# Concrete as a Simulant for Selective Comminution and Material Recovery in Vertical Roller Mills

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**Abstract.** Recycling waste concrete is key to improving resource efficiency in construction. This study investigates parameters influencing selective comminution of homogeneous waste concrete in a vertical roller mill (VRM), aiming to produce clean coarse recycled aggregates for reuse. The fine fraction can be further processed to recover cement paste and fine aggregates, with the cement paste usable as a reactivatable binder or $CO_2$ sink. Waste concrete is also identified as a cost-effective simulant for studying VRM comminution selectivity. Parameter studies examined milling pressure, feed size distribution, process mode, and dry vs. wet conditions. Results show promising potential but indicate a need for further optimization.

## 1. Introduction

The construction industry is the largest market for domestically produced raw materials in Germany, including sand and gravel (211,000 Mt), crushed stone (167,000 Mt), and limestone (42,990 Mt) [1]. A substantial share is used in concrete, composed of cement paste, coarse aggregates, and fine aggregates.

Reducing carbon dioxide ($CO_2$) emissions and conserving non-renewable resources requires more efficient concrete recycling. Clinker production is a major concern, generating about 60% of cement-related $CO_2$ emissions [2]. In Germany, cement production reached 32.9 Mt in 2022, with € 3.4 billion in revenue, supplied entirely by domestic facilities highlighting significant potential for emission reduction through optimisation and recycling [3].

The “BeBreSaRec” project addresses this by improving selective comminution in vertical roller mills (VRMs) to preserve aggregates while liberating them from the cement paste. The aim is to recover high-quality aggregates for reuse and utilise the separated cement paste for reactivation or as a $CO_2$ sink.

## 2. Concrete Recycling – State of the Art

Aggregates for concrete are regulated under DIN EN 12620, which defines coarse aggregates as particles > 4 mm and fine aggregates as < 4 mm. In addition, it provides specifications exclusively for coarse recycled aggregate fractions. Consequently, the appropriate reuse of coarse crushed concrete as recycled aggregate has already been demonstrated at full industrial scale in construction practice [4]. By contrast, the recycling of crushed sand, constituting approximately 25–32 % by mass of crushed concrete, remains largely unexplored.

In Germany, over 78.8% of construction and demolition waste is recycled, but recycled concrete is mainly used in road frost blanket layers due to fine fractions containing adhered cement paste. [5]. This increases the water–cement ratio and reduces strength in new concrete, preventing true closed-loop recycling [4, 6]. Limited demand for fines leads to mixed materials (0–45 mm) being produced instead of high-quality coarse aggregates, wasting valuable resources.

Primary comminution occurs on-site, followed by secondary processing using impact, jaw, or cone crushers [4]. Among these, impact crushers exhibit a particularly high potential for selective comminution due to their force-limited operating principle [7]. They are predominantly utilised to exploit their general comminution characteristics, which are well suited to meeting the granulometric requirements for frost protection layer materials. In parallel, jaw crushers have increasingly become the subject of investigation in recent years concerning their suitability for selective concrete comminution [8].

In order to enable effective recycling of the fine fraction, VRMs have also gained attention in current research and development activities. A process developed by Loesche has demonstrated promising results by employing the force-controlled milling system in conjunction with both internal and external classification stages [9]. The process is capable of generating three distinct product fractions: coarse aggregates, fine aggregates, and a finely divided cement paste fraction.

Current systems are limited by feed moisture variability, highlighting the need for more robust processes as well as a deeper understanding of comminution mechanisms to optimize and advance concrete recycling technologies.

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# 3. Methodology

## 3.1. Material and Pretreatment

The experiments used 23-year-old homogeneous concrete composed of 15.7 % CEM I cement, 49.1 % coarse aggregates (8–22 mm crushed stone), and 35.2 % fine aggregates (0–4 mm sand). Material characterisation included strength, micro-hardness, and fracture toughness. A point load test yielded $I_{S(50)} \approx 2.45$ MPa, corresponding to a compressive strength of $\sigma_D \approx 61.2$ MPa (conversion factor 25) [10]. Vickers hardness (VHN) was measured on prepared sections, and fracture toughness ($K_{Ic}$) was determined [11]. Fracture toughness of the cement paste and base mass could not be reliably determined due to insufficient brittleness. Nevertheless, the obtained results indicate a pronounced disparity in microhardness and fracture toughness between the aggregate particles (Feldspar: VHN = 800 N/mm², Quartz: VHN = 1180 N/mm²) and the hardened cement paste (VHN = 100 N/mm²). This disparity promotes combined compressive and shear stresses under loading, favouring selective comminution.

About 10 t of concrete waste was pre-crushed by REMEX GmbH to 0–45 mm using an impact crusher (28 m/s, 35 mm gap), from which a 2 t representative sample was taken. The remaining 8 t was further crushed to 0–8 mm by recirculating > 8 mm particles, with size limits defined by the downstream VRM. Both fractions were sent to the Institute for Mineral Processing Machines and Recycling Systems Technology (IART), where representative sub-samples were obtained via systematic splitting and rotary division, covering both comminution stages. For the investigations presented in this study, the 0–8 mm particle size fraction was utilized as the primary feed material. Additional trials excluded fines (< 2 mm) by pre-screening the material with at a external sieving machine at a mesh size of 2 mm, producing a feed without fine particles.

## 3.3. Experimental Setup

The pilot-scale overflow VRM with external sieve classification at IART, originally designed for ore processing, was used for both wet and dry milling [12]. The screening unit (2 mm mesh) enabled recovery of the coarse fraction and supported aggregate liberation. A simplified flowsheet is shown in Figure 1.

Each experimental run produced process and material data, including mass flows (fresh feed $\dot{m}_F$ and circulating load $\dot{m}_C$ in kg/h), water input flow rate, torque ($M$, in Nm) and the rotational speed of the milling table ($n$, in 1/min), material bed height and the applied hydraulic pressure. Particle size distributions were obtained via sampling at defined points. The bed height was measured indirectly using calibrated magneto strictive sensors.

Each run included parameter adjustment, a stabilization phase, and a 10-minute measurement interval with synchronized multiple sampling. In batch mode, feed samples were taken only before and after the interval. Mean values were calculated from continuous data, and specific energy consumption was determined from mill throughput ($\dot{m}_M$, sum of fresh feed and circulating load) and mill power (mechanical torque and rotational speed of the mill table. Particle size distributions were analysed by sieve analysis.

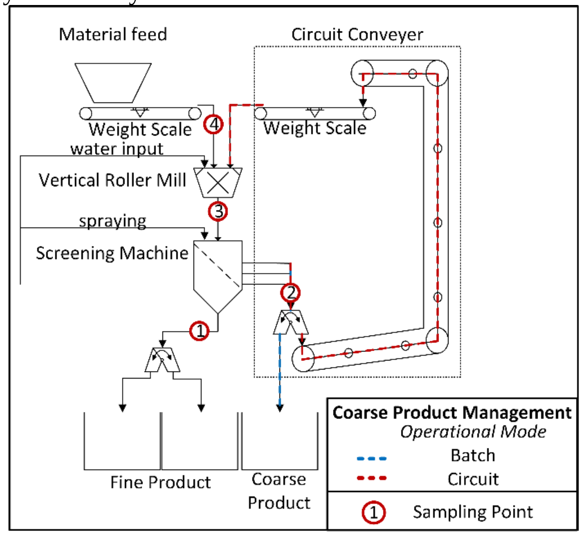


**Figure 1.** Simplified Flowsheet of the pilot plant, modified according to [12]; Sampling Points: ① screening fines, ② screening coarse, ③ milling product, ④ fresh feed

The overall methodology applied for data acquisition at the pilot plant has been previously validated in an independent study and demonstrated to provide a high level of reliability [12].

The scope of the present work encompasses results evaluated with respect to the system boundary of the mill. The influence of selected parameter combinations (see Table 1) is examined accordingly. Where required by process conditions, repeated measurements (RM) were conducted to ensure reproducibility and statistical robustness of the results. Variations in milling table speed and feed throughput were tested but are not included here. For all reported experiments, mill throughput was fixed at $\dot{m}_M = 500\ kg/h$ and table speed at $n = 35\ 1/min$.

Conical rollers (15° inclination) were used to apply combined compressive and shear stresses, promoting selective comminution.

**Table 1.** Milling parameter combinations discussed in this paper

| No. | RM | hydr. Pressure [bar] | Feed fraction [mm] | Process Wet/ Dry | Process Batch/ Circuit |
|---|---|---|---|---|---|
| 1 | 1 | 14 | 0-8 | Dry | Batch |
| 2 | 2 | 24 | 0-8 | Dry | Batch |
| 3 | 2 | 24 | 2-8 | Dry | Batch |
| 4 | 3 | 24 | 2-8 | Dry | Circuit |
| 5 | 2 | 24 | 2-8 | Wet | Batch |
| 6 | 1 | 43 | 0-8 | Dry | Batch |
| 7 | 1 | 74 | 0-8 | Dry | Batch |
| 8 | 1 | 110 | 0-8 | Dry | Batch |

## 3.4. Determination of the composition and selectivity

Assessing comminution selectivity requires reliable and rapid determination of product composition. While X-ray diffraction (XRD) is standard for phase analysis, it is too time-intensive for high-throughput studies.

Instead, this study used pixel-based colour analysis, exploiting the contrast between cement paste and aggregates. Samples were analysed by size fraction, and images processed in MATLAB (Colour Thresholder), enabling fast and reproducible evaluation.

A higher proportion of darker tones indicates increased coarse aggregate content. Analysis focused on size fractions 2–8 mm. The method was validated against XRD using a Bruker D8 Advance and TOPAS program with Rietveld analysis, showing a relative deviation of about ± 2 % in aggregate content [13]. Further validation is beyond this study's scope, though limitations remain due to colour similarity and image resolution.

The selectivity of comminution is evaluated using mass recovery ($R$) and aggregate concentration ($c$) [14]. Analysis focuses on size fractions 2–8 mm, with components defined as cement paste, aggregates, and the mixture. The composition of each fraction ($c_{i,x}$) is determined based on the results obtained from the image analysis. In contrast, the mass proportion of the mixture ($\mu_{3i,m}$) is derived from the sieve analysis. Giving the option to calculate the overall concentration of the components in the coarse fractions. Aggregate mass recovery is based on the mass proportion of the aggregates in coarse product and their concentration relative to coarse feed and concentration.

This approach imply that comminution can be regarded as fully selective when the concentration of aggregates in the coarse fraction reaches $c_{a,CF} = 1$, and the corresponding mass recovery of aggregates attains $R_{a,CF} = 1$. Under these conditions, a complete separation of aggregates from the cement paste is achieved by screening, indicating ideal selectivity of the comminution process.

## 4. Results and Discussion

First, the PSDs of the milling products are analysed in relation to the applied parameters. Figure 2 shows the PSDs for all parameter combinations alongside the feed PSD, with mean values reported for repeated measurements.

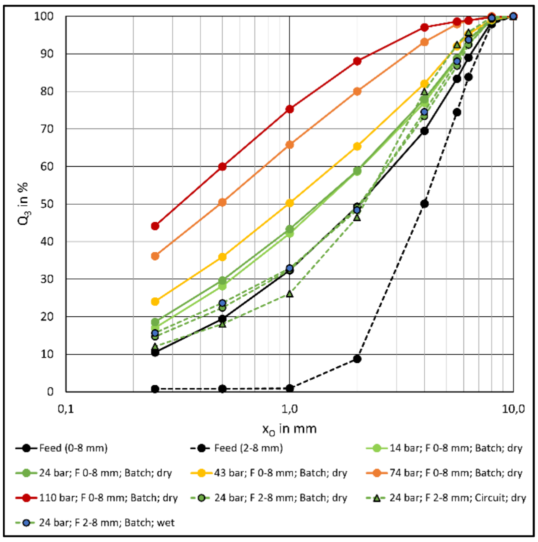


**Figure 2.** Particle size distribution (PSD) of the milling product and the fresh feed

For a 0–8 mm feed, increasing hydraulic pressure (43 to 74 bar) significantly alters the PSD while maintaining a similar slope, accompanied by a drop in bed height (12.43 to 7.94 mm). This indicates a transition from aggregate preservation at low pressure to increased breakage at higher pressure. At equal pressure (24 bar), comparing 0–8 mm and 2–8 mm feeds show reduced bed height (13.63 to 9.25 mm) but similar PSD slopes above 4 mm, indicating comparable comminution behaviour to coarser material. However, overall slope of the milling product is steeper with 2–8 mm feed. Comparing wet and dry milling, no notable difference in PSD despite reduced bed height (9.25 to 6.75 mm) can be recognized. This suggests bed height has limited influence under these conditions.

To further assess parameter effects, aggregate concentration and mass recovery in the coarse fraction are presented in Figure 3.

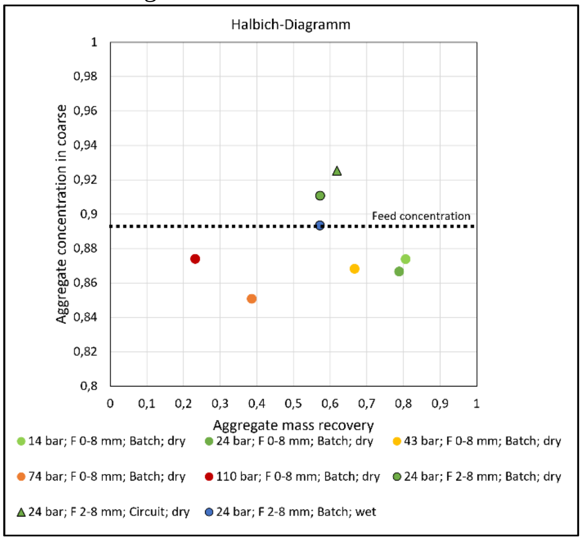


**Figure 3.** Aggregate concentration and mass recovery into coarse fraction

For all trials with a 0–8 mm feed, aggregate concentration decreased relative to the feed, and higher milling pressure reduced aggregate mass recovery, consistent with PSD trends.

In contrast, 2–8 mm feed trials achieved higher aggregate concentration in the coarse fraction with relatively good mass recovery, indicating effective selective comminution, though with some material loss. The highest aggregate concentration ($c_{a,CF} = 0.92$) occurred under circuit operation, but with reduced mass recovery due to continuous recirculation, representing an upper enrichment limit without additional sorting.

Figure 4 compares aggregate mass recovery with specific energy consumption. Increasing hydraulic pressure (14 to 110 bar) leads to a substantial rise in specific energy consumption. In contrast, excluding fine material from the feed and operating under wet conditions show no significant influence on the overall energy demand.

The relationship between specific energy consumption and aggregate mass recovery is further illustrated by evaluating their ratio in discrete intervals. This allows the incremental energy input to be interpreted in terms of the energy required to recover the coarse aggregate fraction.

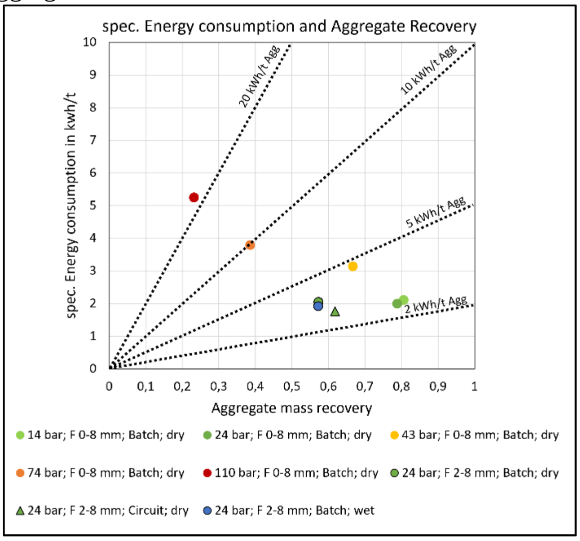


**Figure 4.** Comparison of aggregate mass recovery to specific energy consumption of the mill

Under this perspective, the most favorable efficiency is achieved at low pressures (14–24 bar) with a 0–8 mm feed, yielding approximately 2.5 kWh/t per recovered aggregate. Trials with a 2–8 mm feed show a slightly less favorable ratio of about 3.5 kWh/t, indicating higher energy demand per unit of recovered aggregate.

It should be noted that this evaluation is limited to the coarse aggregate fraction. A comprehensive assessment, including cement paste and fine aggregates, is still pending, and the overall conclusions may change once these additional material streams are considered.

## 5. Summary and Outlook

This study investigates key VRM milling parameters for waste concrete, including milling pressure, feed PSD, recirculation, and wet vs. dry operation. Comminution selectivity was assessed using an image-based colour analysis method, evaluating particle size distribution, aggregate concentration, mass recovery, and specific energy consumption, with focus on the 2–8 mm fraction.

Results show that milling pressure and feed PSD strongly affect aggregate recovery and purity. Low milling pressure is essential to preserve coarse aggregates and maintain selective comminution. Further fundamental research is needed to clarify mechanisms and account for material variability (e.g. aggregate type and cement). The developed method will be refined and compared with established techniques, with potential for future in situ process monitoring.

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