Mechanochemical clay activation: energy demand, stressing mechanics, and implications for industrial scalability

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Abstract. Mechanical activation of clays is a promising route to reduce clinker content in modern cements and to enable sustainable binder systems. However, the transfer of mechanochemical activation from laboratory scale to continuous industrial processing remains a major challenge. This study discusses the limitations of conventional batch-based mechanochemical approaches and presents dry agitated bead mills as a scalable and industrially proven solution. Based on stress energy considerations, contact frequency analysis, and comparison with conventional ball mills, the suitability of dry agitated bead mills for large-scale clay activation is demonstrated. Industrial reference data from the Pamir 12,000 meca-clay plant underline the feasibility of continuous mechanical activation at high throughput and energy density.

1. Introduction

Reducing CO_2 emissions in cement production requires a substantial decrease of the clinker factor, increasingly through the use of supplementary cementitious materials (SCMs). As conventional SCMs such as slag and fly ash become scarce, clay-rich raw materials have gained renewed interest due to their wide availability. Untreated clays usually exhibit low reactivity and therefore require activation prior to cement application [1].

Thermal activation by calcination is well established but associated with high energy demand and CO_2 emissions. Mechanochemical activation has therefore emerged as an alternative or complementary route, relying on intensive mechanical stressing to induce structural disorder and enhance reactivity [1]. Previous studies demonstrate that milling alters clay crystal structures and surface chemistry, but activation efficiency is strongly influenced by operating parameters and equipment type [2,3]. Most investigations rely on laboratory-scale planetary ball mills, which operate in batch mode and suffer from limited industrial scalability [1,3].

Agitated bead mills, in contrast, are widely used in industrial fine and ultrafine grinding and operate at high power densities with predominantly shear and compression stressing. Recent studies indicate that dry agitated bead mills can induce pronounced mechanochemical effects with superior energy efficiency compared to conventional ball mills [4–9]. This work therefore examines dry agitated bead mills as an industrially viable activation technology for clays.

2. Material & Methods

Clay-containing raw materials relevant for use as SCMs were processed in dried condition without prior thermal activation. Standard pre-crushing and drying ensured stable feeding. Wear-resistant ceramic grinding media were selected to enable intensive stressing under dry conditions.

For industrial scale-up, a dry agitated bead mill with a grinding chamber volume of 12,000 L was analysed (see Figure 1). Scale-up was based on maintaining dominant stressing mechanisms rather than strict geometric similarity. Stress intensity and stressing frequency—governed mainly by agitator tip speed, media size, and filling degree—were selected as key scale-up criteria.

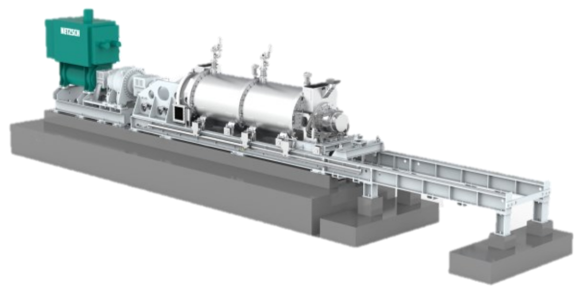

Figure 1. Industrial dry agitated bead mill (12,000 L grinding chamber volume) considered for the scale-up and evaluation of continuous mechanochemical clay activation.

Discrete Element Method (DEM) simulations were conducted to analyse grinding media motion, collision

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frequency, and stress energy distributions. The simulations provided qualitative insight into internal stressing conditions and supported comparison across mill sizes and operating points.

3. Results & Discussion

3.1. Energy demand and tunability of activation quality

Mechanochemical clay activation is governed by cumulative milling input energy rather than discrete activation events [1–3]. Literature data show that comparable activation states can be achieved at very different energy inputs depending on material system and milling configuration. Energy reductions of more than 50 %—and up to approximately 90 %—have been reported while still achieving sufficient reactivity for cement applications [3,10] (see Figure 2).

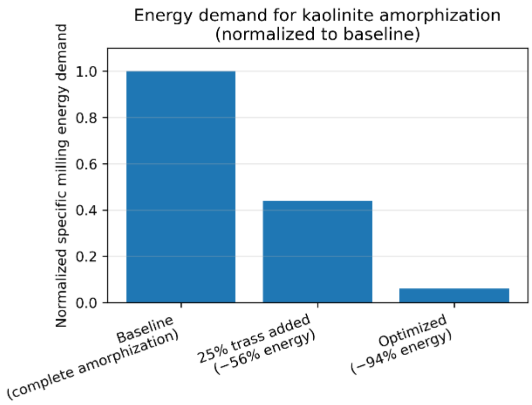

Figure 2. Normalized specific milling energy demand required to achieve comparable kaolinite amorphisation under different material and process configurations, illustrating that activation energy demand is not unique and can be significantly reduced through optimisation.

The energy–reactivity relationship is inherently non-linear. Reactivity increases rapidly at low energy input due to defect formation and early-stage amorphisation, followed by saturation at higher energies where additional input is increasingly dissipated [3] (see Figure 3). Consequently, activation quality is tunable by matching stress intensity and stressing frequency to a material-specific effective energy window, rather than maximising energy input.

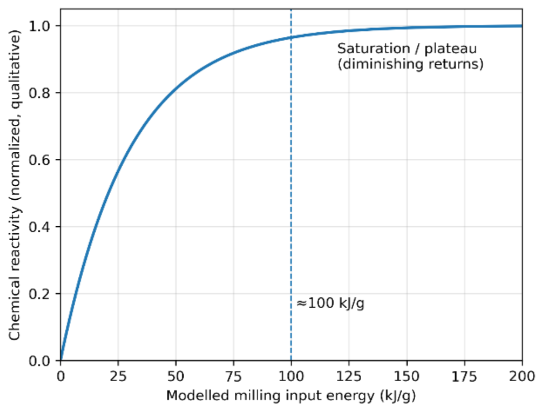

Figure 3. Schematic relationship between cumulative milling input energy and chemical reactivity of clays, showing rapid reactivity increase at low energy input and saturation at higher energy levels (qualitative).

3.2. Limitations of tumbling ball mills

Comparisons between tumbling ball mills and agitated bead mills at comparable scale show fundamentally different stressing characteristics [6,9] (see Figure 4). Ball mills exhibit low stressing frequencies and broad stress-energy distributions, resulting in long residence times to achieve activation-relevant cumulative energy input. Even large two-chamber ball mills require disproportionally large volumes to reproduce the stressing conditions readily achieved in small agitated bead mills.

This leads to unfavourable throughput-to-footprint ratios and restricts ball-mill-based activation to laboratory or pilot scale. While activation is technically possible, industrial implementation becomes impractical due to low achievable throughput relative to installed equipment size.

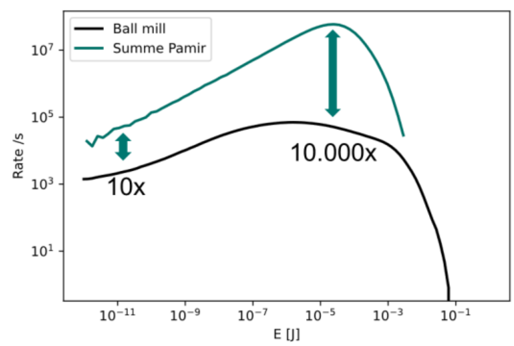

Figure 4. Comparison of stressing rates as a function of stress energy for a tumbling ball mill and an agitated bead mill at comparable mill size, highlighting fundamentally different stressing characteristics governed by the milling principle rather than geometric scale.

3.3. Industrial relevance of agitated bead mills

Figures 5 and 6 together convey a clear scale-feasibility argument for mechanochemical clay activation. Figure 5 illustrates the substantial size difference between the investigated systems, comparing a large two-chamber tumbling ball mill (≈ 125 m³ grinding volume) with a laboratory-scale agitated bead mill (Pamir 40 L). Figure 6 subsequently compares the corresponding stress-energy distributions obtained in these two systems. The figures demonstrate that, in order to reach stressing conditions comparable to those generated in the small agitated bead mill, a ball mill of orders-of-magnitude larger volume is required.

Figure 5. Comparison of system scale between a two-chamber tumbling ball mill (≈ 125 m³) and a laboratory-scale agitated bead mill (Pamir 40 L), illustrating the large volume difference required to access comparable stressing regimes.

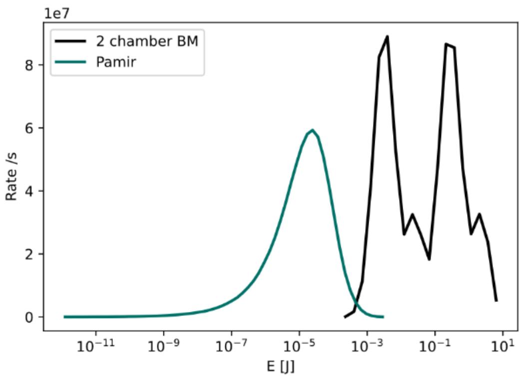

Figure 6. Stress-energy distributions of a large two-chamber tumbling ball mill and a small agitated bead mill (Pamir 40 L), showing that comparable activation-relevant stressing conditions in a ball mill require substantially larger equipment.

3.4. Influence of clay mineralogy

Activation efficiency strongly depends on clay mineralogy. Kaolinitic clays generally respond more readily to mechanochemical activation than 2:1 clays or mineralogically heterogeneous systems [3]. In such cases, stand-alone mechanical activation may be insufficient, and combined mechanical–thermal routes may be required [1–3].

Industrial activation technologies must therefore allow flexible adjustment of stressing conditions and energy input to accommodate clay-specific responses and targeted performance levels.

4. Conclusions

Mechanochemical activation of clays is controlled by cumulative energy input, stressing mechanics, and mineralogy, resulting in a non-linear and tunable energy–reactivity relationship. Tumbling ball mills are intrinsically limited by low stressing frequency and unfavourable scale-up behaviour, restricting activation to non-industrial throughput.

Dry agitated bead mills provide activation-relevant stress intensities combined with very high stressing frequencies, enabling efficient energy utilisation at high throughput and compact scale. Their flexibility further allows adaptation to clay-specific activation requirements. Overall, industrial clay activation favours high-power-density agitated systems over conventional tumbling mills for scalable and energy-efficient mechanochemical processing.

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