Tumbling v. planetary ball mills for mechano-chemical activation of clays at industrial scale: can the tortoise beat the hare?

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Keywords: Clay minerals; Clays; Mechano-chemical activation; Planetary ball mill; Tumbling ball mill

ABSTRACT

Activated clays can be used as pozzolans for partial substitution of Portland cement. Activation of clays is most commonly carried out by thermal activation (i.e. calcination). An alternative activation route is to use an intensive grinding treatment, known as mechano-chemical activation [1]. Interest in this alternative is motivated by the desire to avoid heating clay to high temperatures, and the prospect of being more effective for activating a broader range of clay minerals beyond kaolinite. The intensive grinding process induces structural disorder by dehydroxylation and amorphization of a clay mineral's crystalline structure [1]. Concrete made using mechano-chemically activated clay has shown very similar qualities to conventional concretes [2].

Among the many knowledge gaps around mechano-chemical activation, there is an outstanding question around scalability – mechano-chemically activated clay has not yet been used for construction on any scale. For laboratory-scale studies, the most commonly used mill type is the planetary ball mill (PBM). However, in industry, PBMs have not been used at scale whereas the tumbling ball mill (TBM) is ubiquitous. The difference in rotational movements between a PBM and TBM is shown in Figure 1. Mechanical interactions include the striking of grinding media (in most cases, stainless steel balls) against the material, and the shearing (frictional) force between surfaces. Grinding processes are sensitive to numerous parameters, including: dimensions of a milling system, rotation speed, clay type and moisture content. Practical problems can arise with both the clay (agglomeration, caking) and mill machinery (wear, overheating).

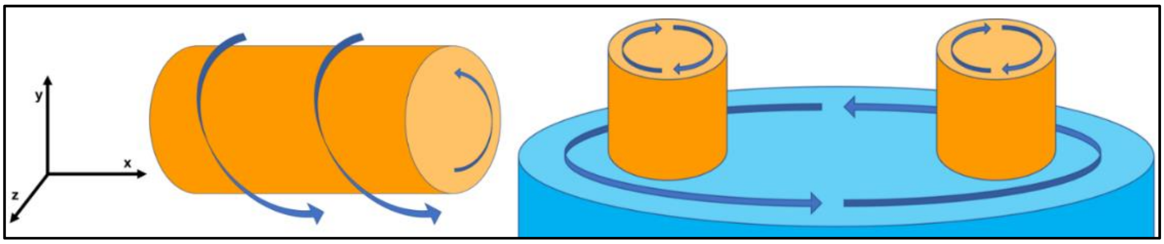

Figure 1. Tumbling (TBM) and planetary (PBM) ball mill schematics. Arrows show directions of rotation.

This study sought to address the question: which of these two mill types offers the best prospect for scaled-up production of mechano-chemically activated clay? A synthesis of current knowledge was used to evaluate their potential, structured around three different aspects: achievable impact energy; evidence base from laboratory-scale studies; and industrial upscaling feasibility.

Impact energy. The grinding rate of a ball mill depends on the intensity and frequency of collisions between the grinding media and milled material. The PBM has rotation speed an order of magnitude greater than the TBM at laboratory scale, up to 600 rpm. The rotation speed of a TBM is limited in practice – a speed too great would result in a transition from a cataracting regime to an unfavourable rolling regime [1]. As a result of this difference in rotation speeds, a PBM can produce acceleration up to 150 times greater than a TBM [3]. Consequently, mechano-chemical activation in a PBM involves milling for a short time at high impact energy, whereas the TBM requires much longer milling times due to its low impact energy. A disadvantage of higher rotation speed is a higher extent of caking [4]. Considering wear of the milling apparatus - a grinding mill that favours direct impact and compression collisions, rather than shearing, could be favourable to reduce wear of grinding balls [5]. This would in theory favour use of the PBM.

Laboratory-scale studies. PBMs dominate the evidence base for laboratory-scale research studies (n > 20) compared to TBMs (n = 2). The milling parameters vary between studies but are usually found within the envelope of: rotation speed = 400 - 600 rpm; grinding time = 15 minutes - 8 hours. The evidence base for TBMs so far shows that far longer grinding times are necessary, compared to PBMs. 20 hours of grinding in a TBM [6] caused comparable (at best) amorphization to what is achievable in a PBM in < 1 hour. These experimental findings validate the theoretical expectation that mechano-chemical activation is a 'fast and furious' process in PBMs, while it is a 'slow and steady' process in TBMs.

Industrial upscaling. TBMs exist at industrial scale in several sizes, with both batch and continuous production possible. However, traditional separation methods (based on particle size) used in continuous production would not be suitable for mechano-chemical activation. General comminution theory suggests that industrial scale processing is more than one order of magnitude worse in energy 'efficiency' than at laboratory scale [7], though it is not yet known whether this relationship is valid for mechano-chemical activation of clays. For PBMs, scale-up may be advantageous for activation efficiency – modelling work has predicted an exponential increase (n = 4.87) in impact energy with increasing system scale, for a given rotation speed [8]. However, PBMs are not yet available on industrial scale, with large installation sizes exhibiting major technical difficulty in mill drive systems, including excessive heat in grinding chambers [9].

Table 1. Summary of key aspects for planetary ball mill and tumbling ball mill.

Aspect	Tumbling Ball Mill	Planetary Ball Mill
Laboratory studies	Very limited available data. For dry grinding only.	Several research studies. Understanding of optimal grinding parameters is still limited.
Impact energy	Ball acceleration is limited to 1 g (i.e. 9.81 ms^{-2}) – classified as a 'low-energy' mill [3].	Ball acceleration up to 150 g – classified as a 'high-energy' mill [3].
Grinding time	Longest trialled time is 20 hours. Large scale production would ideally be much quicker.	Optimum grinding time achieved at as little as 20 minutes. This is efficient timing for large scale production.
Rotation speed	Maximum rotation speed limited by transition to rolling regime.	Capable of higher rotation speed than required for optimal laboratory scale grinding [4].

Production type	Potential for batch and continuous production methods.	Batch production only.
Energy efficiency	Comminution efficiency expected to decrease with upscaling [7].	Impact energy increases with upscaling – but not yet tested beyond laboratory scale [10].
Industrial upscaling	Industrial scale TBMs widely available.	Large PBMs not yet used – major challenges with drive systems [9].

In conclusion – it is too early to predict whether the PBM 'hare' (with its quick process times but uncertain scalability) or the 'TBM' tortoise' (with its slow process times but more straightforward scalability) may win the 'race' to industrial-scale mechano-chemical activation. To better predict optimal grinding conditions for both mill types, an improved understanding of the particle collision mechanics is needed. As a first step to exploring PBM scalability, modelling is needed to predict whether an industrial-scale PBM is capable of safely attaining the necessary rotation speeds. Whilst industrial-scale TBMs exist widely, mechano-chemical activation trials using the necessary grinding times would generate knowledge of high practical value. Input-output analysis of such trials would also help address the open question of whether mechano-chemical activation would be preferable (relative to calcination) in terms of embodied carbon.

Acknowledgment: The authors would like to express appreciation for the support of EPSRC [EP/R001642/1].

References:

1. Tole, I., K. Habermehl-Cwirzen, and A. Cwirzen, *Mechanochemical activation of natural clay minerals: an alternative to produce sustainable cementitious binders – review.* Mineralogy and Petrology, 2019. **113**(4): p. 449-462.
2. CSI/ECRA, *Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead*, in *CSI/ECRA-Technology Papers 2017*. 2017: Dusseldorf.
3. Yokoyama, T. and Y. Inoue, *Chapter 10 Selection of Fine Grinding Mills*, in *Handbook of Powder Technology*, A.D. Salman, M. Ghadiri, and M.J. Hounslow, Editors. 2007, Elsevier Science B.V. p. 487-508.
4. Tole, I., et al., *Activation of a Raw Clay by Mechanochemical Process—Effects of Various Parameters on the Process Efficiency and Cementitious Properties.* Materials, 2018. **11**(10).
5. Meulendyke, M.J. and J.D. Purdue, *Wear of grinding media in the mineral processing industry: An overview.* Mining, Metallurgy & Exploration, 1989. **6**(4): p. 167-172.
6. Ilić, B., et al., *Study on the addition effect of metakaolin and mechanically activated kaolin on cement strength and microstructure under different curing conditions.* Construction and Building Materials, 2017. **133**: p. 243-252.
7. Schneider, M., *Process technology for efficient and sustainable cement production.* Cement and Concrete Research, 2015. **78**: p. 14-23.
8. Mio, H., J. Kano, and F. Saito, *Scale-up method of planetary ball mill.* Chemical Engineering Science, 2004. **59**(24): p. 5909-5916.
9. Rosenkranz, S., S. Breitung-Faes, and A. Kwade, *Experimental investigations and modelling of the ball motion in planetary ball mills.* Powder Technology, 2011. **212**(1): p. 224-230.
10. Mio, H., et al., *Optimum revolution and rotational directions and their speeds in planetary ball milling.* International Journal of Mineral Processing, 2004. **74**: p. S85-S92.