Mutual Interactions in Multi-Component Comminution with Stirred Media Mills: Effects on Breakage Rate and Particle Transport

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Abstract. The comminution of multi-component systems is essential for processing ores and recycled materials, targeting size reduction and phase liberation. Heterogeneous feedstocks exhibit component-specific breakage strengths and transport behaviours, complicating selective comminution. Although high-pressure rolls, ball mills, and stirred media mills have been studied, detailed experimental data supporting population balance models (PBMs) remain scarce. This work investigates the comminution behaviour of a quartz–limestone mixture in a stirred media mill. Breakage rates for single-component and binary systems were measured using five narrow size fractions under varied stress conditions, showing component-specific interactions for both materials. Particle transport and classification by the stirrer deflector wheel reveal temporary accumulation of the harder component under certain conditions. Avoiding this buildup requires sufficient stress energy to fracture quartz and moderating classification intensity.

1. Introduction

Comminution of multi-component systems is critical in minerals engineering. With declining ore grades and increasingly stringent recycling regulations, research is focused not only on particle size reduction, but also on exploiting differences in material properties to achieve the selective enrichment of high-value phases, thereby improving process efficiency and sustainability [1]. Dry and wet comminution follow fundamentally different selectivity mechanisms. In dry operated mills – such as high-pressure grinding rolls and conventional ball mills – coarser, harder particles act as stress concentrators, promoting energy transfer from the mill to the product [2–4]. Conversely, in wet comminution in tumbling or stirred media mills the softer phase often breaks preferentially under relatively low stress energies and short residence times, while particles of the harder component mainly remain intact. Consequently, coarser, harder particles are more frequently captured by the media, which protects the fragments of the softer phase and thus lowers overall selectivity [5, 6]. Material-specific interactions thus open opportunities for tailoring comminution strategies toward valuable components.

In dry processes, these divergent breakage behaviors strongly affect particle classification and overall performance. Tavares & Kallemback [7] showed that comminution of basalt-limestone and copper ore-limestone mixtures in a Bond mill, the harder fractions accumulate under both open- and closed-circuit conditions. Dündar & Benzer [8] observed similar accumulation when dry grinding blended cements, where the lower breakage rates of clinker and porcelain – combined with density differences – complicate process control. In wet stirred media mills, the deflector wheel of the stirrer enables separation of fines from coarse particles [9], yet its impact on multi-component feeds remains unexplored.

Developing predictive models for comminution design and optimization is a current priority. Population balance models have proven effective for multi-component systems, but they require accurate information on particle transport, breakage function, and breakage rate. The breakage function – describing size distributions post-breakage – is only marginally affected by the presence of other components [7]. By contrast, breakage rates – which express the probability that particles of a given size break during a comminution process – are highly mixture-dependent. Most PBM approaches for multi-component comminution build on Kapur & Fuerstenau's [10] energy split factor, which allocates the specific energy input among components based on their breakage behaviour as part of a mixture in relation to the breakage behaviour as a single-component. Zhao et al. [6] applied this concept to a quartz-chlorite slurry in a wet ball mill, finding the chlorite's energy split factor to be below a value of one but increasing linearly with chlorite content – implying reduced chlorite breakage in mixtures.

Despite these advances in modelling and comprehensive understanding of the basic mechanisms in multi-component comminution, key questions remain regarding how process parameters and stress energy levels affect breakage rates and material transport in stirred media mills This study addresses these gaps via systematic

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experiments on a limestone-quartz mixture and with the help of the mechanistic stress energy model proposed by Kwade [11, 12].

2. Stress energy model

The stress energy model developed by Kwade [11, 12] links process parameters to achievable particle size via stress energy SE and stress frequency SF. It describes stress conditions in various mill types – especially wet-operated stirred media mills – and allows optimal conditions for product quality and energy efficiency to be identified with a limited number of experiments. The stress energy is the kinetic energy of colliding grinding media, depending on their relative velocity and mass. Because velocities are distributed, the maximum stress energy SE_{GM} is typically used to characterize grinding processes, calculated as follows:

$$SE_{GM} = d_{GM}^3 \cdot \rho_{GM} \cdot v_t^2 \qquad (1)$$

where d_{GM} denotes the grinding media size, ρ_{GM} its density, and v_t the stirrer tip speed. The stress frequency is the number of media-particle collisions a feed particle experiences per unit time. According to Equation (2), it is calculated from the number of media contacts per unit time n_c, the capture probability P_{cap} and the total particle count n_p.

$$SF = n_c \cdot P_{cap} / n_p \qquad (2)$$

The number of media contacts is assumed to be proportional to the stirrer speed n and the number of grinding media n_{GM}, while also accounting for the grinding chamber volume V_{GC}, the media filling ratio φ_{GM} and the porosity of the grinding media bulk ε (see Equation (3)). Assuming spherical particles, the total particle count can be determined from Equation (4) under consideration of the solids volume concentration c_v.

$$n_c \propto n_{St} \cdot n_{GM} = \frac{n_{St} \cdot V_{GC} \cdot \varphi_{GM} \cdot (1-\varepsilon)}{\frac{\pi}{6} \cdot d_{GM}^3} \qquad (3)$$

$$n_p = \frac{V_{GC} \cdot (1 - \varphi_{GM} \cdot (1-\varepsilon)) \cdot c_v}{\frac{\pi}{6} \cdot x^3} \qquad (4)$$

3. Materials & methods

The breakage rates and transport behaviour were characterised using limestone (KSL Staubtechnik GmbH) and quartz (Quarzwerke GmbH) as individual components, as well as a 50:50 mixture of these two materials. Figure 1 shows the corresponding particle size distributions. With a Mohs hardness of 7, quartz can be considered the harder of the two components compared to limestone, which has a Mohs hardness of 3.

The breakage rate S was determined from the disappearance of material in the top size class m_1 as a function of comminution time t, using data obtained from batch experiments. The calculation was performed according to Equation (5), assuming first-order breakage kinetics. To investigate the influence of particle size, the feed material was separated into five size fractions.

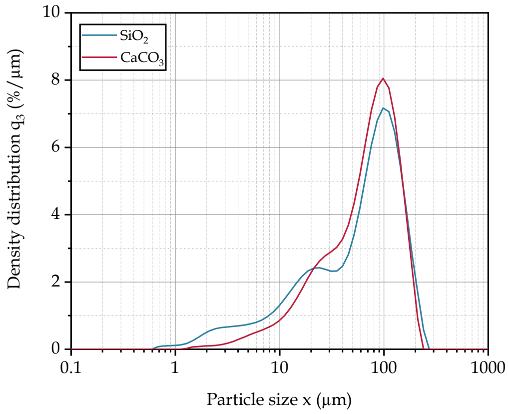

Figure 1. Particle size distributions of feed materials.

$$S = -\ln \left(m_1(t) / m_1(0) \right) / t \qquad (5)$$

All batch experiments were conducted at laboratory scale in a horizontal stirred-media mill (PML 2, Bühler Group). A constant solid mass concentration of 20 wt. % and a media filling ratio of 80 % were maintained throughout. To evaluate the effect of stress conditions on breakage rate, both stirrer tip speed and media size were varied. As summarized in Table 1, four process parameter sets per material were tested, yielding grinding media stress energies between 0.032 mJ and 0.515 mJ. In every trial, zirconia grinding beads (ρ = 6050 kg/m³) were used.

Table 1. Process parameter combinations for determination of specific breakage rate.

Parameter set	v_t [m/s]	d_{GM} [µm]	SE_{GM} [mJ]
1	6	530	0.032
2	6	755	0.094
3	8	755	0.167
4	8	1100	0.515

The transport behaviour was characterised using experiments conducted in batch mode. The slurries were first prepared in a stirred vessel with a solids concentration of 20 wt.% and then continuously pumped through the mill at a flow rate of approximately 40 l/h. Samples were taken continuously at the outlet during the experiment and analysed for solids concentration, particle size and, in the case of mixture comminution, also for composition by x-ray fluorescence. In these investigations, only grinding media with a size of 755 µm were used, with the stirrer tip speed varying between 6 m/s and 12 m/s.

4. Results

To explore the mutual interaction of limestone and quartz during multi-component comminution, Figures 2 and 3 plot the breakage rates at grinding media stress energies of 0.032 mJ and 0.515 mJ against the volumetric energy input. Following Fragnière et al. [13], this input is defined as the product of grinding media stress energy SE_{GM} and stress frequency SF divided by the total particle count n_p. In all cases, the breakage rate rises with energy input until it peaks at $SE_{GM} \cdot SF/n_p = 2 \times 10^{-24}$ J/s, demonstrating effective comminution regardless of the applied stress energy. Beyond this maximum, for $SE_{GM} \cdot SF/n_p > 2 \times 10^{-24}$ J/s, the breakage rate declines as coarser particles become increasingly resistant to breakage. Throughout the stress energy spectrum, quartz consistently shows lower breakage rates than limestone, owing to its greater hardness. Moreover, both minerals exhibit reduced breakage in the mixed system versus their single-component performance – limestone because of the protecting effect by harder quartz particles, and quartz because of its decreased capture probability under the short process times studied.

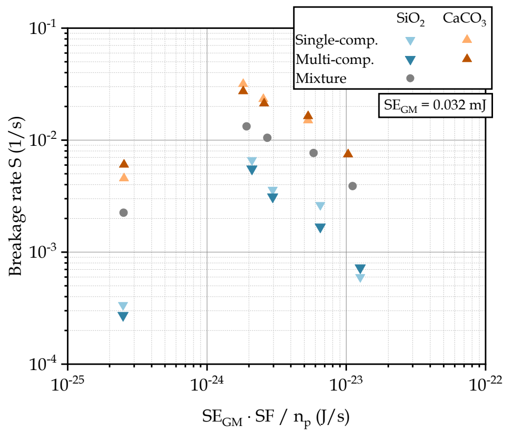

Figure 2. Breakage rate of quartz, limestone and their mixture as a function of $SE_{GM} \cdot SF/n_p$ for a grinding media stress energy of 0.032 mJ.

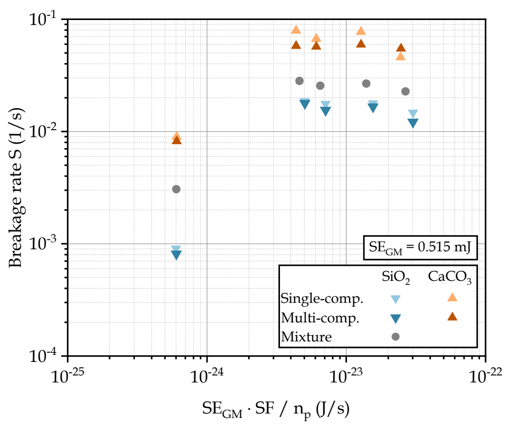

Figure 3. Breakage rate of quartz, limestone and their mixture as a function of $SE_{GM} \cdot SF/n_p$ for a grinding media stress energy of 0.515 mJ.

These interactions also strongly affect particle transport in passage mode operation. Figure 4 plots the quartz fraction in the mill discharge over time and shows that, at media stress energies up to 0.26 mJ, the harder quartz component accumulates at relatively constant values inside the grinding chamber. Insufficient breakage of quartz particles means that the relatively coarse particles are held back by the centrifugal forces at the deflector wheel rather than being discharged. With a constant media size, higher stirrer speeds exacerbate this retention. By contrast, at a sufficiently high stress energy (SE_{GM} = 0.375 mJ), quartz is broken more effectively, weakening the deflector's classification effect and allowing the quartz fraction in the product to rise steadily toward the feed composition. In practice, as comminution continues and quartz particles become progressively weaker, even lower energy regimes will eventually deliver a product whose quartz content matches that of the feed mixture.

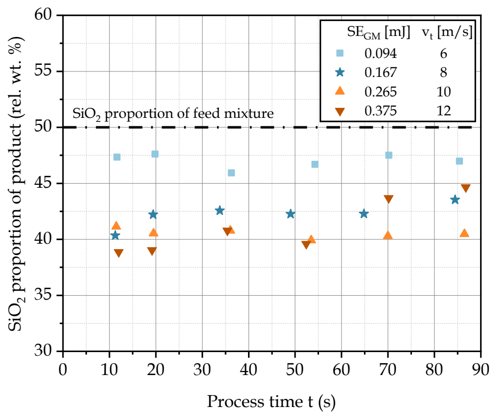

Figure 4. Quartz proportion of the product at the outlet of the stirred media mill as a function of process time for varying stirrer tip speeds and corresponding grinding media stress energies operating the stirred media mill in passage mode.

5. Conclusion

This study used quartz and limestone to investigate multi-component comminution in short-term batch tests, comparing single-component and multi-component systems. Breakage rates were directly correlated with grinding media stress energy, stress frequency and particle count. Limestone consistently exhibited higher breakage rates than quartz due to its lower hardness, both alone and in the mixture. In multi-component systems, both minerals break less efficient than in single-component tests – attributed to a protection effect of quartz on limestone and to a reduced capture probability for quartz. Different breakage kinetics also influenced material holdup: in 90 s passage mode tests, quartz accumulated in the mill regardless of stirrer speed, although higher stress energies mitigated this build-up. Future work will combine comminution and transport studies via residence time distributions to refine predictive PBM models.

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