# A cement Vertical Roller Mill modeling based on the number of breakages

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# A cement Vertical Roller Mill modeling based on the number of breakages

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ABSTRACT

This study investigated a mathematical model for an industrial-scale vertical roller mill(VRM) at the Ilam Cement Plant in Iran. The model was calibrated using the initial survey's data, and the breakage rates of clinker were then back-calculated. The modeling and validation results demonstrated that according to the bed-breakage mechanism in VRM, clinker particles only stay in the VRM for a short time. Particles in the VRM haven't a 1 to 3 times greater chance of breaking due to their brief time in the VRM. Matrix model's results model provides a more robust prediction based on the number of 2-times clinker breakage in VRMs ($R^2$ = 0.9916, MSE = 5.3526, accuracy = 94.6474). Also shown by the results of the matrix modeling, the S increased with decreasing the particle size. In contrast, the population balance model increased with increased particle size.


## 1. Introduction

Vertical roller mills (VRM) are widely used to grind, dry, and select powders from various materials in the cement, electric power, metallurgical, chemical, and nonmetallic ore industries. For the sectors above, the VRM is a powerful and energy-intensive grinding field [1,2]. It is used to grind slag, nonmetallic ore, and other block and granular raw materials into the fine powders necessary for production. In the mid-1990s, Loesche GmbH developed the VRM technology, which was first used for grinding clinker and slag [3]. Fig. 1 shows the components of a Loesche mill used for grinding. VRMs are the most popular choice for finished cement grinding over other machines due to low power consumption, higher capacity, process simplifications, and compactness. However, VRMs are extremely sensitive to vibrations, and productivity can be negatively affected if process optimization is slightly altered [4]. VRMs, which have achieved widespread adoption in the cement industry and are used for crushing raw materials (mainly limestone), represent an exciting alternative [5].

The VRM operates on the principle of interparticle comminution, considered the most efficient form of particle breaking [7]. The gap between the rotating grinding table and the stationary grinding rollers is where interparticle comminution occurs [8]. Although there are various VRMs, the breakage principles are the same. Loesche uses a master and supports the roller mechanism. Support rollers(S-Rollers) are used to prepare and stabilize the grinding bed, while the master rollers(M-Rollers) transmit the grinding force for interparticle comminution [9]. This mechanism decreases the dynamic load on each component during operation and ensures that the mill runs smoothly [10]. Fig. 2 illustrates the operation principle of M-Rollers and S-Rollers in VRM. The material layer generated between the roller and the revolving table is the grinding bed. The grinding bed is the fundamental factor in the proper operation of a VRM, as defined by the feed size, feed material, moisture content, dam ring height, fineness of grind, and nozzle ring airspeed [4]. VRMs have several advantages over conventional grinding equipment regarding mining industry difficulties. An energy-efficient breaking up of a particle bed results in a smaller particle size distribution (PSD). Because they only grind a small quantity of each particle before classification, VRMs reduce the need for excessive over-grinding.

Simulation is a valuable tool in process technology if the process models are accurate and can determine model parameters in a laboratory or plant. It is now widely utilized for designing and optimizing wet grinding circuits, resulting in significant cost savings [11].

Austin was the first to develop a full-scale cement mill mathematical model [12,13]. His approach has two key concepts: the

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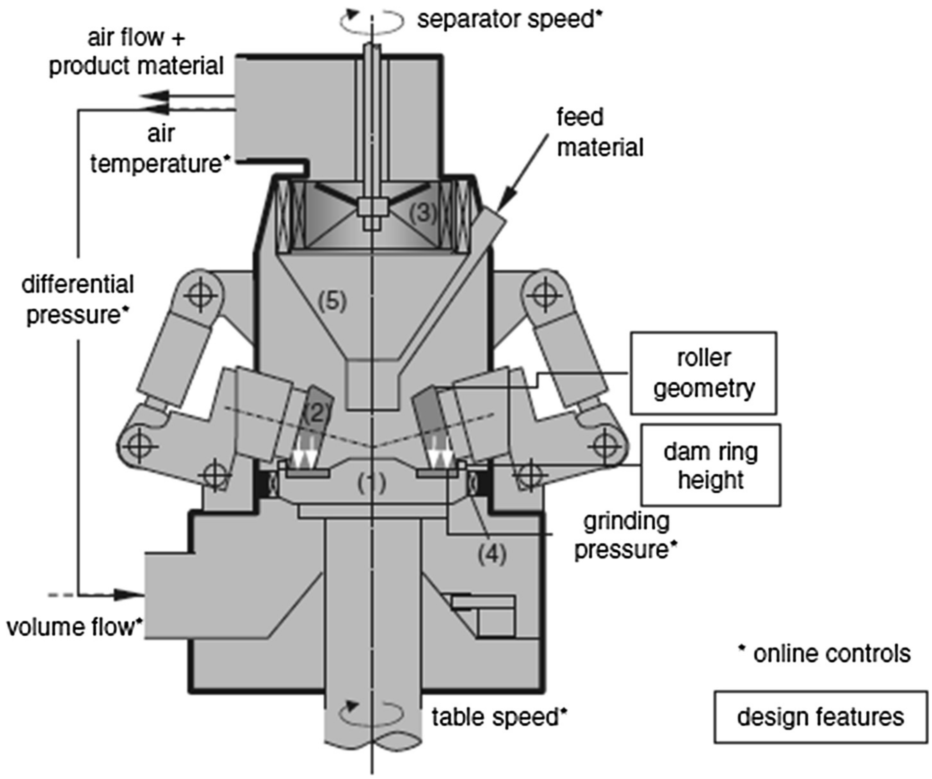


**Fig. 1.** Schematic operation principle of a VRM [6].

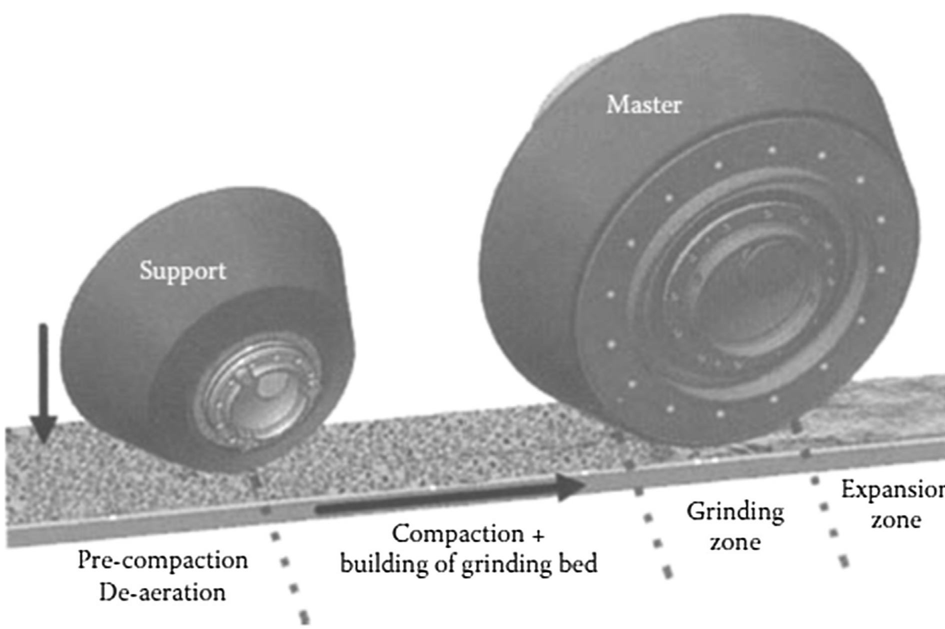


**Fig. 2.** Working principle of the M and S rollers.

breakage rate and the mill residence time. The model considers the mill equivalent to several grinding stages with internal classification in series, assuming the cement mill model was equivalent to a thoroughly mixed ball mill [14]. Only a few studies have been conducted on the simulation of VRMs [15]. Wang, Chen et al. 2009 use a matrix model to replicate the grinding process in VRMs. It was developed based on experimental data from cement clinker, coal grinding lines, and laboratory experiments [15]. VRMs are simulated using high-efficiency classifiers, matrix models, and other methods. Faitli, J. and P. Czel developed a matrix model to model a VRM with a high-efficiency slat classifier [16]. Esnault et al. predicted the breakage particles in milling under pressure using a population balance model [17]. There were no breakages in the clinker cement, limestone, and quartz modeling tests. The difference in particle weakening behaviors in pure and mixed feed grinding by HPGR was effectively explored by [18].

In a study by [19], the compressed bed breakage test in a piston-die cell device was used to establish the breakage distribution function of the material in the VRM, to simulate cement grinding, the perfect mixing model was applied. The results demonstrated that the perfect mixing model accurately predicted the grinding process of a VRM (VRM). Fatahi and Barani used the population balance model to model the VRM, and According to the findings, the specific breakage rates increased as particle size increased [20]. In the cement clinker grinding circuit, the residence time distribution in a VRM was measured by applying the dispersion model, the tank-in-series model, and the perfect mixer with a bypass [21]. In Research by [15], to the expression of the probability of material breakages in the grinding circuit, by using the selection function, the breakage function, simulation of VRM has been done in Research by [16]. Also, artificial intelligence techniques have been used in the cement industry to simulate vertical roller and ball mills [22,23]. A matrix model for a VRM with a high-efficiency classifier has been used. The behavior of material breakages, their mechanism, and their relationship with the mean residence time (MRT) haven't been investigated. In contrast, in this Research, the relationship between the MRT of VRMs and the number of breakages has been studied, which provides a proper understanding of particle breakage behavior in VRMs.

So far, no research has been done to investigate the number of particle breakages inside VRMs. Because the residence time is so short in VRMs, the number of times the particles are broken is relatively low, resulting in few particle breakages. Modeling the number of breakages in these mills can help us better understand the impact of comminution behavior and mechanism as well as the relationship between comminution efficiency and the mill's capacity to grind. The excellent efficiency of these mills is attributable to the breakage of particles in the least amount of time; therefore, it is nessacary to investigate the breaking of particles in these mills.

## 2. Experimental method

In this study, all the samples were obtained from the clinker grinding line 2 of the Ilam cement plant in the Iranian province of Ilam-karezan. Used a VRM (Loesche mill) with 160 t/h to grind the clinker, fed into the mill during the grinding process (%90 passing 32 mm). Fig. 3 shows the grinding circuit for VRMs. The Loesche VRMs at the Ilam cement plant are equipped with four rollers, two of which are master rollers and small support rollers performing grinding and layering of the material on the grinding table, respectively.

### 2.1. Sampling

In the VRM, critical operational parameters, such as classifier rotor speed, grinding pressure, and gas flow rate of the VRM, are effective in the grinding process [24] and would be constant during sampling Table 1. On the grinding circuit, we carried out two sampling surveys. The first set of survey data was utilized for circuit simulation and modeling, using the second set of survey data for circuit validation and verification. Used the feed and product samples to measure the PSD with high accuracy in the Iran Mineral Processing Research Center using the Laser Particle Size Analyzer devices. The PSD of product results is needed to create the PSD curve. Fig. 4 shows the PSD curve of feed and product.

### 2.2. Breakage function

The breakage function, $B$, represents the relative distribution of each size fraction after the breakage. The function depends on the property of the material and can be expressed as a matrix [15]:

$$B = \begin{bmatrix} B_{ij} & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ B_{i1} & \dots & B_{ij} & \dots & \dots \\ \dots & \dots & \dots & \dots & 0 \\ B_{n1} & \dots & B_{nj} & \dots & B_{nn} \end{bmatrix} \quad (1)$$

The breakage functions of VRMs are distinct compared to ball mills because the breakage mechanism in VRMs is compression and shear forced. The materials are placed between the rollers and grinding tables in layers of particles and comminuted under the pressure of compressive forces [25].

The breakage function utilized during this study was developed by [19]. The breakage function was evaluated using the well-known lab-scale compressed bed breakage test during a piston-die cell system, which has been extensively investigated. Furthermore, used the following equation to fit the data [26]:

$$B_{i,j} = \left(\frac{x_i}{x_j}\right)^{\gamma} + (1-\phi)\left(\frac{x_i}{x_j}\right)^{\beta} \text{ or } B_{i,j} = (R)^{\gamma} + (1-\phi)(R)^{\beta} \quad (2)$$

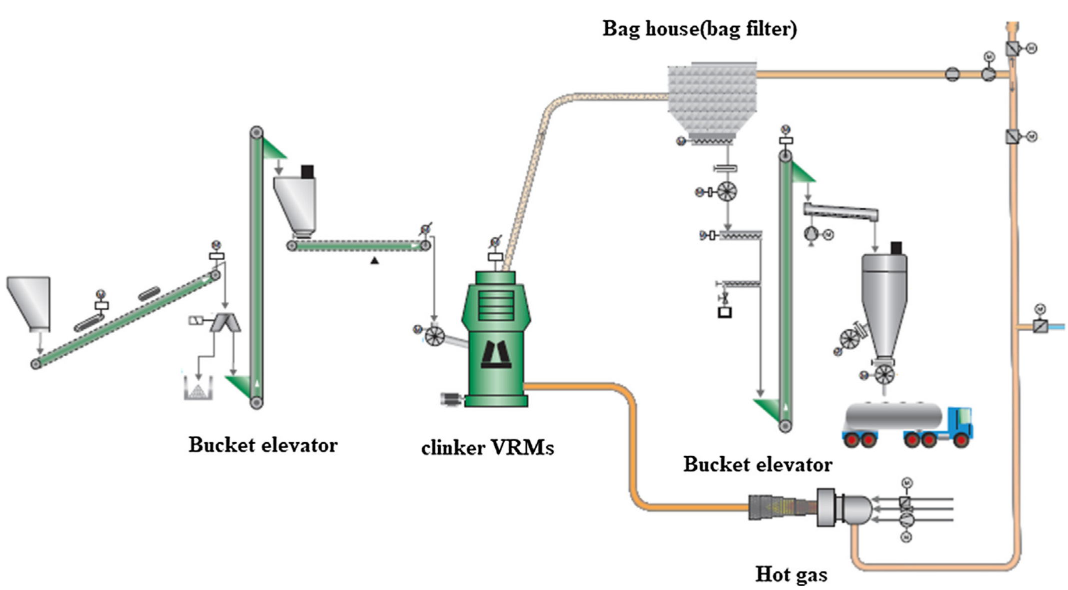


**Fig. 3.** Grinding circuit of the VRMs.

**Table 1**
Operational variables for the VRMs of the Ilam cement plant.

| Description of variables | Variables | Value |
|---|---|---|
| The speed of the classifier rotation | Classifier Speed (rpm) | 65 |
| A load of mill feed | Feed rate(ton/hr) | 140 |
| The required pressure of the master roller for clinker grinding | Working Pressure (bar) | 84–85 |
| The required pressure for lifting the master roller | Counter Pressure (bar) | 18–20 |
| The speed of mill fan rotation | Mill fan Rotation (rpm) | 700–750 |
| The required gas flow for cement transportation | gas flow rate ($m^3$/hr) | 510000–520000 |

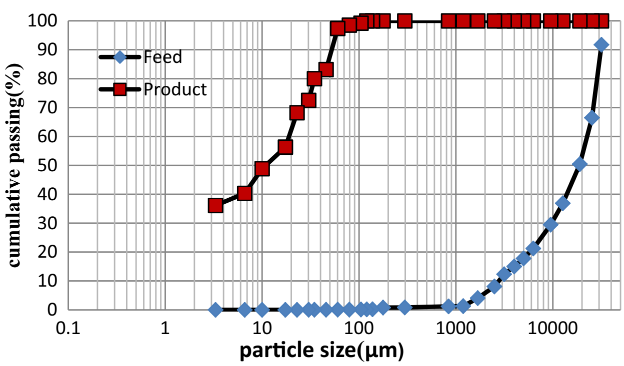


**Fig. 4.** Measured PSD of feed and product of the VRM.

$B_{i,j}$ is the fraction of particles from the jth interval broken and transferred to the ith interval of particles. $X_i$ and $X_j$ are the sizes of friction ith and jth fraction, respectively, $\varphi$, $\gamma$, and $\beta$ are model parameters, and $R$ is the relative size (x/x) ratio of $i$-th and first size fraction. The values of φ, γ, and β were determined using lab-scale compressed bed breaking experiments as Shahgholi, Barani et al. (2017). The fitted model parameters were employed since the sample feed of Shahgholi et al. and the sample feed (clinker) of the previous study (Fatahi and Barani 2020) was the same. By fitting Eq. (2) to the model's data, the following parameters were calculated: φ = 0.966, γ = 0.31863 and β = 0.31862 [19].

Because clinker samples have the identical physical charactries and chemical composition, the re-producibility of these coefficients for all PSDs of feed holds true. According to Eq. (1), Table 2 shows the breakage function as a lower triangular matrix, where:

$$B_{1,1} = B_{2,2} = B_{3,3} \ldots\ldots\ldots\ldots B_{n,n} = 1 \qquad n \geq 1$$
$$B_{2,1} = B_{3,2} = B_{4,3} \ldots\ldots\ldots\ldots B_{n,n-1} = 1 \qquad n \geq 2$$
$$B_{1,1} = B_{2,2} = B_{3,3} \ldots\ldots\ldots\ldots B_{n,n-2} = 1 \qquad n \geq 3$$

### 2.3. Selection function

Let the breakage probability of size fraction $i$ will be $S_i$. This selection function can be expressed as a diagonal matrix [15]. Here is what the selection function looks like, which can be represented as a diagonal matrix:

$$S = (S_1, \ldots, S_i, \ldots, S_n) \tag{3}$$

### 2.4. Matrix model

The relationship between the selection function S and feed analysis was illustrated using a matrix model [27]. The feed and product size distributions were represented as N size ranges to represent the feed and product size distributions. Created the matrix based on the assumption that Si represents the proportion of particles within a sieve fraction, i, that would break preferentially (the others being too small). Now that the total number of broken and unbroken particles has been calculated, the generic equation can use Eq. (4) to express the entire breakage operation [28]:

$$P = [B.S + (I - S)].F \tag{4}$$

This model, which provides a quantitative relationship between feed and product, has been frequently used and presented with acceptable results. Of course, this equation is only valid for one-time breakage cycles. Eq. (4) can be stated in the following form for further breakage:

In the grinding process of a VRM, three types of forces are assigned: compression, shear, and centrifugal, with compression forces attributed to breakage function (B) in the matrix model. The grinding process (S) determines the mill's selecting function. When a compression force is given to the particle bed, the material is moved and disseminated onto the rotating plate (table) by centrifugal force. In contrast, the mill's table rotates, and compression breakage occurs.

### 2.5. Number of breakages

According to the previous study, the clinker particle spends around 67 s in the VRM [21]. Because the residence time is short, it is possible to estimate the number of particle breakages between 1 and 3 times the total number of particles [20]. Table 3 compares the breakages in cement VRM and cement ball mills [29]. In the

**Table 2**
Lower triangular matrix of breakage function.

| i | j 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | …28 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **1** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **…...** |
| **2** | **0.93137** | **1** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **…...** |
| **3** | **0.84979** | **0.93137** | **1** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **…...** |
| **4** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **0** | **0** | **0** | **0** | **0** | **…...** |
| **5** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **0** | **0** | **0** | **0** | **…...** |
| **6** | **0.5973** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **0** | **0** | **0** | **…...** |
| **7** | **0.5549** | **0.5973** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **0** | **0** | **…...** |
| **8** | **0.51681** | **0.5549** | **0.5973** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **0** | **…...** |
| **9** | **0.47893** | **0.51681** | **0.5549** | **0.5973** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **0** | **…...** |
| **10** | **0.44493** | **0.47893** | **0.51681** | **0.5549** | **0.5973** | **0.68139** | **0.7468** | **0.84979** | **0.93137** | **1** | **…...** |
| **…28** | …… | …… | …… | …… | …… | …… | …… | …… | …… | …… | **1** |

**Table 3**
Comparative performance parameters for the two systems when used for grinding cement.

| Characteristics | Ball mill (closed circuit) | VRM |
|---|---|---|
| Comminution by | Impact and attrition | Pressure and shear forces |
| Residence time(miutue) | 20–30 | Less than 1 min |
| Crushing before separation(time) | Infinite | 1–3 |
| Circulation factor(C.L/Feed) | 2–3 | 6–20 |
| Wear rate(g/ton) | 50 | 3–6 |

VRM, MRT indicates that the particles are broken just once and maybe up to three times in the grinding process. Can use Eq. (5) to calculate the Si-based on a 1 to 3-times breaking scenario (V = 1 to 3).

$$P = [B.S + (I - S)]^V.F \tag{5}$$

$$\begin{bmatrix} P_1 \\ P_2 \\ P_n \end{bmatrix} = \left[\left(\begin{bmatrix} B_{i,j} & 0 & 0 \\ B_{i,1} & B_{i,j} & 0 \\ B_{n,1} & B_{n,j} & B_{n,n} \end{bmatrix} * \begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_n \end{bmatrix}\right) + \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_n \end{bmatrix}\right)\right]^v * \begin{bmatrix} F_1 \\ F_2 \\ F_n \end{bmatrix}$$

where P is product Column matrixes(N × 1), F is feed Column matrixes(N × 1), and S is selection function diagonal matrixes (N × N). I is that the identity matrixes(N × N), and B could be is a lower triangular matrix(N × N) where N: sieve number and V is the number of breakage times, which is proportional to the (MRT).

### 2.6. $S_i$ calculations

To calculate $S_i$ by inserting the calculated values of the breakage function(B) in Table 2 and identity matrix(I) and feed(F) as well as product (P) matrixes in Equation (5), the number of times of breakage(V) 1 to 3 times(Table 2). The selection function for the state (V = 2) was well calculated using the inverted calculations in the Excel spreadsheet. It used Eq. (5) to get the selection function values for 28 size fraction classes after applying the 2-times comminution(V = 2). Table 4 shows the results. The selection function is zero for feed particles with a particle size of less than 79.43 µm, indicating there's no possibility of comminution. Only a few particles have a particle size of less than 100 µm. The feed's PSD must be considered while designing a VRM. The PSD of feed and also the mill's operational parameters are essential for the product's PSD.

The majority of the clinker particles (d80 = 25 cm) are coarse. In VRMs, the bed-breakage mechanism is described Fig. 5. For breaking, coarse particles are chosen. Large feed particles were broken in the 1-time, but within the 2- time, most of the particles were broken and therefore became fine particles. As a result, decreasing the

**Table 4**
Model fitting results.

| Sieve number (i) | Sieve size (µm) | Cumulative Passing (%) | | Selection function $S_i$ |
|---|---|---|---|---|
| | | Feed | Product | |
| 1 | 31,750 | 90.8 | 90.8000 | 0.2180 |
| 2 | 25,400 | 63.24 | 100.1285 | 0.1297 |
| 3 | 19,050 | 48.94 | 100.1048 | 0.1701 |
| 4 | 12,700 | 35.14 | 100.0834 | 0.1272 |
| 5 | 9525 | 29.54 | 100.0819 | 0.1864 |
| 6 | 6300 | 21.54 | 99.9619 | 0.1494 |
| 7 | 5000 | 18.35 | 100.0011 | 0.1968 |
| 8 | 4000 | 13.05 | 99.8657 | 0.1926 |
| 9 | 3150 | 10.15 | 100.0356 | 0.2045 |
| 10 | 2500 | 7.55 | 99.6358 | 0.2982 |
| 11 | 1190 | 3.05 | 97.9242 | 0.3207 |
| 12 | 1000 | 1.12 | 97.8401 | 0.3446 |
| 13 | 841 | 0.95 | 98.2963 | 0.4622 |
| 14 | 297 | 0.63 | 98.6608 | 0.4999 |
| 15 | 177 | 0.57 | 98.7733 | 0.5399 |
| 16 | 138.038 | 0.34 | 98.7582 | 0.5744 |
| 17 | 120.33 | 0.00 | 98.5721 | 0.6244 |
| 18 | 104.71 | 0.00 | 98.2514 | 0.6011 |
| 19 | 79.43 | 0.00 | 96.9090 | 0.4720 |
| 20 | 60.26 | 0.00 | 92.9757 | 0.0000 |
| 21 | 45.71 | 0.00 | 83.7794 | 0.0000 |
| 22 | 34.67 | 0.00 | 75.6091 | 0.0000 |
| 23 | 30.200 | 0.00 | 68.1534 | 0.0000 |
| 24 | 22.91 | 0.00 | 61.4483 | 0.0000 |
| 25 | 17.38 | 0.00 | 55.5822 | 0.0000 |
| 26 | 10.00 | 0.00 | 49.7194 | 0.0000 |
| 27 | 6.607 | 0.00 | 44.3520 | 0.0000 |
| 28 | 3.311 | 0.00 | 39.1940 | 0.0000 |

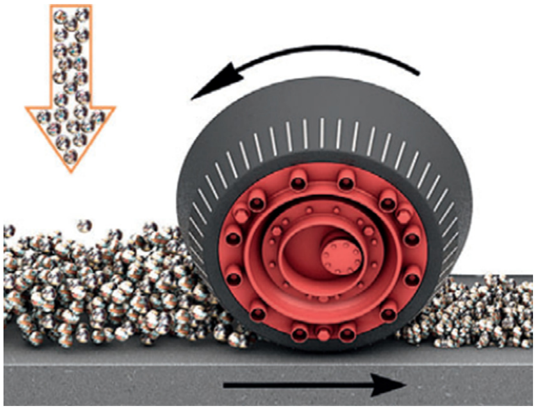

**Fig. 5.** The grinding mechanism of VRMs.

particle size enhanced the values of the selection function for the 2-times. According to the matrix model in VRMs and the bed-breakage mechanism, completed breakage in 2-times.

## 3. Results and discussion

### 3.1. Comparison between calculated $S_i$ matrix model and population balance model

A previous study focused on the population balance model in vertical roller [20]. This model used the (MRT), breakage function, selection function, and feed and product PSD. For a perfect mixed mill at a steady-state, the equation becomes [30]:

$$P_i = F_i + \left( \tau \sum_{\substack{j=1 \\ i>1}}^{i-1} b_{ij} S_j m_j \right) - S_i m_i \tau \tag{6}$$

for $N \geqslant i \geqslant j \geqslant 1 \quad P_i = \frac{F_i + \sum_{j=1}^{i-1} b_{ij} s_j \tau p_j}{1 + s_i \tau}$

where $\tau$ = MRT; $b_{ij}$ = breakage function; $S_j$ = selection function; $F_i$ = PSD of feed; and $P_i$ = PSD of product.

According to Eq. (6), to measure the size distribution of the final product, the mill ($P_i$), MRT ($\tau$), selection functions of different classes ($S_i$), breakage functions ($b_{ij}$), and mass in the screen classes ($m_i$) must be computed. In the population balance model, based on the modeling residence time distribution of mills, which predicts the mixing pattern of particles, particles with different ($S_i$), and ($b_{ij}$) have a different probability of breakages or different selection functions. In the population balance model, the selection functions of different classes ($S_i$), indicates that particles with different mixing patterns have different breakage probabilities, which are presented by units (1 / minute). At the same time, in the matrix model, it is expressed as values between 0 to 1 or 0 % to 100 %, which implies the probability of breakages using a number of breakages.

To examine specific breakage rates, researchers [20] analyzed a previous work that applied a population balance model to the VRM. In step with the results, the specific breakage rate declined as reduced the particle size from 25.4 cm to zero. Therefore the specific breakage rate of particles under 100 µm became zero Fig. 6. Smaller than 100 µm particles don't have any possibility of being ground. Breakage is proportional to particle size larger than 79.43 µm in the matrix model; hence, the likelihood of breakage is zero to particle size under the 79.43 µm. So, in the population balance model, larger particles have a greater chance of grinding, which is similar to the finding that larger particles are more likely to be ground than smaller ones. As seen in the 1-time matrix model, wherein the 2-times, smaller particles are more likely to be ground because coarse particles do not exist between the rollers and table. The common element in the matrix and population balance model is the selection function which is the breakage possibility of particles with PSD bigger than 177 µm.

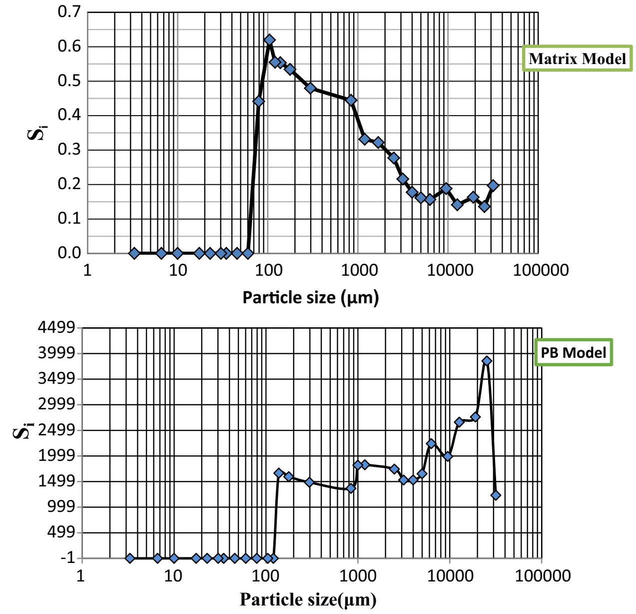


**Fig. 6.** Comparison $S_i$ matrix model and population balance model.

In VRM, the particles don't have much opportunity to be ground because of the short residence time. Therefore, the number of breakages is considerable, avoiding over-grinding. Concurrently, the population balance model has predicated on the mixing pattern inside the mill and also the hypothesis that the number of times of breakage doesn't amplify. The matrix model provides a good insight into the number of particle breakages in the VRM. In keeping with the results; it matches with the breakage number of times equal to 2 in VRMs.

### 3.2. Validation of the matrix model

Used sampling data from the second survey to validate the model's parameters. Operating pressure, classifier speed, and feed rate were all left unchanged. (Grinding pressure on the table or working pressure equals 85 bar). Other parameters, like material circulation rate, mill temperature, hot gas flow rate, material reject rate, and grinding table speed, were constant between the primary and second surveys. Because it didn't change expected S values. In Fig. 7, It can be deduced that the dimensions size distribution of the simulated product within the range of 3175 µm to 6.607 µm is approximately well fitted ($R^2$ = 0.9916, MSE = 5.3526, accuracy = 94.6474, Fig. 8) on the measured product for fraction classes from 6.607 µm to zero thanks to in 2-times of grinding. Before the grinding by master rollers, particles leave the grinding table by the ventilation of the mill fan. Depending on the ventilation rate of mills, size fractions larger than 6.607 µm may also leave the grinding table before comminution.

### 3.3. Comparison between 1-time breakage and 2-times breakage

Fig. 9 shows the measured PSD of the VRM product supported by the number of breakages(actual sample and calculated:1-time

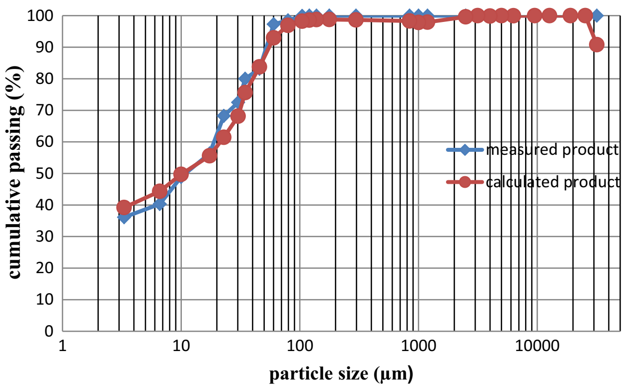


**Fig. 7.** Comparison between simulated and measured product size distributions.

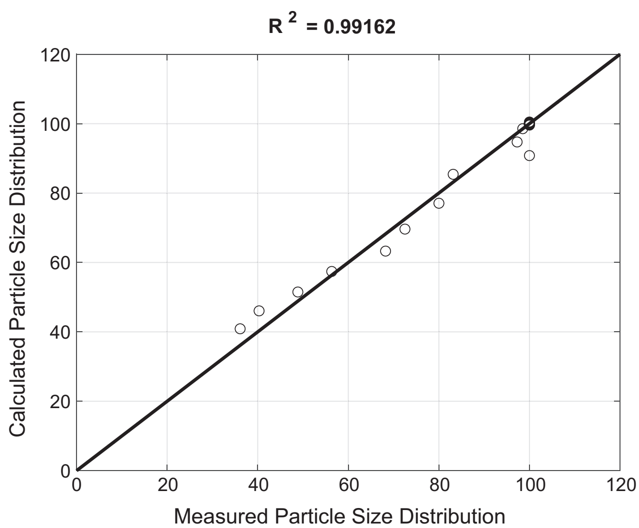


**Fig. 8.** Correlation assessments between measured and calculated PSD of product.

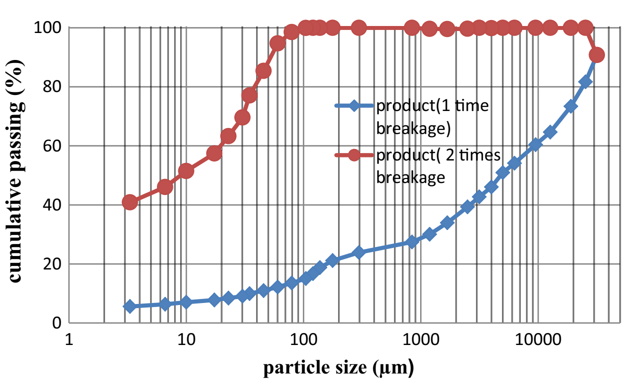


**Fig. 9.** Comparison between one-time breakage and two times breakage.

and 2-times breakage). Consistent with the cumulative passing percent of various fractions of product for two-state, for 1-time breakages, most of the particle size is coarse. It means the particles aren't sufficiently comminuted for a 1-time breakage state and must be comminuted 2- times. For two-times breakages, the particles produced are near the actual sample.

## 4. Conclusions

According to the MRT, clinker particles spent a short time within the VRM during in this study, with an MRT of about 67 s. Due to the short residence time, the number of particle breakages within the VRMs is 1 to 3 times lower, avoiding unneeded over-grinding. The matrix model's results showed that this model provides a more robust prediction that supported the quantity 2-times clinker breakage in VRM. A comparison between the matrix model and population balance model within the VRM; showed that the matrix model provides **a** decent insight into the number of particle breakages, whereas the population balance model; in step with the mixing pattern material inside the mill, the hypothesis is that the number of times of breakage does not amplify. Also, the comparison of the calculated product produced for the 1-time and 2-time showed that the number of 2 breakages is far closer to the actual product size distribution. Confirmed the findings of the matrix model by using 2-time grinding; however, because the effective parameters on the number of particles breakage are various, it's possible to average the number of breakages for multiple states, equal 1 to 3 times.

## 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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