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EFFECT OF MILL FEED SIZE DISTRIBUTION AND GRINDING MEDIA SIZE ON SIZE REDUCTION PERFORMANCE OF AN INDUSTRIAL SCALE VIBRATING BALL MILL (VBM) IN CEMENT CLINKER GRINDING

ÇİMENTO KLİNKERİNİN ÖĞÜTÜLMESİNDE DEĞİRMEN BESLEMESİ BOYUT DAĞILIMININ VE ÖĞÜTÜCÜ ORTAM BOYUTUNUN ENDÜSTRİYEL ÖLÇEKLİ TİTREŞİMLİ BİLYALI DEĞİRMENİN (VBM) BOYUT KÜÇÜLTME PERFORMANSINA ETKİSİ

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ABSTRACT

In this study, open circuit single and two stage industrial scale vibrating ball mill (VBM) grinding performance of raw (uncrushed) cement clinker was investigated using different mill feed size distributions and grinding ball size configurations. The mill was modelled for the test cases using perfect mixing mathematical modelling approach. Different ball size configurations were applied in the grinding tests to estimate the effect of ball size configuration on grinding performance. Proposed coarse ball size configuration (30-20-15mm) was determined to increase the size reduction performance of single stage VBM grinding when coarse mill feed material was fed to the VBM ($F50=185\mu m$) as compared to the finer mill feed case ($F50=24\mu m$). VBM grinding performance was determined to increase with finer mill feed material ($F50=24\mu m$) and application of finer ball size configuration (10-8-6mm) in single stage grinding case as compared to the two stage grinding case.

Anahtar Sözcükler:
Öğütme,
Titreşimli bilyalı değirmen,
Matematiksel modelleme,
Çimento klinkeri.

ÖZ

Bu çalışmada, -fırın çıkışı (kırılmamış) çimento klinkerinin açık devre tek aşamalı ve iki aşamalı endüstriyel ölçekli titreşimli bilyalı değirmen (VBM) öğütme performansı farklı besleme dağılımları ve öğütücü bilya boyu konfigürasyonları kullanılarak incelenmiştir. Değirmen, test koşulları için mükemmel karışım matematiksel modelleme yaklaşımı kullanılarak modellenmiştir. Öğütme testlerinde, bilya boyu konfigürasyonunun öğütme performansı üzerine etkisini tahmin edebilmek için farklı bilya boyu konfigürasyonları uygulanmıştır. Önerilen iri bilya boyu konfigürasyonunun (30-20-15mm) tek aşamalı VBM boyut küçültme performansını, birikimli %50 geçen boyu 185µm olan değirmen beslemesinin beslenmesi koşulunda birikimli %50 geçen boyu 24µm olan değirmen beslemesi koşuluna göre artırdığı belirlenmiştir. VBM öğütme performansının, daha ince değirmen beslemesi ($F50=24\mu m$) ve daha ince bilya boyu konfigürasyonu (10-8-6mm) uygulamasıyla iki aşamalı öğütme koşuluna göre tek aşamalı öğütme koşulunda arttığı belirlenmiştir.

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INTRODUCTION

Since the beginning of 20th century the tube mills played critical role in fine cement production. The capability of achieving mass production provided wide application area to the tube mills despite of the fact that, their energy utilisation is very inefficient. Therefore, any better energy performance systems have started to find application opportunities within the industry. Definitely, the compressed bed breakage systems such as roller presses, VRM's or Horomills took their positions in the market. Energy efficiencies of these grinding technologies are proven and well known by the industry as well. But on the other hand, the steep size distribution obtained from high compression systems created a gap in quality assurance. So to overcome these problems fine grinding compared to conventional systems have to be implemented. Otherwise, final grind necessitates fine tuning. Intense energy utilised systems such as VBM's can easily be utilised for this stage. Fine grinding media provides higher media surface area which results with improved quality. Therefore, both energy saving and quality improvement can be achieved in one system to a certain extent.

Vibrating ball mills are known to be applicable in grinding of metals such as aluminum alloys, nickel/ferrochrome alloys, abrasives, coal and coke, aggregates, paint pigments such as barite and ores (copper, iron, gold, chromite ore etc.). They can be operated both in wet and dry grinding mode of open and closed circuit configurations. Fundamental grinding mechanisms in a VBM are attrition with high impact, shear and attrition with short retention time and less overgrinding. Typically, maximum feed size is 5mm in dry grinding. Recorded dimensions of the mills manufactured are; 1120x1780x1350mm and 1680x2790x2130mm. They are low cost, low capacity and easy to install mills (Metso, 2010). A schematical view of an industrial scale vibrating ball mill manufactured by Metso Minerals Company is given in Figure 1.

Cement production capacity of Turkey was recorded as 84,000ton/year in 2018 and ranked in the fourth row in the World. On the otherhand, annual clinker production capacity of Turkey was recorded as 82,000ton/year and ranked in the fifth row in the world (US Geological Survey, 2019). These figures show the importance of this industry in Turkey. Thus, production of cement with lower energy consumption has vital importance in this sector. As grinding is the most energy consuming stage among the cement production stages, any improvement in grinding performance will lower the energy consumption of this stage. In this context, investigation of new ways of grinding systems are being studied in this industry which is crutial in terms of energy savings. VBM grinding could be another way for producing cement.

Clinker is the main raw material in the production of cement and thus, grinding behaviour of clinker was analyzed in different VBM grinding conditions in this study. In this context, it was aimed to demonstrate the effect of mill feed fineness and grinding media size configuration on grinding performance of an industrial scale vibrating ball mill (VBM) operating in open circuit. For this purpose, industrial scale open circuit grinding tests were performed using different mill feed fineness and grinding ball size configurations. Industrial VBM used in the experimental program had a similar design with the Metso VBM and was manufactured in Turkey. Results indicated that, VBM grinding performance could be improved with finer feed material (F_{50}=24μm) and application of finer ball size configuration (10-8-6mm) in single stage grinding as compared to the two stage grinding case.

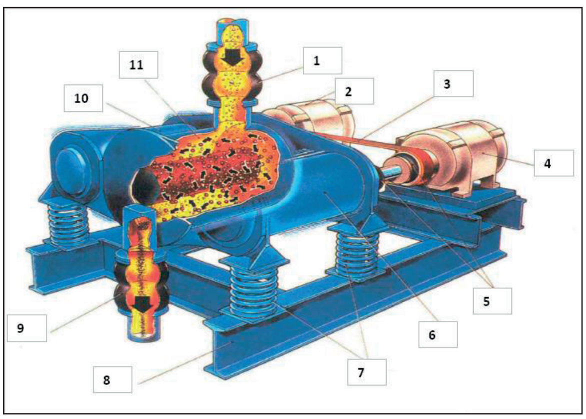

Figure 1. Vibrating ball mill (Metso catalogue, 2010)

VBM parts given in Figure 1 are:

[1] Flexible feed connector

[2] Drive motor

[3] Synchronizing belt

[4] Drive motor

[5] Flexible couplings

[6] Eccentric drive mechanism

[7] Spring mountains

[8] Steel mounting frame

[9] Flexible discharge connector

[10] Eccentric drive mechanism

[11] Grinding chamber

1. MATERIALS AND METHODS

1.1. VBM Grinding Tests

Design specifications of the industrial VBM used are tabulated in Table 1. Industrial scale VBM was operated in single and two stage open circuit grinding conditions. Single and two stage industrial scale open circuit grinding tests were conducted on raw clinker samples to test the size reduction performance using different ball size configurations. Applied ball size configurations are given in Table 2. Ball charge weight % compositions were not allowed to be published by the company.

Simplified flowsheets of the processes are given in Figures 2 and 3. Raw clinker was ground by using coarse and fine ball size configurations in both grinding test applications.

Table 1. Design specifications of industrial scale test VBM

Vibration frequency (Hz)	1160
Capacity (t/h)	7
Motor (kW)	75
Internal Diameter (m)	0.78
Internal Length (m)	1.20
Critical speed %	77
Operational ball load %	90

Table 2. Applied ball size configurations in the grinding tests

Grinding test	Ball size configuration	Ball size (mm)
Single stage open circuit	Coarse	30-20-15
	Fine	10-8-6
Two stage open circuit	Coarse (stage-1)	30-20-15
	Fine (stage-2)	15-12.70-9.52

Figure 2. Single stage open circuit grinding

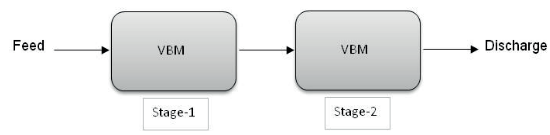

Figure 3. Two stage open circuit grinding

1.2. Determination of Particle Size Distributions

Particle size distributions of the VBM feed and products were determined by dry sieving of +150μm material. Sub-sieve range (-150μm) down to 1.8μm was analyzed using a SYMPATHEC® laser diffractometer in dry mode. Dry sieving and dry laser sizing results were combined to represent the full size distribution from the top size down to 1.8μm.

1.3. Evaluation of Grinding Performance

Size reduction in VBM was modelled by using perfect mixing mathematical model (Whiten, 1972) for the grinding cases to estimate grinding performance.

In the context of the modelling study, specific breakage rate parameters of particles were determined and the resulting functions were presented as a function of particle size. Specific breakage rate parameters which were defined as a ratio of specific breakage rate to normalized discharge rate functions were estimated for each grinding case by implementing perfect mixing mathematical model (Whiten,1972) using the model fit module of the JKSimMet Mineral Processing Software

V4.32. A number of researchers have used perfect mixing mill approach to model multi-compartment ball mills used in the cement industry (Zhang, 1992; Benzer, 2000; Hashim, 2003; Genç, 2008). Perfect mixing mathematical model is given in Equation 1. (Napier Munn et.al., 2005).

$$f_i + \sum_{j=1}^{i} a_{ij}\, p_j \left(\frac{R_j}{D_j}\right) - p_i \left(\frac{R_i}{D_i}\right) - p_i = 0 \tag{1}$$

f_i and p_i are the mass flowrates (t/h) of size fraction i in the mill feed and discharge respectively, a_{ij} is the breakage distribution function (in the form of single column step triangular matrix), R_i is the specific breakage rate of size fraction i (tonnes broken per hour per tonne in the mill, h^{-1}), D_i is the specific discharge rate of size fraction (i) (tonnes discharged per hour per tonne in the mill, h^{-1}). f_i and p_i can be directly measured in industrial scale or experimental grinding cases whereas aij can be determined experimentally or theoretically to reflect material breakage characteristic on breakage rate parameter (R_i/D_i). It is usually difficult to measure mill load sensitively which is required in determining the discharge rate through the mill. Thus, the breakage rate is assumed to be characterized by a ratio of breakage rate to discharge rate (R_i/D_i) where the discharge rate effect is reflected on the combined parameter value. Discharge rate effect is usually normalized according to the mill volume and volumetric feed rate (Q) to the term D_i* as given in Equation 2 in the estimation of (R_i/D_i) combined breakage rate parameter (Napier Munn et.al., 2005).

$$D_i^* = \frac{D_i}{4Q/D^2L} \tag{2}$$

Where, D and L are the diameter and the length of the mill respectively. In this study, VBM was considered as a perfectly mixed single tank and grinding performance was evaluated through particle size versus R/D* breakage rate parameter variation where the discharge rate effect was normalized. The R/D* breakage rate parameters were estimated from perfect mixing model for each size in the mill product in the model fit module of JKSimMet Simulator. Standard breakage distribution function (a_{ij}) proposed by Broadbent and Callcott (1956) was used in the estimation of breakage rate parameter. Broadbent-Callcott function assumes that, the distribution obtained after the breakage of a particle relative to the initial particle size is independent of the initial size of the particle. The breakage distribution function was calculated from Equation 3.

$$A_{x,y} = \frac{\left(1 - e^{x/y}\right)}{\left(1 - e^{-1}\right)} \tag{3}$$

A(x,y) represents the proportion of particles after breakage in Equation 1.3. The function A(x,y) represents the proportion of particles initially of size y which appear in size fractions smaller than x after breakage. Broadbent-Callcott breakage function defined in the simulator which is used in the breakage rate parameter estimation is given in Figure 4.

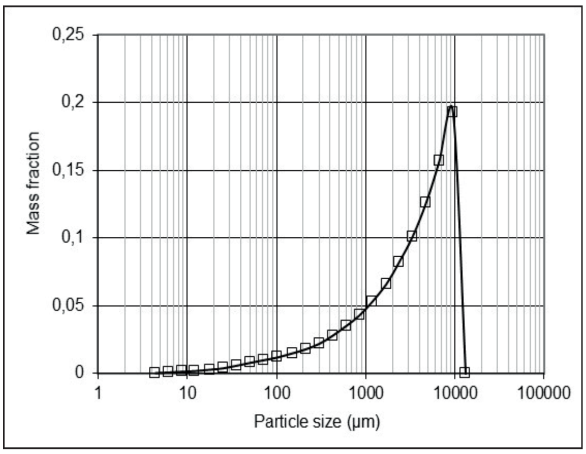

Figure 4. Broadbent-Callcott breakage function

2. RESULTS AND DISCUSSIONS

Particle size distributions in single and two stage grinding processes are given in Figures 5 and 6 respectively. Grinding time was kept constant in each grinding test. Coarser clinker feed was fed to the two stage grinding as compared to the single stage grinding application in order to determine the grinding performance of the coarse ball size configuration. Size reduction performance was determined on the basis of the 50% cumulative passing particle size. In this context, 50% cumulative passing particle sizes of VBM feed denoted by F_{50} and VBM discharge denoted by P_{50} were determined from the particle size distributions. Size reduction ratio for the grinding cases were determined. Determined values with the size reduction ratios are tabulated in Table 3. Size reduction ratio was determined to be higher in two stage grinding case as compared to single stage grinding case which indicated that, mill feed size distribution used in two stage grinding case was more convenient to 30-20-15mm ball size configuration in VBM grinding.

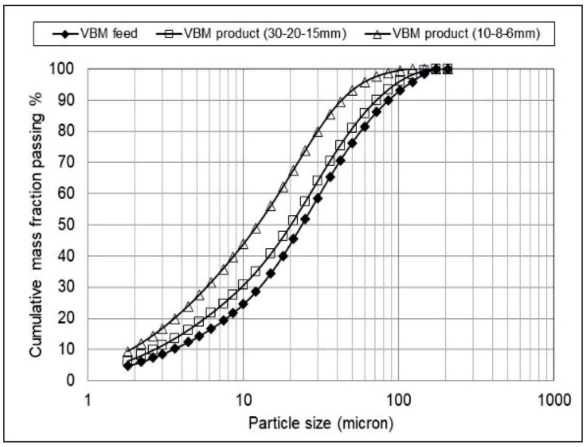

Figure 5. VBM particle size distributions in single stage open circuit grinding case

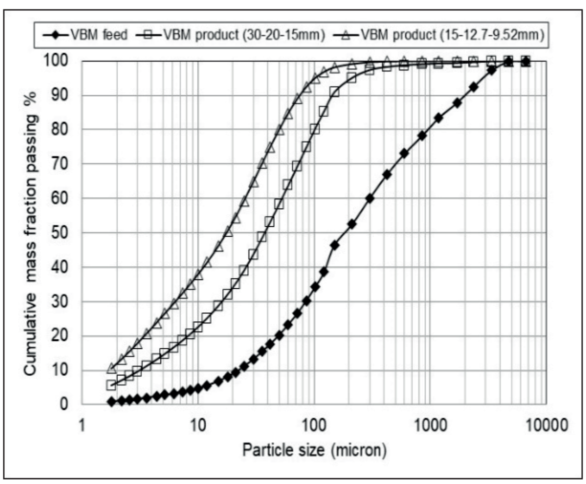

Figure 6. VBM particle size distributions in two stage open circuit grinding case

Table 3. Size reduction performance when 30-20-15mm ball size configuration was applied under different mill feed particle size distributions

Application	F_{50} (μm)	P_{50} (μm)	Size reduction ratio=F_{50}/P_{50}
Single stage grinding case-1	24	20	1.2
Single stage grinding case-2	185	38	4.9

Size reduction performance of VBM was determined to increase with coarser mill feed (F_{50}=185 μm) material and application of coarser ball size configuration of 30-20-15 mm in single stage open circuit. Size reduction ratio was found to decrease as the VBM feed got finer thus grinding performance was decreased. Size reduction performance was increased in single stage grinding case-2 which indicated that coarser mill feed particle size distribution was more suitable for the applied ball size distribution.

VBM product obtained from the grinding of mill feed of 50% passing size of 185 μm was ground with 15-12.7-9.52 mm ball configuration. 50% passing size of VBM product was determined as 17 μm. On the otherhand, VBM product obtained from the grinding of mill feed of 50% passing size of 24 μm was ground with 10-8-6 mm ball configuration. VBM feed and obtained VBM product fineness values on the basis of 50% passing size are given in Table 4. Higher size reduction performance was obtained in coarser grinding case.

Table 4. Size reduction performance under different mill feed particle size distributions

Application	F_{50} (μm)	P_{50} (μm)	*F50/P50
15-12.7-9.52mm	38	17	2.2
10-8-6mm	20	12	1.7

*Size reduction ratio=F_{50}/P_{50}

Specific breakage rate to normalised discharge rate functions for the grinding cases were determined using the model fit module of the JKSimmet simulation software. Estimated perfect mixing model breakage rate parameters are tabulated in Tables 5 and 6 for the test conditions. Model fitted breakage rate parameters (R/D*) as a function of mill internal particle size in single and two stage grinding of raw clinker are given in Figures 7, 8 and 9. Variations of specific breakage rate parameters were used to estimate the grinding performance of the mill at different operational conditions.

Table 5. Perfect mixing model breakage rate parameters for single stage open circuit grinding

Particle size (mm)	30-20-15mm ball configuration	10-8-6mm ball configuration
	ln (R/D*)	ln (R/D*)
0.0026	-2.98	-3.77
0.018	3.31	4.06
0.050	3.08	5.22
0.102	4.34	7.19

Table 6. Perfect mixing model breakage rate parameters for two stage open circuit grinding

30-20-15mm ball configuration		15-12.7-9.52mm ball configuration	
Particle size (mm)	ln (R/D*)	Particle size (mm)	ln (R/D*)
0.0086	1.59	0.0026	0.38
0.03	3.33	0.018	3.66
0.15	5.64	0.05	4.48
0.85	10.73	0.102	5.83

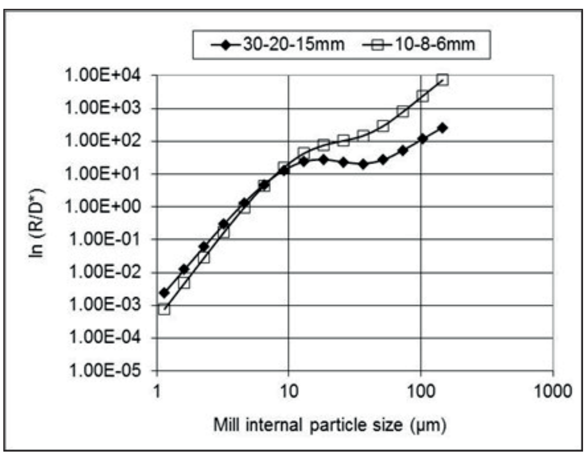

Figure 7. Specific breakage rate parameter in industrial scale single stage open circuit grinding case at different grinding media applications

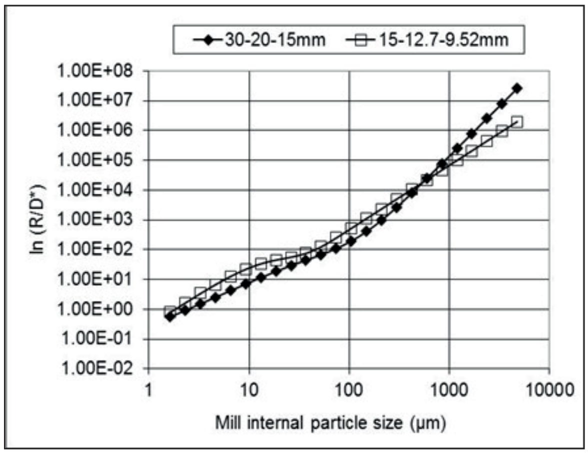

Figure 8. Specific breakage rate parameter in industrial scale two stage open circuit grinding case at different grinding media applications

Application of fine ball size configuration of 10-8-6mm resulted in an increase in the breakage rate parameter of particles coarser than 9μm whereas the parameter value did not change significantly below this size which is the ultrafine particle size range (Figure 7). Due to the fineness of the VBM feed (F_{50}=24 μm), particles were possibly agglomerated and thus, grinding performance was decreased slightly in the ultrafine size range when finer ball size configuration was applied. Applied coarse ball size configuration (30-20-15 mm) was found to be not suitable for the test VBM feed size distribution (F_{50}=24 μm) for single stage open circuit grinding case. Grinding performance was decreased in the application of coarse ball size configuration. However, proposed finer ball size configuration of 10-8-6 mm was determined to be more convenient configuration for grinding of raw clinker for the defined feed size distribution (F_{50}=24 μm) if the slight decrease in the ultrafine particle size range due to the possible particle agglomeration was neglected.

Two VBMs were operated in series in open circuit. Coarser feed was fed to the VBM with the coarse ball size configuration of 30-20-15 mm in the first stage of two stage grinding case. First stage represented the coarse grinding stage. Second stage was the fine grinding stage and VBM discharge from the first stage was the feed of the second stage. Due to the finer VBM feed size distribution, finer ball size configuration

(15-12.7-9.52 mm) was applied in the second stage. Grinding test was conducted for the same grinding time with that of the first stage. It was found that, applied coarse ball size configuration (30-20-15 mm) increased the breakage rate parameters of particles coarser than 593µm and thus grinding performance. Applied moderate ball size configuration of 15-12.7-9.52 mm was found to be not effective on grinding performance of particles coarser than 593 µm but effective on the grinding performance of particles finer than 593 µm (Figure 9) in two stage open circuit grinding of raw clinker under fine feed condition (F_{50}=37 µm).

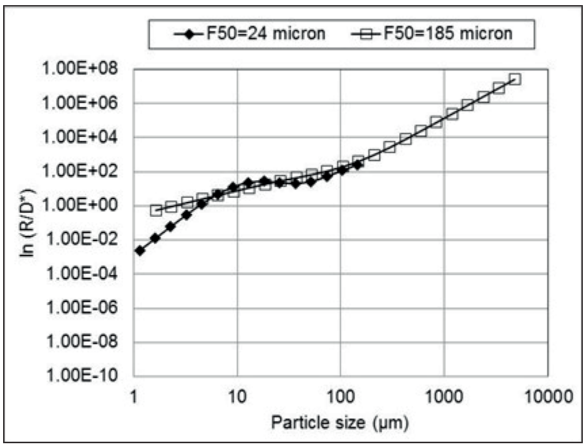

Figure 9. Effect of mill feed particle size distribution on breakage rate parameter when 30-20-15 mm ball size configuration was applied in single stage grinding

Mill product particle size distributions for the single and two stage grinding cases are compared in Figure 10. Particle size distribution was determined to be finer below 25 µm in two stage grinding as compared to single stage product obtained with ball size configuration of 30-20-15mm. Increase in mill product fineness indicated a higher grinding performance in two stage grinding as the two stage grinding feed size distribution is much coarser (F_{50}=185 µm) as compared to that of single stage (F_{50}=24 µm). Application of two stage open circuit grinding with coarser feed material and different ball size configuration application could not achieve the mill product fineness obtained with finer feed and finer ball size configuration (10-8-6 mm) in single stage grinding. VBM grinding performance was determined to increase with finer feed material (F_{50}=24 µm) and application of finer ball size configuration (10-8-6 mm) in single stage grinding.

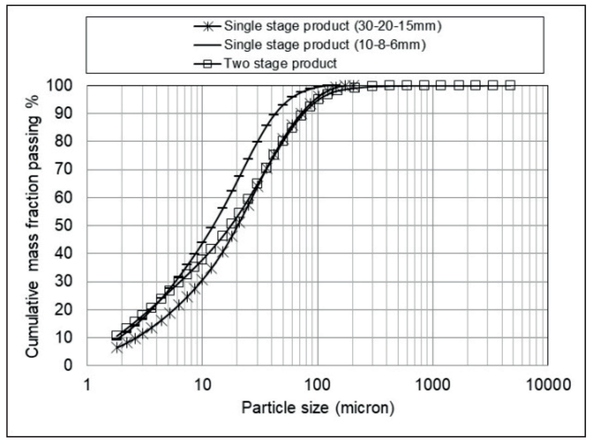

Figure 10. VBM product particle size distributions for single and two stage grinding cases

CONCLUSIONS

Raw cement clinker grinding performance of an industrial scale VBM was investigated using different feed size distributions and grinding ball size configurations when the mill was operated in single and two stage open circuit grinding cases.

Ball size configuration of 10-8-6 mm was determined to increase the breakage rate parameter under the fine mill feed condition (F_{50}=24 µm). Applied coarser ball size configuration 30-20-15 mm was found to be effective on the grinding performance of particles coarser than 593µm when coarser material was fed to the VBM (F_{50}=185 µm). Ball size configuration of 10-8-6mm was found to be more suitable for fine feeds (F_{50}=24 µm) whereas ball size configuration of 30-20-15mm was found to increase the grinding performance of coarser mill feeds (F_{50}=185 µm). Test results demonstrated that, VBM grinding performance increases with finer feed material (F_{50}=24 µm) and application of finer ball size configuration (10-8-6 mm) in single stage grinding as compared to the two stage grinding case in cement raw clinker grinding.

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