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Influence of quartz particles on wear in vertical roller mills. Part I: Quartz concentration

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ABSTRACT

The standard closed circuit comminution process commonly employed in industrial vertical roller mills has been analyzed to determine the influence of typical abrasive minerals on wear rates. With the main focus on raw mixes used in cement plants, synthetic mixtures imitating were prepared.

Using statistical planning, a total of 10 tests were carried out with two different limestones and one type of quartz sand. The size distributions were kept constant and only the mixing ratios were varied. It appears from the investigation that mixtures consisting of minerals with different grindabilities result in an increased concentration of abrasive particles in the grinding bed ($R^2 > 0.99$). The present study shows that the quartz concentration in the grinding bed is determining the wear rate.

1. Introduction

Quartz is a hard mineral frequently being part in cement raw mixes. Hence it is of interest to correlate its content in the mixture with the wear rates experienced in vertical roller mills (VRM). From the experience of numerous laboratory VRM tests, it is known that the measured wear rates might not correlate with wear rates in full scale VRMs. So far it has not been possible to observe the material flow inside VRMs and thus wear rate discrepancies have been accepted without any acceptable explanation (Private Communication with FLSmidth R&D Department, 2009).

The abrasive mechanism of quartz will physically change the geometry of the mechanical parts thus lowering the performance of machinery and further increase the operating costs. The replacement of wear parts is both time consuming and laborious and will often require a shut-down of the entire plant with the consequence of high economic losses (Röhrig, 1971).

Ozkahraman (2005) has studied two different limestones and observed that there is a relation between the physical mechanical properties (such as point-load-test) and their grinding properties (such as bond work index): Two limestones might have the same physical mechanical strength but highly different energy requirements when ground to the same final product size. Tavares and das Neves (2008) have studied the relations between rock textures and different physical mechanical properties; however the same difficulties arise as the rocks behave differently when processed on different types of laboratory mechanical testing equipment.

Several authors have stated that quartz is the most important abrasive found in cement raw mixes, because the hardness ratio of this mineral is higher compared to most alloys used as wear resistant materials (Jung, 2000).

A VRM test is very costly and time consuming and requires approx. 600 kg of raw materials for one single test. Thus, there is a need to develop a simplified characterization procedure to predict the wear rates. The first necessary step is to determine a relationship between quartz concentration in the new feed raw mix and the wear rate.

1.1. VRMs

On a large scale, the mining, cement and coal industry are the three industries being highly dependent on mineral size reduction equipment.

The mining industry is based on wet-grinding of ores and the final comminution stage is typically a SAG-mill or a ball mill. In this

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industry, the final product size is often 75 μm and as a result of the abrasive ores, the equipment suffers elevated wear part material losses requiring machinery based on simple and inexpensive maintenance plans.

The cement industry is based on dry-grinding and two comminution stages are necessary:

1. A raw mix based on limestone and adjusting silicates often containing quartz. The raw mix is inter-ground to a fineness with a sieve residue 15%, 90 μm.
2. The subsequently sintered product, also known as cement clinker, is inter-ground with a fraction of gypsum to a fineness with a sieve residue +10%, 45 μm.

Coal is often used as fuel in power and cement plants and ground to a particle size with a sieve residue +15%, 90 μm. Coal may contain quartz and pyrite with amounts of more than 10%. Whereas the mining industry is still dependent on SAG-mills and ball mills, the cement and coal industry is increasingly using VRMs as the final comminution stage.

1.1.1. VRM process

The VRM operates with three simultaneous processes: Grinding, drying and separation. The VRM design has an ancient predecessor based on a horse driven oil mill (Fig. 1), but modern VRMs employ a fixed roller set and a rotating table.

The VRM has been accepted in the cement industry mainly due to its low power consumption which is decreased by 40% compared to a ball mill (3–11 kWh/t). The differences in power consumption originates solely from the differences in the physical and textural properties of the raw mix compounds. The VRM has a few drawbacks: In a closed circuit VRM process, the abrasive minerals from the feed will up-concentrate on the grinding table resulting in increased wear rates. The optimal VRM production is based on fixed geometrical wear part surfaces and if these are altered due to abrasive wear, the VRM will perform unsatisfying. Experience shows, that the VRM is most suitable with respect to maintenance costs if wear rates do not exceed 10 g/ton.

The standard industrial VRM is equipped with two to four rollers and basically only the shape and support system of the rollers varies between the manufacturers. In this study focus will be on the FLSmidth ATOX setup (Fig. 2).

The table diameter on a VRM varies between 1.5 and 7.5 m. As the net weight of the roller itself is inadequate to generate the necessary grinding pressure, the rollers are exerted by a hydraulic force. The angular velocity of the table exerts sufficient centrifugal force to move the particles towards the table periphery. An adjustable dam ring at the periphery controls the bed thickness and will invariably form a parabola shaped grinding bed (Fig. 4).

During operation a large fan draws hot kiln gasses into the lower part of the VRM making it possible to dry raw materials with moisture contents up to 20%. At the inlet close to the dam ring, the air flow reaches speeds of up to 60 m/s which is sufficient for carrying particles upwards (Figs. 3 and 4). Due to this operation a differential pressure and thus a vacuum is present inside the VRM.

The uneven thickness of the grinding bed is inevitable and consequently the grinding pressure increases towards the perimeter of the table. If the angular velocity of the table is decreased (and the feed rate kept unchanged), the feed is stowed in front of the rollers and the VRM is quickly choked. Contrary, if the angular velocity is increased, the feed is thrown off the table and the grinding efficiency becomes unsatisfactory.

In case of dry feed, it is often necessary to spray water onto the grinding bed in front of each roller in order to secure a satisfactory compaction of the bed by which the grinding efficiency increases. Entrapped air in dry feed is disadvantageous as the viscosity decreases and the results might be intense vibrations.

The circulations in closed circuit VRMs is complicated and yet not fully understood (Fig. 3). Approximately understood, the new feed entering the VRM is compressed by the rollers. The hot air flow (approx. 200 °C, 60 m/s) draws the ground fine material upwards into the separator. Due to the different particle sizes, three circulations and thus separation processes take place inside the VRM (Figs. 3 and 4):

1. The large fragments fall through the jet ring and are collected by a bucket elevator which passes the material to the new feed.
2. The medium sized particles circulate within the VRM as their weight equals the buoyancy of the air flow.

Fig. 1. The ancient oil mill is the ancestor of the modern VRM. The roller set is turned while the table is at rest.

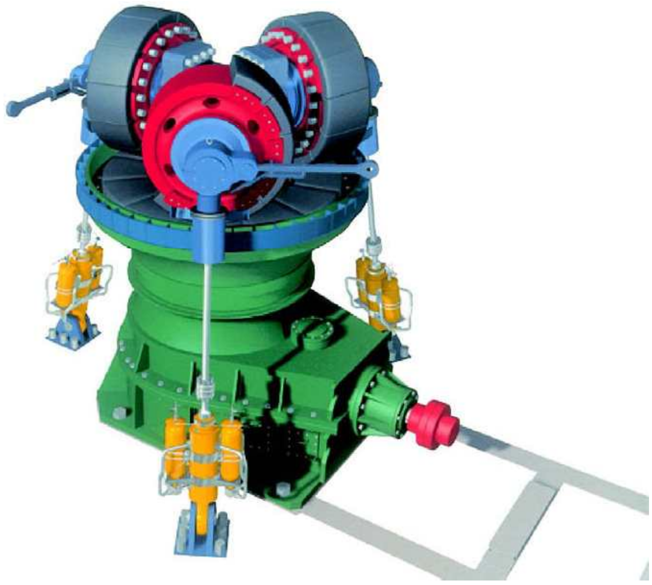

Fig. 2. The core components of the FLSmidth ATOX VRM. The horizontal circular table is driven by an electrical motor. Raw materials are added on the table. The raw materials are drawn underneath the rollers during operation. The frictional force between the table-bed-roller assembly ensures that the rollers will turn without any external power supply.

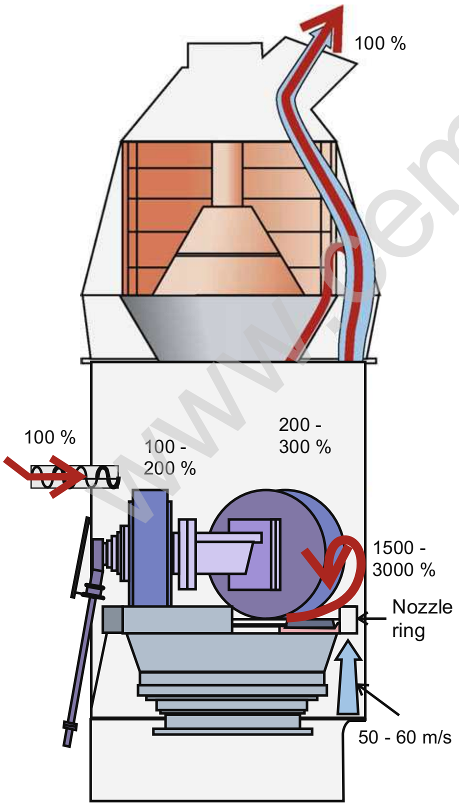

Fig. 3. Approx. material circulations in a VRM. The percentages indicate the degree of circulations: The input on the left by a screw conveyor and the output on the top are both at 100% indicating an input–output process with no losses. The circulations above the table are shown as being 1500–3000% which indicates a material flow 15–30 times larger than the input flow. In the same way, the separator flow is 1–2 times the input flow.

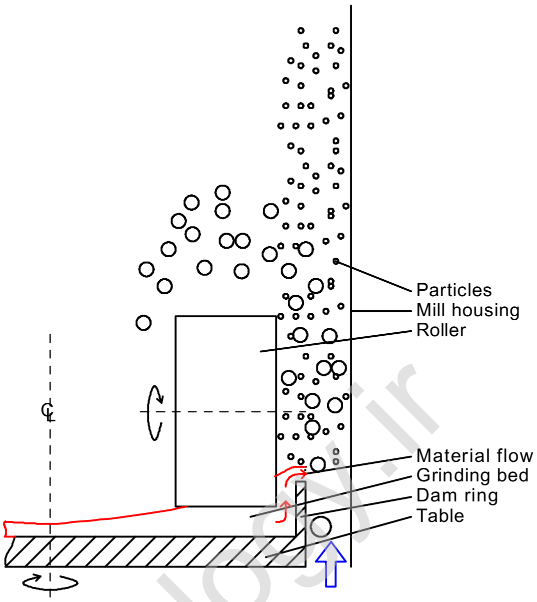

Fig. 4. Close up view of VRM. The centrifugal forces generate an uneven grinding bed which becomes thicker at the perimeter. The air flow is generated by a differential pressure. This explains the upward particle flow towards the separator. The largest fragments fall through the jet ring, the medium sized particles circulate above the roller and the smallest particles are swept to the separator.

3. The smallest particles (approx. −1000 μm) are drawn to the separator. The separator splits the particles in two streams plus and minus 90 μm respectively. However, the separator has a certain efficiency at splitting the particle flow in two material flows and this efficiency results in a sieve residue. By changing the vane angles (static) or the rotor speed (dynamic) of the separator, the relative amount of the two fractions can be controlled. The fraction 90–1000 μm (approx.) is returned to the grinding table whereas the −90 μm fraction with a certain sieve residue leaves the system as a final product.

Due to the multiple circulation processes and the closed circuit process, a steady state condition is established resulting in an up-concentration of abrasive particles on the grinding table.

1.1.2. VRM wear part materials

The preferred wear part materials in VRMs are typically either heat treated chromium carbide cast alloys or chromium carbide hard facings. The latter usually has the better wear resistance against quartz. However the former is still supplied as a standard material and a common alloy is a modified 21988/JN/HBW555XCr21 (ISO 21988, 2006, Fig. 5). In large VRMs each wear segment might have a net weight of more than 1200 kg and this size is unfavorable for the solidification process resulting in coarse primary carbides (unsatisfying wear resistances).

2. Experimental

2.1. General setup

For the investigations a laboratory scale VRM with the same features as discussed in Section 1.1 was used (Figs. 6 and 7). The laboratory VRM is a small scale model of a large industrial VRM with a few mechanical changes and simplifications as to accommodate the raw materials. The table diameter is ∅350 mm, and is equipped with three rollers with the dimensions ∅210 mm × 70 mm. The power is supplied by a 7.5 kW asynchronous electric

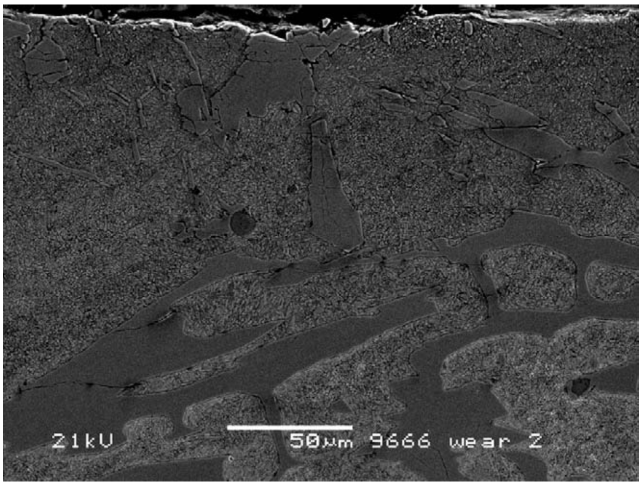

Fig. 5. 21988/JN/HBW555XCr21 commonly used in VRMs. The matrix (grainy structure) has a measured hardness of approx. 700 HV0.025 and the chromium carbides (smooth structure) a hardness of 1200–1600 (Hutchings, 1992).

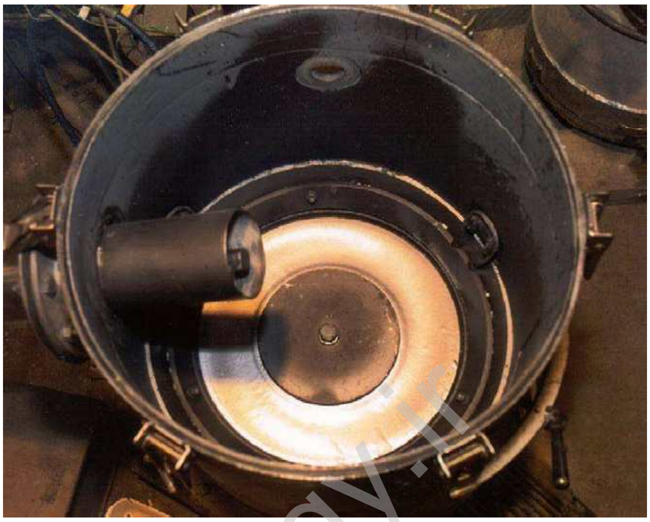

Fig. 7. View on the grinding table (bright surface) of the FLSmidth ATOX laboratory VRM. Material is fed into the VRM by means of a screw conveyor.

motor. The wear part material is similar to the 21988/JN/HBW555XCr21 as discussed in Section 1.1.2.

Each test was carried out at the exact same settings: The angular velocity of the VRM table was $59/\sqrt{D} = 100$ rpm. The grinding force on each roller was adjusted to 10 kN with the inaccuracy in defining the true pressure as described in Section 1.1.1. From defining an approximate grinding zone, the grinding pressure can be set to 100 MPa. The moisture of the feed was 2% and the moisture of the final product was 0.2%. The separator was adjusted to produce a final product with a fineness of approx. 12% + 90 μm equal to the fineness found in industrial cement production. The differential pressure was fixed at 230 mm H_2O during testing. After each test, the wear liners were removed from the VRM and weighted on a digital balance with an accuracy of 0.1 gr. Besides the finish product, three important samples influence the operation of the VRM:

Fig. 6. FLSmidth ATOX laboratory VRM. The VRM has a height of approx. 1.5 m and is equipped with a static separator. The grinding force is generated by a hydraulic system and the table driven by an electric motor.

1. *New feed sample.* Sample entering the VRM as fresh material. The quartz content of this sample is known because the limestones are very pure (synthetic limestone/quartz mixture).
2. *Table sample.* Sample in direct contact with the wear parts.
3. *Separator sample.* Return feed sample from separator due to closed circuit process. The separator is an integrated and important part of the closed circuit VRM and cannot be neglected.

The separator and table samples were treated with 16% hydrochloric acid in order to determine the percentage of acid insoluble residue with specific interest on quartz content. The limestones in this study are very pure and thus show a very limited amount of insoluble residue (Section 2.2). The addition of quartz to the mixture will fully dominate the insoluble residue and further XRF or XRD analysis is therefore not necessary (see Table 1).

The insoluble residue was wet sieved on a 90 μm as this is the cut size in the separator. It is thus our hypothesis that all abrasive particles below 90 μm will be part of the final product leaving the VRM and their contribution will be regarded as negligible. The standard deviations for laboratory work is shown in Table 2.

SEM micrographs for general characterization were performed on a Jeol JSM-5900 and polarization micrographs were performed on a Leica DM5000 equipped with a CCD.

2.2. Test plan

Ten laboratory VRM tests were carried out to determine the relationship between the quartz content in the raw mix and the wear rate. Usually limestones contain a substantial amount of impurities which will add to the insoluble residue and increase wear rate. To avoid interference with the wear rate results, two

Table 1
Average Vickers hardness of common minerals found in cement raw materials (Uetz, 1986). A traditional wear part material in VRMs has a bulk hardness of 750 HV. Notice that other minerals have hardnesses above 750 HV, but they are rare compared to quartz and thus not of interest to this study (Hewlett, 2004).

Mineral	Hardness (HV)
Quartz	1150
Rutile	1150
Silimanite	1100
Flint	1000
Pyrite	950
Hematite	950
Feldspar	675
Amphibole	625
Pyroxene	625
Wollastonite	600
Hornblende	550
Apatite	525
Dolomite	450
Fluorspar	180
Limestone	140
Clay	80

Table 2
Standard deviation and coefficient of variation for laboratory work.

Method	Standard deviation (%)	Coefficient of variation
Acid insol. residue	0.781	0.033
Sieving	0.079	0.008
VRM wear measurements	0.403	0.023
VRM power measurements	0.216	0.022

types of very pure limestones were used (Table 3): A fine crystalline limestone designated Costantinopoli and a coarse type designated Visnes. Each limestone was pre-crushed to −8 mm. This size conforms with the VRM size. The quartz −8+5 mm was used as received (Fig. 8 and Table 3).

The test plan is shown in Table 4. Each batch consists of two components imitating industrial conditions. However, in many industrial raw mix'es a clay component would be added to the mixture in order to adjust with the necessary aluminum- and iron oxide. Clays are phyllosilicates with crystal sizes typically below 4 μm and they are believed to have some sort of lubrication effect on the wear liners. Unfortunately, very often clays are impure containing abrasive particles like quartz and flint. In some cases, abrasive rock fragments of more than 100 mm are present.

3. Discussion

3.1. General characterization

Three components were investigated in this study. Some of their properties are shown in Table 3. From a microscopical textural analysis it appears that the limestones are very different in nature:

Fig. 8. −8 + 5 mm quartz particles as received. Each increment on the ruler represents 1 mm.

- *Costantinopoli*: Characterized as a dense and microcrystalline micritic limestone originating from the southern part of the Apennines in Italy. Each calcite crystal has a size of less than 10 μm. This limestone is high metamorphic showing typical marble properties. During handling (crushing, transportation) this limestone produced a high amount of dust. The acid insoluble residue fraction on the +45 μm sieve is approx. 0.2% (Fig. 9).
- *Visnes*: Characterized as a dense and coarse crystalline white marble limestone originating from the Western Fjords of Norway. The calcite crystals reach sizes of approx. 10 mm. During handling (crushing, transportation) the dust generation is inferior to the Costantinopoli limestone. The acid insoluble residue fraction on the +45 μm sieve is approx. 0.2% (Fig. 10).
- *Quartz*: Sea quartz sand consisting of rounded particles originating from Jutland, Denmark.

So far no full understanding of the interrelationships between new feed, table sample, separator sample and wear rate is present. Thus, each sample has been analyzed in order to make a set of overall conclusions. Common belief has been that quartz is up-concentrated progressively (non linearly) in the VRM and hence this issue has been examined thoroughly in the following.

3.2. Wear vs. quartz in new feed

The Costantinopoli and Visnes limestones are both composed of calcite crystals. Calcite has a Vickers hardness of approx. 140 HV and for comparison a standard wear part material and quartz has a hardness of 750 HV and 1150 HV respectively.

It is a common accepted statement that if the hardness ratio (wear part material to abrasive) is above 1.2, the abrasive wear is drastically reduced (Uetz, 1986):

$$HV_{rel} = \frac{H_w}{H_a} = \frac{750}{140} = 5.4 \tag{1}$$

Table 3
Mineral properties. In this study two limestones (Costantinopoli and Visnes) and one abrasive (quartz) were investigated. The column "Minor comp." refers to traces of clay and small quantities of insoluble residues such as iron oxides.

Rock	Hardness (HV)	Density (gr/cm^2)	$CaCO_3$ (wt.%)	SiO_2 (wt.%)	Minor comp. (wt.%)
Costantinopoli	140	2.7	98	1	1
Visnes	140	2.7	98	1	1
Quartz	1150	2.7	0	99	1

Table 4
Test plan with results. The tests were carried out as a one-on-one test only changing one parameter. The maximum percentage of quartz (16 wt.%) has been chosen according to the worst case scenario when producing cement.

Run	Visnes (wt.%)	Costantinopoli (wt.%)	Quartz (wt.%)	Wear (gr/ton)	Quartz sep. sample (wt.%)	Quartz table sample (wt.%)	Power (kWh/t)
1	99	0	1	6.1	5.8	6.0	4.72
2	98	0	2	10.4	7.4	9.5	4.39
3	96	0	4	17.1	11.4	14.5	4.53
4	92	0	8	29.2	21.3	25.8	4.98
5	84	0	16	60.7	38.7	43	5.72
6	0	99	1	2.2	3.1	3.0	9.84
7	0	98	2	5.3	5.7	5.1	9.04
8	0	96	4	10.3	8.7	9.3	8.89
9	0	92	8	21.2	15.8	16.5	9.96
10	0	84	16	39.7	27.1	27.7	9.38

where HV_{rel} is the hardness ratio, H_w is the wear part material Vickers hardness and H_a is the calcite Vickers hardness. The results shown in Fig. 11 confirm the statement. However, wear rates are expected if the limestone as experienced in raw mix grinding, contains abrasive particles such as quartz.

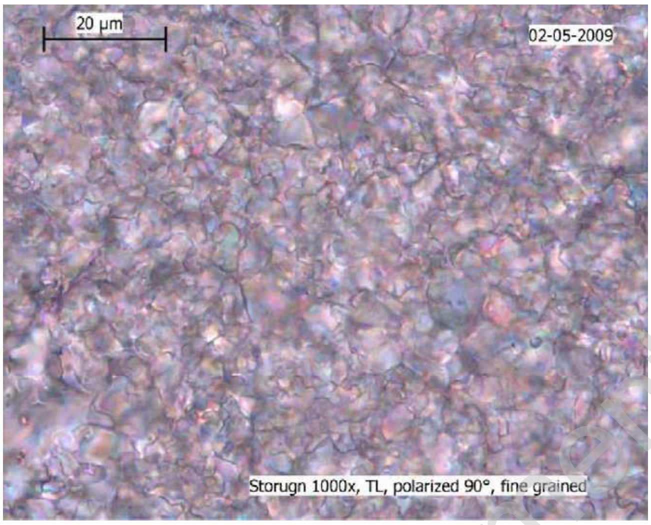

Fig. 9. Transmitted polarized light micrograph of Costantinopoli limestone thin section. Each colored fragment represents a single crystal. The average crystal size is less than 10 µm. The crystals are so small that the transmitted polarized light is diffracted many times (due to stacking of crystals in the z-axis).

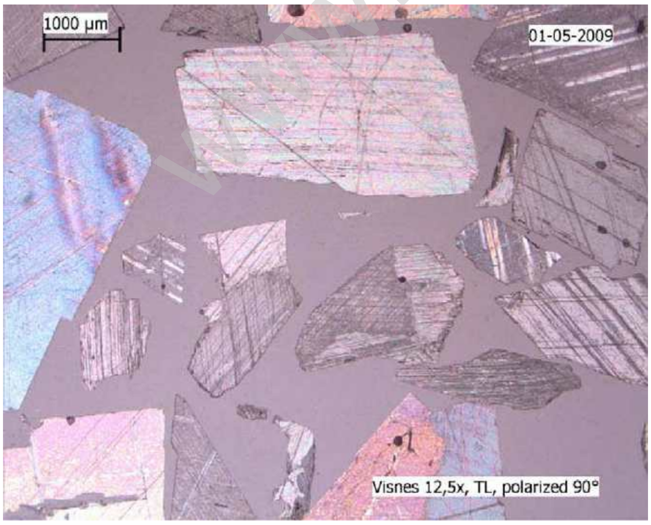

Fig. 10. Transmitted polarized micrograph of Visnes limestone thin section. Each colored fragment represents a single crystal. The calcite crystals reach size of more than 10 mm. The sample was crushed to –4 + 1 mm prior to preparation and thus it is obvious that some crystals are larger than 4 mm.

From Fig. 11 it is seen that the type of limestone has a distinct influence on the wear rate. Quartz is the only abrasive mineral in each mixture, but it is seen that the wear rate is highly dependent on structure of the limestone. Both limestones have a low insoluble residue of 0.2% and are accordingly not expected to exert any wear on the wear parts. This is verified by analyzing Fig. 11: Each regression line originates from approx. origin (0,0) indicating if no abrasive was added to the mixture, the wear would have been zero. There is a linear relationship between percentage of quartz in the mixture and the wear rate. From Fig. 11 it can further be concluded, that it is possible to extrapolate from one single VRM test to all other quartz concentrations. However, this feature is only valid in the region of low quartz concentrations (<16%): For quartz concentration above this range, the relation becomes non-linear. From intuition, the linear curves need to converge at a quartz concentration of 100% (Fig. 12).

It is evident that the influences of the limestone texture decreases in case of increased quartz concentrations present on the grinding table: With a quartz feed concentration of 16%, the grinding table quartz concentration for the Costantinopoli and Visnes

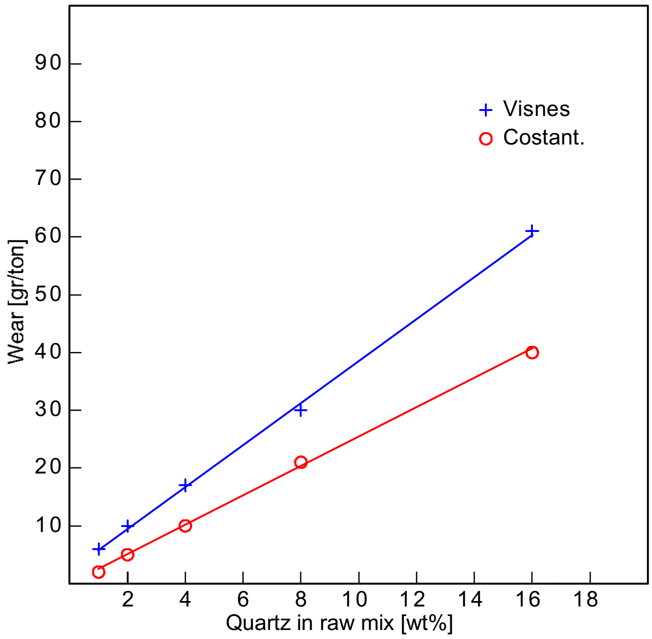

Fig. 11. Wear vs. quartz in raw mix. Visnes shows a $R^2 = 0.99$ and Costantinopoli $R^2 = 0.99$. This figure represents a close up view of the low concentration region shown in Fig. 12. The graph confirms that wear rates approach zero when the hardness ratio increases beyond 1.2.

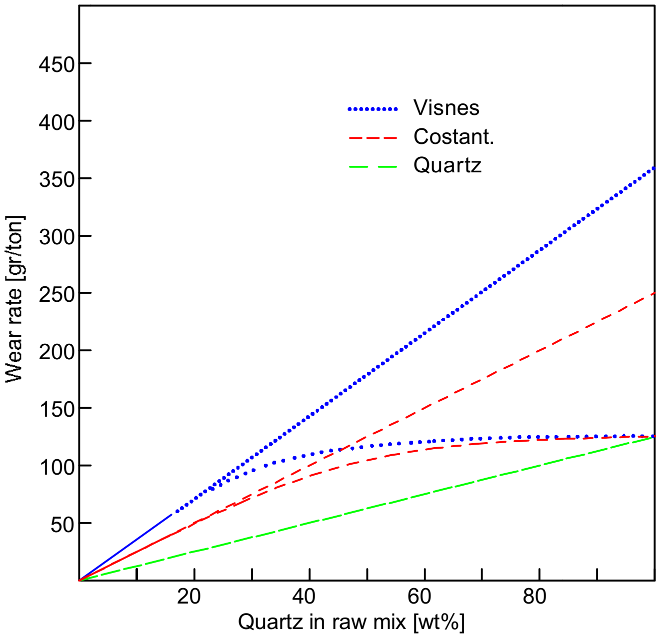

Fig. 12. Theoretical behavior of limestone–quartz interaction. The linear relationships for the low quartz concentrations (<16%) have already been proofed (Fig. 11). Regardless of the limestone of interest, the wear rate has to be the same at a quartz concentration of 100%. The two linear correlations cannot diverge infinitely and need to converge fully towards 100%. Consequently it is obvious that quartz ground alone will always yield the lowest wear rate (lower straight line).

mixtures will reach approx. 40% and 60% respectively (Table 4 and Fig. 11). At elevated quartz concentrations the quartz will increasingly experience autogenous grinding which is beneficial to the overall comminution process.

The lowermost straight line in Fig. 11 represents an imaginary wear rate behavior of quartz mixed with an ideal non-interfering material having no influence on the grinding process. This ideal material can be imagined as being air or something like styrofoam pellets which only act as to keep the quartz particles apart. As the quartz concentration is increased beyond 16%, autogenous grinding of the quartz particles will influence the overall grinding behavior. At increased quartz concentrations, the quartz particles will dominate the grinding bed with quartz particles being in direct contact with each other. In that mode, quartz particles are effectively size reduced within the bed away from the bed/wear part surface. Thus assuming the same grinding bed thickness a high concentration quartz mixture will be size reduced more effectively.

Hence it will always be favorable to grind quartz separately (Damtoft et al., 2009).

3.3. Up-concentration of quartz in separator sample

Due to the mineralogical differences between quartz and limestone and their corresponding degree of grindability, the quartz will up-concentrate in the separator returns sample. The circulation factor of separator returns sample becomes approx. 2–3 and thus this fraction will be more dominant on the grinding table compared to the new feed fraction.

There is a linear relationship between the wt.% quartz in the raw mix and the wt.% quartz in the separator sample (Fig. 14): Due to the pureness of the two limestones, the quartz could be determined very accurately by an acid insoluble test. The acid insoluble residues were wet sieved on a 90 μm sieve to determine the largest size fraction (Fig. 13). As indicated in Fig. 14 there is a very good correlation between the weight fractions of quartz in the samples.

3.4. Up-concentration of quartz on grinding table

The relationships shown in Fig. 14 are also observed on the grinding table where a linear correlation between the wear rate and the grinding table quartz concentration is found (Fig. 15).

3.5. Wear vs. quartz on grinding table

Comparing Figs. 14 and 15 it can be concluded that the up-concentrated quartz concentrations are the same in all three internal circulations of the VRM once steady state is obtained.

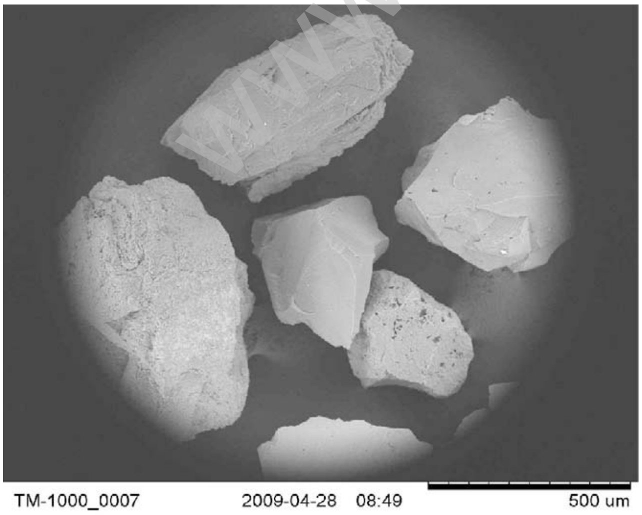

Fig. 13. SEM micrograph of quartz particles in separator sample. The particle size ranges from approx. 200–500 μm. The quartz particles found in the separator and table sample are very similar in their appearance and shape.

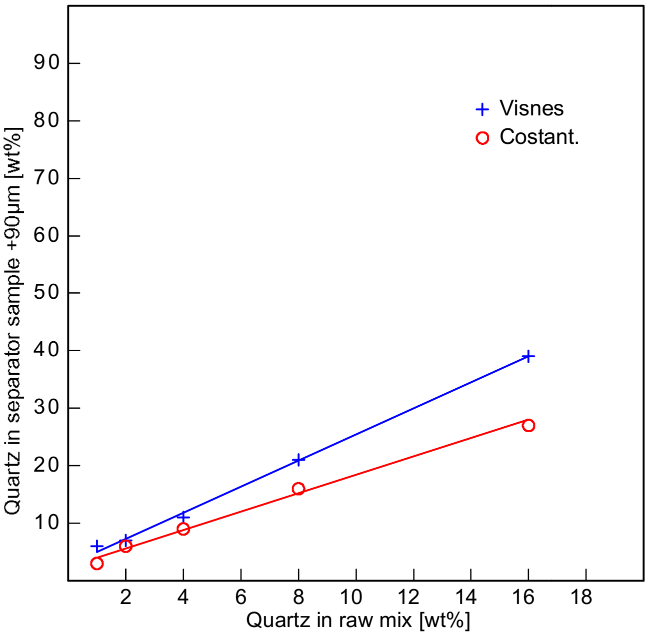

Fig. 14. Wt.% quartz in raw mix vs. wt.% quartz in separator sample. The figure shows how quartz is upconcentrated due to the closed circuit process. Visnes: $R^2 = 0.99$. Costantinopoli: $R^2 = 0.99$.

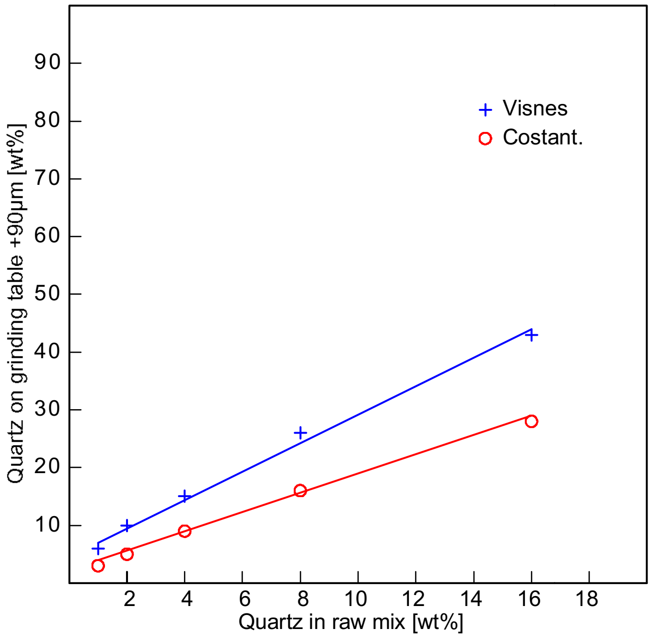

Fig. 15. Wt.% quartz in raw mix vs. wt.% quartz on table. The figure shows how quartz is upconcentrated due to the closed circuit process. Visnes: $R^2 = 0.99$ Costantinopoli: $R^2 = 0.99$.

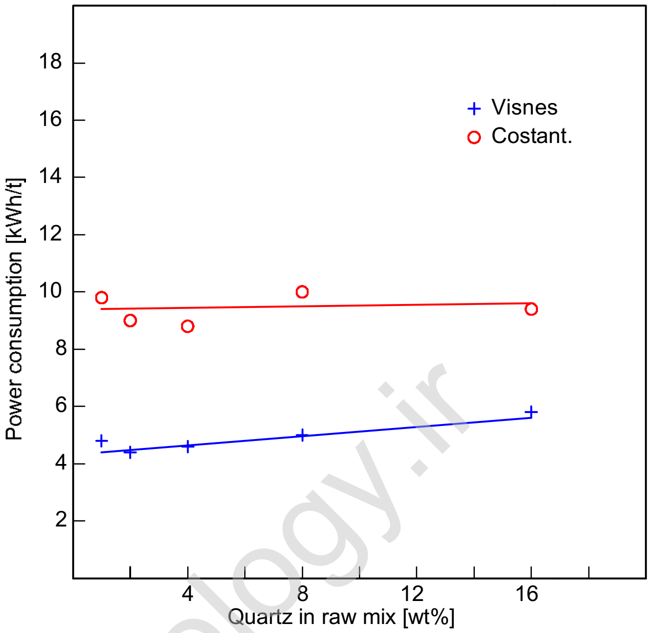

Fig. 17. Specific power consumption of Visnes and Costantinopoli limestone as function of quartz content in new feed. Note how the specific power consumption of the Costantinopoli mixture remains approx. constant.

With reference to Figs. 11, 14 and 15 it can be concluded that the wear rate is determined by the quartz concentration alone. Thus, irrespective of limestone type, the amount of quartz in contact with the wear parts will fully determine the wear rate (Fig. 16).

The more abrasive particles pr cm^2, the more wear part material is removed during each sequence. For the lower quartz concentrations (<16%) there is a linear relation between abrasive wear and quartz content. From running a single test at a known quartz concentration, it is possible to predict the wear rate at all other quartz concentrations below 16%.

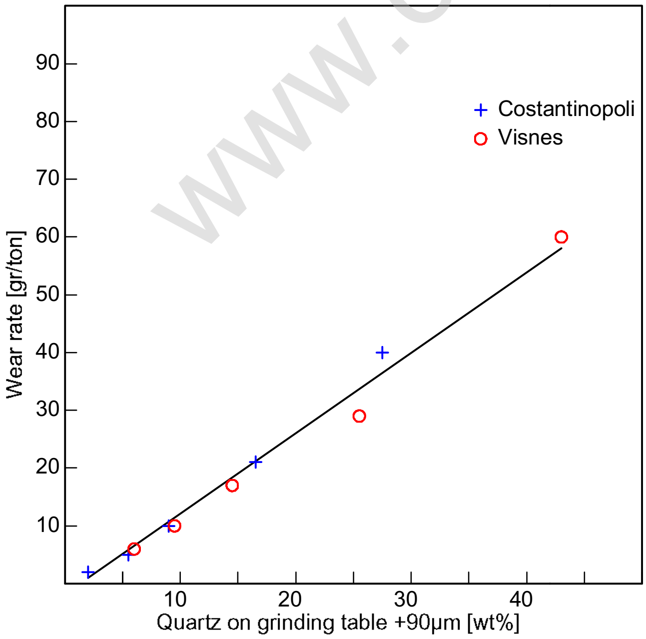

Fig. 16. Wear rate vs. quartz concentration on VRM table. $R^2 = 0.99$.

3.6. Power consumption vs. quartz concentration

By analyzing Fig. 11 and comparing to the power consumption figures in Table 4 there is a strong indication that a limestone with a low power consumption will lead to larger wear rates compared to a limestone with a high power consumption. At first, this might intuitively seem to be contradictory because high-power limestones could be expected to generate increased internal circulations. The Visnes limestone shows a general increasing power consumption as the quartz content is increased. The Costantinopoli limestone however shows an almost unaffected power consumption: The Costantinopoli limestone resembles quartz in terms of grindability, and this property causes a power consumption independent of quartz content. The Visnes limestone however, has a grindability very much different from quartz and thus an increasing quartz content will result in increased power consumption. Because limestone is still the dominating component during the tests carried out (quartz <16%), the physical properties of the grinding process will still largely be controlled by the limestone only (see Fig. 17).

4. Conclusion

The wear rates are determined by the relative differences in grindabilities between the abrasive components and the non-abrasive components: If quartz and limestone are crushed separately in a single cycle, limestone will produce more fines than quartz, because it is easier to grind than quartz. At the beginning of a closed circuit comminution process, the equilibrium will shift and slowly settle at a mixing ratio which is inversely proportional to the grinding rate of the separate components. Hence, the more the non-abrasive components resemble the abrasive components in terms of grindability, the less the process will change the input mixing ratio (new feed). Consequently and theoretically, the wear rate is minimized if the grindability of limestone could become equal to quartz. If the grindability of a non-abrasive component exceeds the grindability of the abrasive component, the wear rate will be minimized even further.

In this particular investigation, the coarse crystalline Visnes limestone is fragmented easier than the microcrystalline Costantinopoli limestone. As a result the Visnes limestone governs the more abrasive mixture. The degree of limestone crystallinity determines the steady state equilibrium in the VRM and thus the wear rate.

This study shows a linear relationship between the wear rate and the quartz concentration on the grinding table as well as the quartz concentration in the separator returns sample: This finding has simplified the understanding of the VRM. The wear rates for a limestone mixture may be predicted at different quartz concentrations from one single test (<16%).

In terms of wear, the quartz concentration in a synthetic limestone/quartz mixture will solely influence the abrasive wear. For the Visnes limestone mixture, an increased concentration of quartz of approx. 2.5 times the input concentration was observed. Each raw mix individually governs the up-concentration of quartz, but the quartz concentration has no influence on the total power consumption (<16%).

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