45.23	43.65
LOI	14.47	14.87	15.39
CaO (without LOI)	30.06	30.25	29.93
SiO ₂ (without LOI)	51.40	53.13	51.59
XRF (wt%) 32 mm			
CaO	15.54	10.47	11.49
SiO ₂	67.23	73.31	74.32
LOI	8.78	6.08	5.41
CaO (without LOI)	17.04	11.15	12.14
SiO ₂ (without LOI)	73.70	78.06	78.57

the RCF was analyzed with XRF. As shown in Table 6, the SiO₂ content changes from 43.97 wt% to 45.23 wt% and to 43.65 wt% with the addition of the 8 mm and 2 mm aggregates. Simultaneously, the LOI increases slightly (+0.4 wt% and +0.52 wt%) with each addition, whereas the calcium content remains constant for all three experiments. As the increase in LOI could indicate an increase in carbonated HCP, the composition without LOI is also shown in Table 6. Again, the calcium content remains constant, which means that the RCF quality remains constant and is not related to the change in fracture energy in Fig. 8.

In addition to the RCF, the 32 mm aggregates were analyzed with XRF to establish if the increased packing resulted in cleaner RCA. As shown in Table 6, the addition of 8 mm aggregates to the material feed reduces the CaO content by ~5 wt%. The addition of 2 mm aggregates does not lead to a further reduction in CaO content, thus confirming that they do not improve the separation. Although the quality of the 32 mm aggregates improves with the addition of the 8 mm aggregates, the RCF quantity does not increase significantly; instead, the amount of material between 125 and 500 μm increases most (Fig. 8). Further research on the quality per size fraction before and after crushing could further clarify this behavior.

Based on these results, it can be concluded that the increased packing primarily increases the energy consumption without improving the efficiency of separation.

4. Conclusions

In this work, a modified jaw crusher (SC) was used to study the impact of material feed, CSS width, and crushing frequency on the liberation of HCP from RCA during concrete recycling. The major findings are:

1. The design of the SC promotes abrasion and friction between aggregates, which improves the liberation RCF and reduces the fracture energy per m² compared to a conventional jaw crusher, using the same settings. When not accounting for the increase in surface area, the energy efficiency of the JC exceeds the efficiency of the SC.
2. Lowering the crushing frequency and/or increasing the packing density of the material feed increases the RCF liberation and the energy consumption, due to energy loss on heat and friction. Yet, the addition of small aggregates does not improve the quantity or quality of the RCF and reduces the energy efficiency.
3. Increasing the packing density of the material feed increases the throughput at low crushing frequencies but decreases the throughput at higher crushing frequencies. Similarly, decreasing the CSS width increases the throughput with decreasing crushing frequency. More research on the kinematics of the obstruction plate is required to understand this behavior.
4. The fracture energy is primarily impacted by friction and not by aggregate chipping, and thus does not reflect the separation efficiency.
5. The Rosin-Rammler and Gates-Gaudin-Schuhmann models can be used to model the PSDs, but fail to model the increased HCP liberation. Modeling with multimodal models in future research could provide a more accurate description of the change in PSDs.

Based on the presented results, the use of the SC is shown to have the potential to further close the concrete loop and improve the recycling of both RCA and the liberated HCP. Future experiments on the translation of these experiments to continuous industrial-scale operations are essential, where wear of the machines, heat generation during crushing, optimized throughput, and packing density should be investigated in more detail.

CRediT authorship contribution statement

I.E. Teune: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **H.J.H. Brouwers:** Funding acquisition, Supervision, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.clet.2026.101259>.

Data availability

Data will be made available on request.

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