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Effect of Quartz in Clay on Grindability of Raw Mixes for Cement Production

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ABSTRACT: *High quartz content in clay substantially impacts the grinding of raw mix, quality of clinker and final cement produced. The presence of quartz requires very fine grinding and a long sintering time to react significantly, all of which are very expensive. This study assessed an extensive plant sample which involved a vertical roller mill to determine the correlation between quartz content in clay to the 90 µm residue, feed rate, clinker microstructure and mill power. The characterisation study performed on raw materials revealed three clay categories based on quartz content, namely low, normal and high quartz at (42.4%–48.8%), (57.1%–64.9%) and (81.5%–89.3%), respectively. The grinding test showed an increment of 90 µm residue for high-quartz clay. Meanwhile, high, medium and low feed rates generated the most coarse, coarse and fine products, respectively. Based on the distribution curve of mill products, high quartz content in clay significantly reduced the particles passing percentage. Coarser particles were observed to be present in mill products for the high-quartz category compared to the low-quartz clay and normal-quartz clay, signifying inadequate size reduction for the high-quartz clay in the vertical roller miller. The power consumption was higher (7.2 kWh/t–9.0 kWh/t) for grinding raw mixes that contained high-quartz clay than low-quartz clay. This study provided a significant relationship between grindability and the amount of quartz content in clay with the purpose of optimising the grinding process when dealing with high-quartz content in clay.*

Keywords: cement production, clay, grindability, quartz, roller mill

1. INTRODUCTION

Ordinary Portland cement consists of four major raw materials: carbonates, aluminosilicates, iron and aluminium compounds (oxides) along with other minor constituents. These raw materials are crucial in the cement industry. Hence, the significance of optimising raw materials at the preparation stage is important for clays which are the source of aluminosilicates. This is a challenging task as clays differ vastly in terms of physical, mineralogy and chemical properties.[1–4] High quartz content in clay is not suitable to be used as a component of raw material in the cement industry because the high quartz content creates problems during grinding and clinkering stages. This is due to the neat and open chains bonding of Si-O that produces a solid crystal structure which makes quartz hard, brittle and stiff, thus affecting the process.

Although it is crucial to optimise the grinding circuit when dealing with high quartz content in clay, costing should be considered as the grinding process consumes a large amount of electricity.[5] The ball mill system in grinding machines is substituted with a compact and modern vertical roller mill which has better drying capacity and energy efficiency. Vertical roller mills consume less energy than tumbling mills, require less space per unit and have cheaper investment costs.[6] The vertical roller mills can grind harder clinkers and raw materials as they possess enhanced roller profiles, better internal lining to avoid wear, and better metallurgy.[7–13] Although the vertical roller mill is used, reducing the size of raw materials when dealing with high quartz content in a cement processing plant is a never-ending issue. A lot of studies have indicated that the amount of free quartz in clay should be kept to a minimum because it can affect the grindability and burnability of raw mix during the clinkering process, which will indirectly affect the quality of final product.[14,15] Quartz requires very fine grinding and a long sintering time to react significantly, all of which are energy-consuming and expensive.[16] This is due to the properties of quartz with a seven-point hardness in Mohs scale which quickly wears off mill lining and poses a challenge in the grinding process in order to gain the desired particle fineness.[17] Composition uniformity and fineness are two crucial aspects that dictate viable blended materials for heat treatment in the kiln for producing quality cement.[18] Yao et al. (2020) investigated pozzolanic activity of quartz and hydration properties in mine tailings after undergoing mechanical grinding. They found that the particle size achieved a limit after 80 min of grinding, but the specific surface area hit a limit after 120 min due to the continuous grinding that increased the pore volume of micropores and mesopores. The prolonged grinding not only led to a progressive increase in the pozzolanic activity index and percentage of dissolving in an alkaline solution, but also resulted in a decrease in relative crystallinity.[19] However, prolonged grinding is not desirable as it consumes large energy and cost. Besides that, prolonged grinding can contribute to inefficient process due to agglomeration.[20] Particle size reduction and interparticle agglomeration in milky and clear quartz using a planetary ball mill were conducted by Guzzo et al. for 32 h of grinding time. Lower grinding rates were obtained for milky quartz which displayed higher fracture strength of its polycrystalline micro texture. They also found that the agglomeration occurred earlier for clear quartz (4 h) compared to milky quartz (16 h).[21] In another study conducted by Tripathy et al., the increasing feed rate decreases the retention time of particles inside the mill, thus reducing the generation of ultrafine particles. It is important to avoid agglomeration and reduce the power consumption per ton ore produced.[22] However, the research was conducted on chromite with Mohs hardness of 4.5. This was different compared to the quartz investigated in this study that has 7 Mohs hardness, which probably required less feed rate in order for an efficient grinding to occur. The effect of increasing feed rate to power consumption in grinding clays with high quartz content needs to be further investigated. In a recent study, Prziwara and Kwade reviewed the effect of grinding additives on size reduction, particle stressing inside the mill and powder properties.[23] However, it was found that the size reduction was still lower for quartz, even with the presence of grinding additives.[24,25]

The average quartz content in clay typically limits at the range of 50% to 65%, which is shown in Table 1. However, the Malaysian cement industry deploys clay with quartz content exceeding 70%.[26] In this study, the normal and high quartz content in clay ranges from 57.1% to 89.3%, which is shown in Table 2. This raises concerns on the use of high-quartz clay in the cement industry due to its impact on the end product.[27] The problem of particle size reduction and agglomeration associated with structural alterations which occurs in intensely ground quartz particles in clay for the cement industry is still an unresolved issue. When dealing with high-quartz content in clay, the optimised operational parameters such as feed rate need to be determined while lowering energy and cost consumption in cement processing. This study assessed the impact of low, normal and high quartz content in clay upon grindability based on the following aspects: 90 μm residue, size particle distribution of mill products and consumption of mill power.

Table 1: Composition of clay, ranges and limit

Composition	Ranges and limit in clay (%)
CaO	Unrestricted but consistent
MgO	5% (maximum but in agreement with the content in limestone)
SiO_2 (free quartz)	50%–65%
Al_2O_3	15%–20%
Fe_2O_3	6%–10%
Alkalies ($Na_2O + K_2O$)	3% (maximum but in agreement with the content in limestone)
S as SO_3	1% (maximum but in agreement with the content in limestone)

Table 2: The average oxide compositions of the raw materials

Composition	Limestone (%)	Iron ore (%)	Clay-low quartz content (%)	Clay-normal quartz content (%)	Clay-high quartz content (%)
CaO	52.31	1.52	1.41	1.41	1.41
SiO_2	5.62	12.80	42.40–48.8	57.10–64.9	81.50–89.3
MgO	1.10	10.24	–	–	–
Al_2O_3	0.64	–	17.63	17.63	17.63
Fe_2O_3	0.29	58.56	3.25	3.25	3.25
K_2O	0.24	–	–	–	–
SO_3	0.12	–	–	–	–
Na_2O	0.12	–	–	–	–

2. METHODOLOGY

Samples for this study were collected by conducting surveys at a cement processing plant in Kedah. Sampling was conducted for two hours and twice a day (morning and afternoon) with steady-state conditions in order to achieve excellent sample representation. The samples were gathered at 20 min intervals in each survey to obtain a composite sample for every sampling point. Figure 1 shows the processes undertaken in this study, starting from the sampling point to the grinding process of the samples in the mill, heat treatment in the kiln and the final product. Samples for milling and kiln were obtained from external feed streams and air sluices, respectively. The homogenising silo was left empty during the sampling surveys to ensure that the kiln feed was obtained directly from the mill product. Upon gathering 3 kg–5 kg of samples from every sampling point, the operating settings used in the cement processing were recorded using circuit tools which were available. Mill power and feed rate were operational variables in this study. A vertical roller mill was deployed (roller diameter: 1000 mm, roller width: 630 mm, speed: 1500 rpm and press motor: 2 × 300 kW). All parameters of mill operation were recorded. With 280 tph capacity, the mill could grind materials of 90% passing 90 µm. Feed rates above and below the normal value were categorised into high (321 tph–350 tph) and low (140 tph–279 tph) groups, respectively. In order to examine the effect of quartz in clay upon the grindability of raw mixes, the following tests were executed on mill feed and mill product samples: moisture content, chemical composition, grain size, quartz content analyses as well as particle size distribution and residue tests. The effect of quartz content on the microstructure of the clinker was also analysed by using scanning electron microscopy (SEM), Hitachi TM3000, Japan.

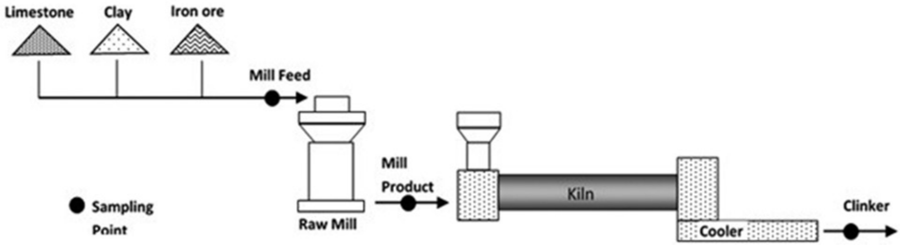

Figure 1: Plant circuit and sampling points.

3. RESULTS AND DISCUSSION

3.1 Chemical Composition, Moisture Content and Grain Size

The limestone samples were grey to dark grey with 2.0%–3.0% moisture content and 14.88% quartz content on average. The chemical composition of limestone samples were 52.31% of CaO, 5.62% of SiO_2, 1.10% of MgO, 0.64% of Al_2O_3, 0.29% of Fe_2O_3, 0.24% of K_2O, 0.12% of SO_3 and 0.12% of Na_2O. To address the low content of Fe_2O_3 in the samples, iron ore was included with the following composition: 58.56% of Fe_2O_3, 12.80% of SiO_2, 10.24% of Al_2O_3 and 1.52% of CaO with 11.5%–12.2% moisture content. The iron ore samples had 5.40% quartz, whereas the clay samples were composed of 70.25% of SiO_2, 17.63% of Al_2O_3, 3.25% of Fe_2O_3 and 1.41% of CaO with 15.6%–16.4% moisture content. The oxide compositions of raw materials are summarised in Table 2. As the quartz content differed by 42.4%–89.3%, the clays were classified into low (42.4%–48.8%), normal (57.1%–64.9%) and high-quartz clay (81.5%–89.3%), which are shown in Figure 2. Different colours were observed for low, medium and high quartz clays. The average diameter of quartz particles in clay samples was in the range of 90 µm to 125 µm.

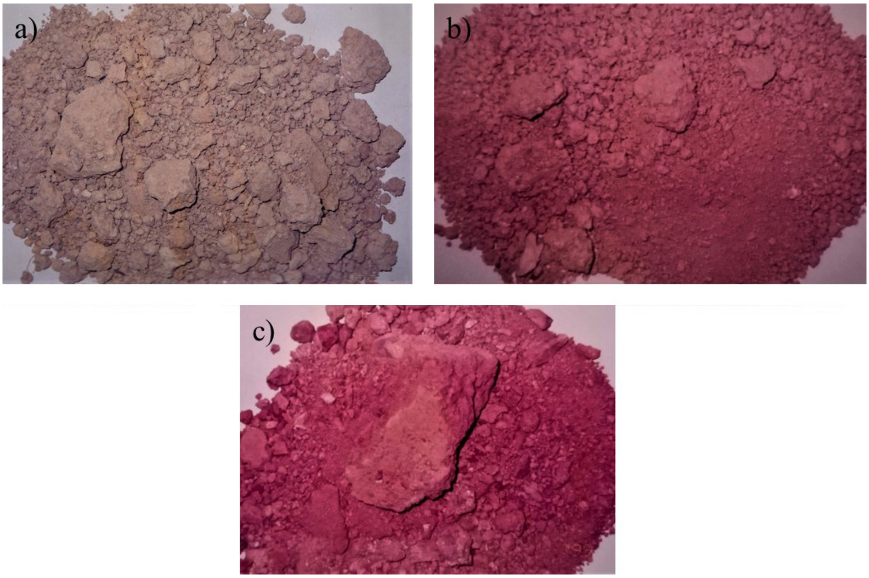

Figure 2: Different colours of (a) low quartz content, (b) normal quartz content and (c) high quartz content.

3.2 Effect of Quartz Content on 90 µm Residue

A residue of 90 µm was selected as a criterion to assess the efficiency of vertical roller mill. A cement plant normally targets 10%–12% of 90 µm residue. Residue above 12% affects material burnability, which is not desired in cement processing. Controlling the 90 µm residue percentage is important because sintering is proportionate to the inverse of particle size. Figure 3 shows the impact of quartz on 90 µm residue for all quartz categories. It could be seen that the > 90 µm residue percentage increases from low quartz to high quartz for all operating feed rates. Higher quartz content generated higher residue (> 90 µm) due to particles breakability aspect dictated by interactions among roller mill design, physico-chemical properties of particles (size, hardness and density) and grinding process. Particles in raw materials with various shapes and sizes have different breakability based on their physico-chemical properties. Different feed rate was also used to grind clays with low, normal and high content quartz. It could be seen that a low feed rate produced lower > 90 µm residue percentage compared to normal and high feed rate for all quartz content conditions. The low quartz group recorded 8.31% and 14.49% as the feed rate was increased to normal and high, respectively. For the normal quartz group, the increase of residue by 9.28% and 14.66% was noted for normal and high feed rates, respectively. When a higher feed rate was operated on the samples, 12.0%–12.5% and 12.5%–13.5% were recorded for high-quartz silica, exceeding the allowable limits of the > 90 µm residue percentage as shown in Table 2. This was due to high feed rate which caused more particles to enter the mill and decrease their surface area, thus reducing particles breakability. From this graph, it could be concluded that the low quartz content clay (at all feed rate), normal quartz content clay (at all feed rate) and high quartz content clay (only at low feed rate) showed the acceptable limits of > 90 µm residue percentage. In contrast, the high quartz content clay that operated at normal and high feed rate showed high > 90 µm residue percentage which exceeded the allowable limits.

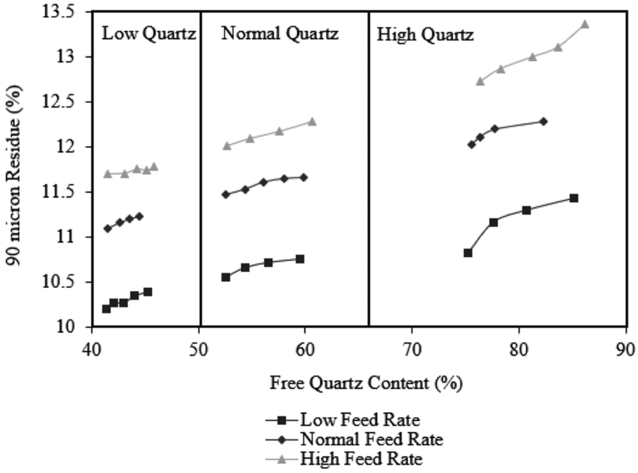

Figure 3: Effect of quartz content on 90 µm residue at low, normal and high feed rates.

3.3 Effect of Quartz on Particle Size Distribution

The particle size distribution was determined to identify the breakability of particles (size: 0.038 mm–0.106 mm). Figures 4 to 6 show the particle size distribution for all quartz categories at the three fixed feed rates, namely low, normal and high feed rates, respectively. Evidently, particle size distribution turned coarser with higher quartz content for all conditions. Figure 4 showed the passing percentage to size (mm) for low, normal and high feed rates, respectively. The passing percentage reduced substantially at finer size (0.038 mm–0.075 mm), although variations were minimal for coarser size (0.090 mm–0.106 mm). In Figure 4(a), at a low feed rate with 0.038 mm–0.075 mm size, mixes with low quartz displayed 65%–57% passing percentage, which later decreased to 55%–48% as the quartz content increased to normal percentage in Figure 4(b). The passing percentage reduced to below 45% for high quartz clay, which is shown in Figure 4(c). More even distribution could be observed for low quartz content than those with normal quartz and high quartz contents. Notably, narrowed down and stringent distributions were observed for raw mixes with normal quartz and high quartz clay, respectively. Raw mixes gained from grinding high quartz clay generated a more stringent particle size distribution that reduced percentage passing in finer size fraction (0.038 mm–0.075 mm) due to inadequate grinding of high quartz material. High quartz clay with neat and open chains bonding of Si-O produces a solid crystal structure that makes quartz hard, brittle and stiff, thus posing challenges when performing grinding process. Although coarser size fraction displayed minimal variations (90 µm residue), a significant decrease was observed for finer size fractions in the percentage passing. A similar trend could be observed for raw mixes at high and normal feed rates. The passing percentage for the size range of 0.038 mm–0.075 mm reduced as the feed rate was increased from low to normal and high. For clay with low quartz content, the passing percentage at low feed rate was 65%–57% (Figure 4[a]) and further reduced to 53%–48% at normal feed rate (as shown in Figure 5[a]) and 45%–38% at high feed rate (as shown in Figure 6[a]). The feed rate and the volume of particles inside the mill are directly proportional. For instance, a lower feed rate decreases the amount of material left inside the mill, thus increasing its retention time and breakability.

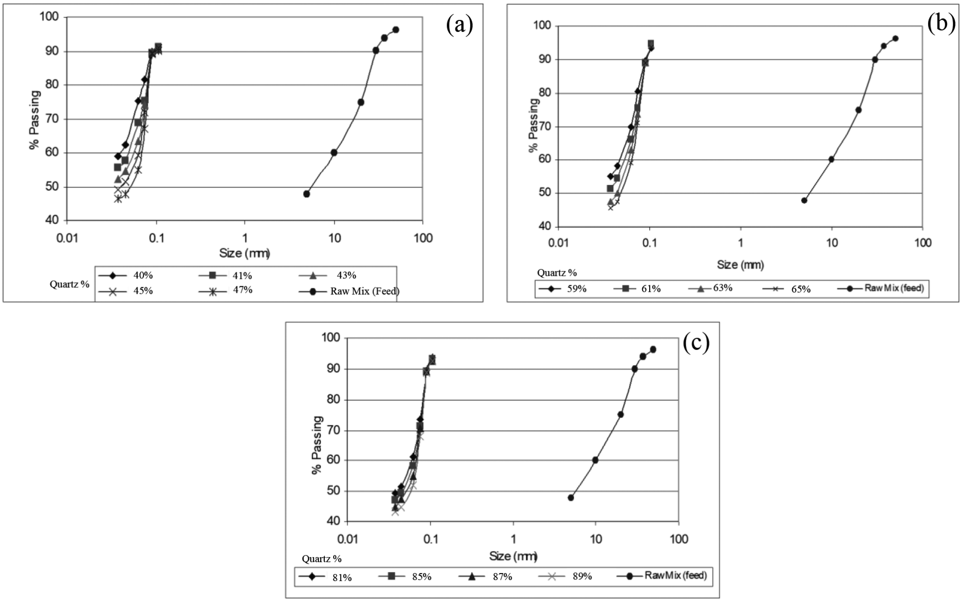

Figure 4: Distribution of particle size at low feed rate: (a) low quartz clay, (b) normal quartz clay and (c) high quartz clay.

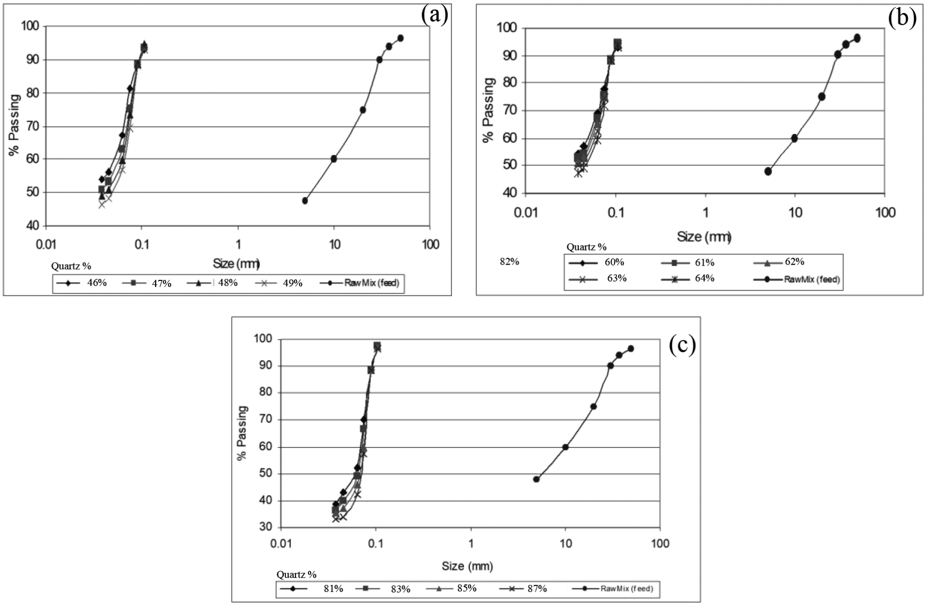

Figure 5: Distribution of particle size at normal feed rate: (a) low quartz mixes, (b) normal quartz mixes and (c) high quartz mixes.

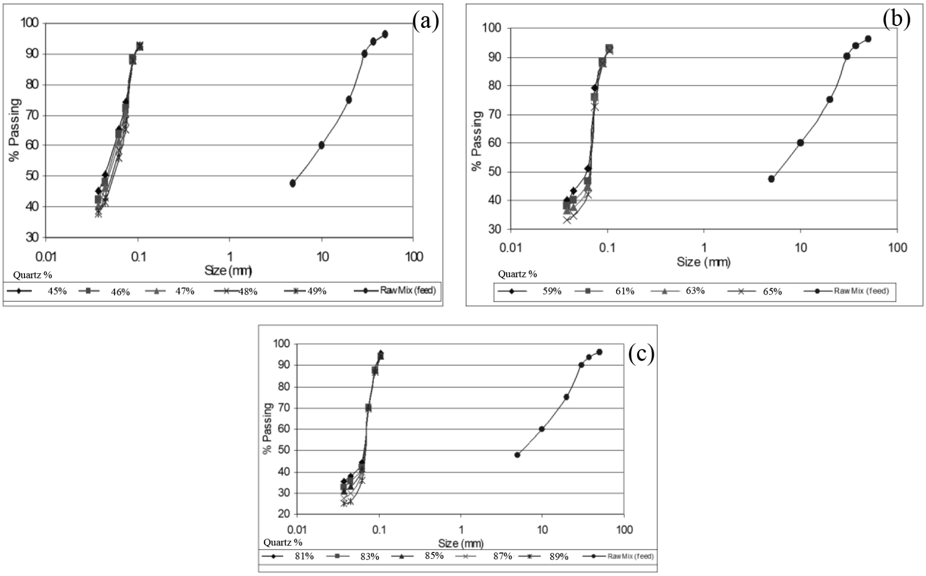

Figure 6: Distribution of particle size at high feed rate: (a) low quartz mixes, (b) normal quartz mixes and (c) high quartz mixes.

3.4 Effect of Quartz Content on Clinker Microstructure

Clinker quality may also be determined by examining its microstructure under a microscope. The size of alite and belite crystals can be utilised to assess clinker quality. The typical size of six-sided angular crystals of alite in a normal clinker is 25 µm–50 µm long, while the average size of belite-rounded crystals is 25 µm–40 µm long. From Figures 7, 8 and 9, it could be seen that the belite (dicalcium silicate) from the high quartz clay (as shown in Figure 9) was larger (belite nest) than those of low and normal quartz clay (as shown in Figures 7 and 8). This was due to the course particles produced from the raw mix caused by the high quartz. It was supported by the particle size distribution results in Figure 6. During the clinkering process, the migration and exchange of materials took place and smaller grain size gave shorter transport distance for achieving complete reaction compared to larger grain size. Drop-like belite and belite streaks could be observed at normal quartz due to the inhomogeneity and course raw mix.

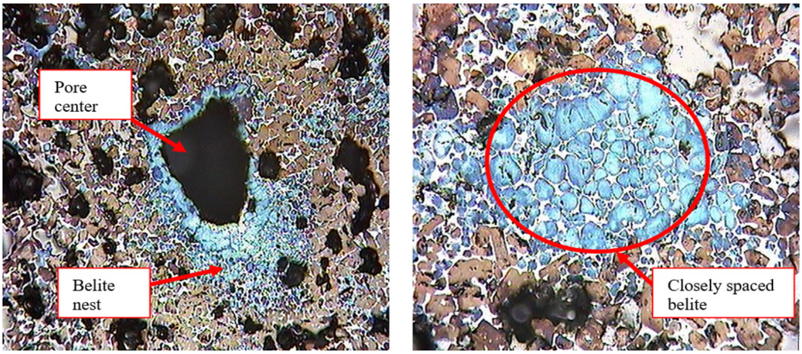

Figure 7: Photomicrographs of cement clinkers at low quartz, high feed rate.

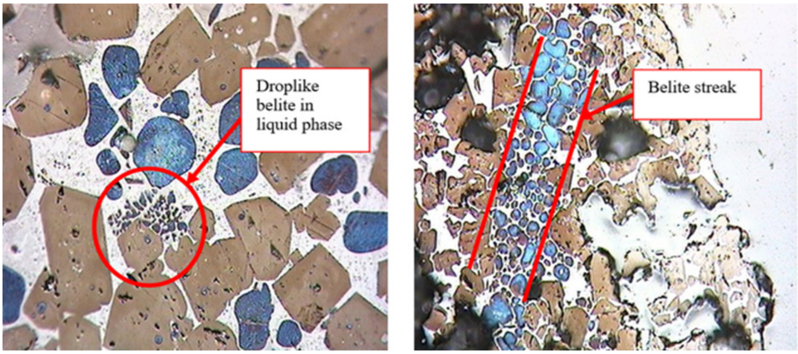

Figure 8: Photomicrographs of cement clinkers at normal quartz, high feed rate.

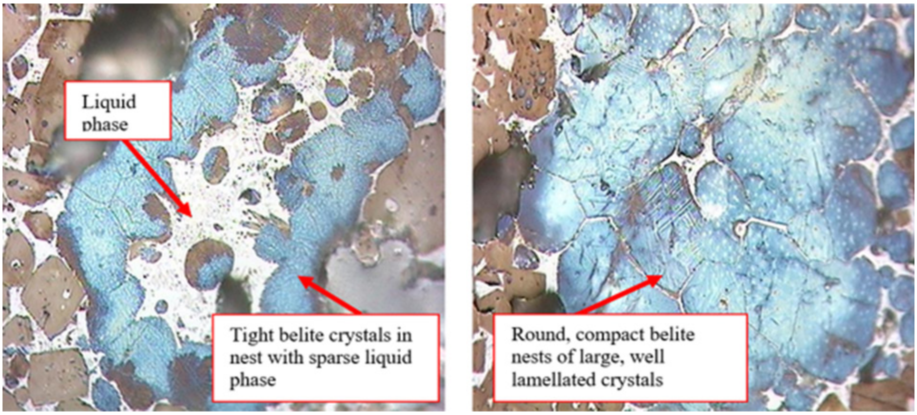

Figure 9: Photomicrographs of cement clinkers at high quartz, high feed rate.

3.5 Effect of Quartz Content on Mill Power

Consumption of mill power is vital to optimise mill efficiency as the grinding stage demands more than 30% of energy consumption. A typical vertical roller mill operation consumes 5 kW–7 kW to generate a tonne of raw mix within an hour. Figure 10 displays mill power usage for all quartz groups. Based on Figure 10(c), high quartz content led to high mill power consumption, especially for high feed rate with the range of 7.2 kWt/h to 9.0 kWt/h that exceeded the typical plant power usage. In previous study, grinding chromite with Mohs hardness of 4.5 increased the feed rate, thus showing an increase in power consumption. However, the overall production cost can be decreased when higher throughput is achieved due to the increase of production rate for the same level of energy consumption.[22] However, this study did not achieve higher throughput as an inefficient grinding process with a coarser particle size of clay was produced at a higher feed rate. Materials with high quartz content are harder and more granulometric. A high feed rate should be avoided when grinding high quartz content due to the usage of abominable power that exceeds 7 kWt/h. In order to effectively grind raw mixes using a roller mill, suitable pressure and draw-in action should be considered to form a stable bed of material. Essentially, the draw-in action is controlled by the friction coefficient and granulometric composition of the raw material. The bed of material for high quartz content possesses higher stability to avoid displacement by rollers. Hence, substantial frictional force should be present between mill circumference and material to ensure the rollers can effectively roll on the material instead of sliding along the material to generate a finer product.

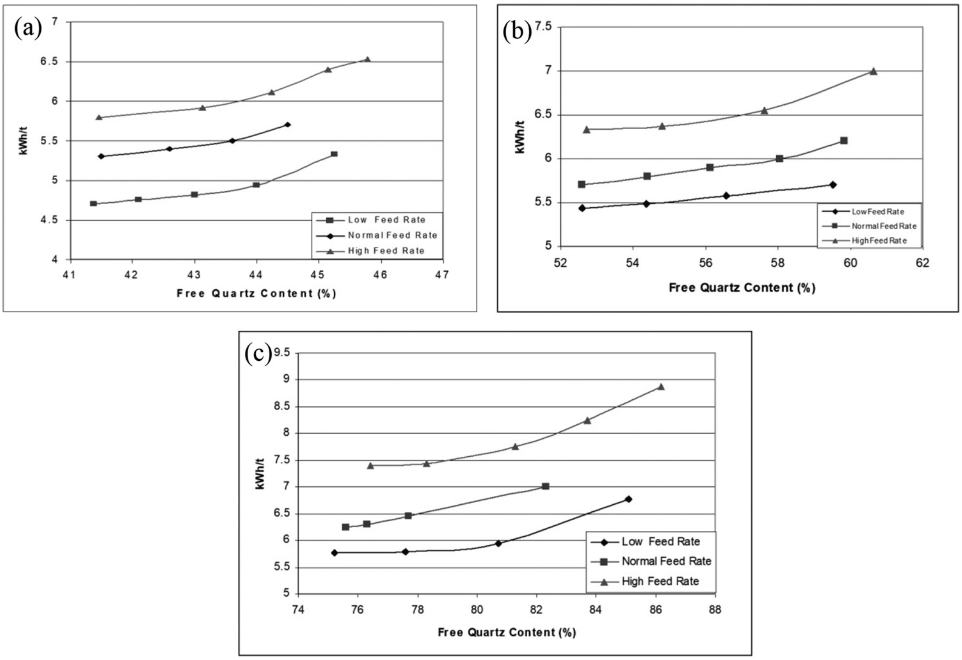

Figure 10: Effect of: (a) low quartz content, (b) normal quartz content and (c) high quartz content on kWh/t at varying feed rates.

4. CONCLUSION

This research assessed the impact of quartz in clay upon grindability of raw materials based on the following aspects: 90 µm residue, size particle distribution of mill products and consumption of mill power. The following conclusions were made based on the findings:

1. The percent of 90 µm residue was highly affected by quartz content as high quartz content increased the percentage of the 90 µm residue.

2. Mill feed rate also influenced the 90 µm residue. A higher percentage of 90 µm residue was observed for a high feed rate. For the low quartz group, an increment from low feed rate (140 tph–279 tph) to normal (280 tph–320 tph) and high (321 tph–350 tph) feed rates increased the 90 µm residue from 10.2%–10.4% to 11.07%–11.23% and 11.76%–11.87%, respectively. Meanwhile, increment of feed rate for the normal quartz group to normal and high feed rates caused the 90 µm residue to increase from 10.55%–10.76% to 11.56%–11.76% and 12.02%–12.43%, respectively. The results

for high quartz content showed higher residue from 10.83%–11.42% for low feed rate to 12.1%–12.4% as well as 12.72%–13.36% for normal and high feed rates, respectively.

3. In order to address the different quartz contents found in clay, a mill should viably operate at a low feed rate (140 tph–279 tph) to grind high quartz clay in order to meet the 90 μm residue target. Normal feed rate (280 tph–320 tph) is suitable for normal quartz clay, while a high feed rate (321 tph–350 tph) is adequate for low quartz clay. However, grinding clay with high quartz content at a high feed rate consumes more mill power (> 7 kWt/h) and should be avoided.

5. ACKNOWLEDGEMENTS

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