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The influence of parent rock, mining and processing technologies on the industrial quality of kaolin concentrate –case study from Bombowha kaolin, Ethiopia

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ABSTRACT: Bombowha kaolin deposit is a primary deposit formed mainly through weathering of granite and pegmatite. This research was designed to evaluate the influence of parent material, mining practices and processing technology on the quality of processed kaolin. Geochemical, mineralogical, and technological properties of kaolin were analyzed and field observations conducted to evaluate the influence. Samples of the parent rocks, kaolin deposit, Run-Of-Mine, and processed kaolin were analyzed for their geochemistry, mineralogy and physical properties. Results show that the kaolin derived from pegmatite has better quality (high alumina, low silica, better plasticity, low coloring elements and others) than the granite-derived one. The poor quality of the granite-derived kaolin is ascribed to its incomplete kaolinization as evidenced by the presence of minor halloysite. The geochemical analysis of the Run-Of-Mine shows close similarity to that of the parent granite demonstrating severe dilution during mining, hauling and storage of kaolin ore. The high pit-wall angle (80-85°), the rheologically weak overburden, old excavation machinery and unsystematic delineation of mineable portion of the deposit contributed to high level of dilution. The properties of processed kaolin show the wet processing method brought substantial improvement in the quality of the kaolin (Al_2O_3 increased by nearly 98% and SiO_2 decreased by 36% with respect to the Run-Of-Mine). Had the feed kaolin ore not been diluted, the kaolin concentrate would have been better than what is achieved through the adopted processing method. Systematic mine design, selective mining, and graded stockpiling of kaolin ore are advised for better quality kaolin concentrate.

Key words/Phrases: Ethiopia, Kaolin Concentrate, Mining, Wet Processing

INTRODUCTION

Kaolin is one of the most widely used industrial raw minerals. It has a wide range of applications including paper coating and filling, plastic, ceramic, paints, refractories, fiberglass, rubber and chemicals (Manning,1995; Kogel *et al*., 2006). The versatility of kaolin in industrial applications comes from such properties of kaolin including crystal size distribution, shape of clay particles, bulk chemical composition, rheological and abrasion properties, whiteness and gloss (Pyrillos *et al*., 1999). The quality of kaolin is usually compromised by impurities originating from parent rocks, nature of geologic process of kaolinization, and inappropriate mining practice like dilution or inefficient beneficiation method. The major impurities causing quality reduction in kaolin include anatase, iron oxide, quartz, muscovite, tourmaline, feldspar, biotite and others (Bloodworth *et al*., 1993; Miranda-Trevino and Coles, 2003; Murry, 2007; Ismail *et al*., 2015).

Extraction of kaolin is mostly through open pit mining method. Inappropriate mine design, collapse of non-ore pit-wall materials and mixing of inappropriately placed overburden material are the major sources of kaolin ore dilution. Kaolin processing is critical for removal of impurities and enhancing the quality of the clay ore so that it meets the stringent specifications set by different industries. There are two methods of kaolin beneficiation- Dry and Wet processing. The choice of either of the methods is dependent on the nature of the kaolin deposit and quality specifications set by the consuming industry. The wet process is usually selected for end uses requiring the highest quality of kaolin (Kogel *et al*., 2006; Murry, 2007).

Bombowha kaolin deposit is located in the northern part of the Adola Belt which is constituted by low to medium grade metamorphic rocks of Precambrian age (Fig.1). The belt is intruded by syn-to post-tectonic granitoids. The

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kaolin deposit is developed from the alteration of the syn-to post-tectonic granitic intrusion and associated pegmatites (Hailemichael and Tibebu, 1998; Said and Sentayehu, 2000). The deposit is the result of in-situ weathering of granite and pegmatite. The upper part of the intrusion is kaolinized to a depth of 20m. The parent rock is highly weathered, kaolinized, pinkish to white in color (Said and Sentayehu, 2000). The deposit contains a kaolin grade of 32-36%. It has 0.7-0.8% Fe_2O_3, and 1.75% fluxing components (Na_2O+K_2O). The proved reserve of the deposit is around 150,000 tons (Said, 1993).

Bombowha kaolin deposit has been one of the main suppliers to kaolin consumer industries of Ethiopia, primarily Tabor Ceramics and Melkasa Aluminum Sulphate and Sulfuric Acid factories. However, the demand for the Bombowha kaolin has drastically dropped to almost zero, and the above-mentioned factories stopped buying raw kaolin from Bombowha deposit. This is partly ascribed to low quality of the kaolin delivered to these companies. The significant decrease in quality and hence market may be related to either inherent quality problems especially as mining reaches the lower and weakly kaolinized part of the deposit, faulty mining practice or inefficient beneficiation. This research examines the physical, chemical and mineralogical properties of the deposit and the processed kaolin vis-à-vis mining and processing methods used, and evaluates the effectiveness of the mining and processing methods in enhancing the quality of the crude kaolin ore.

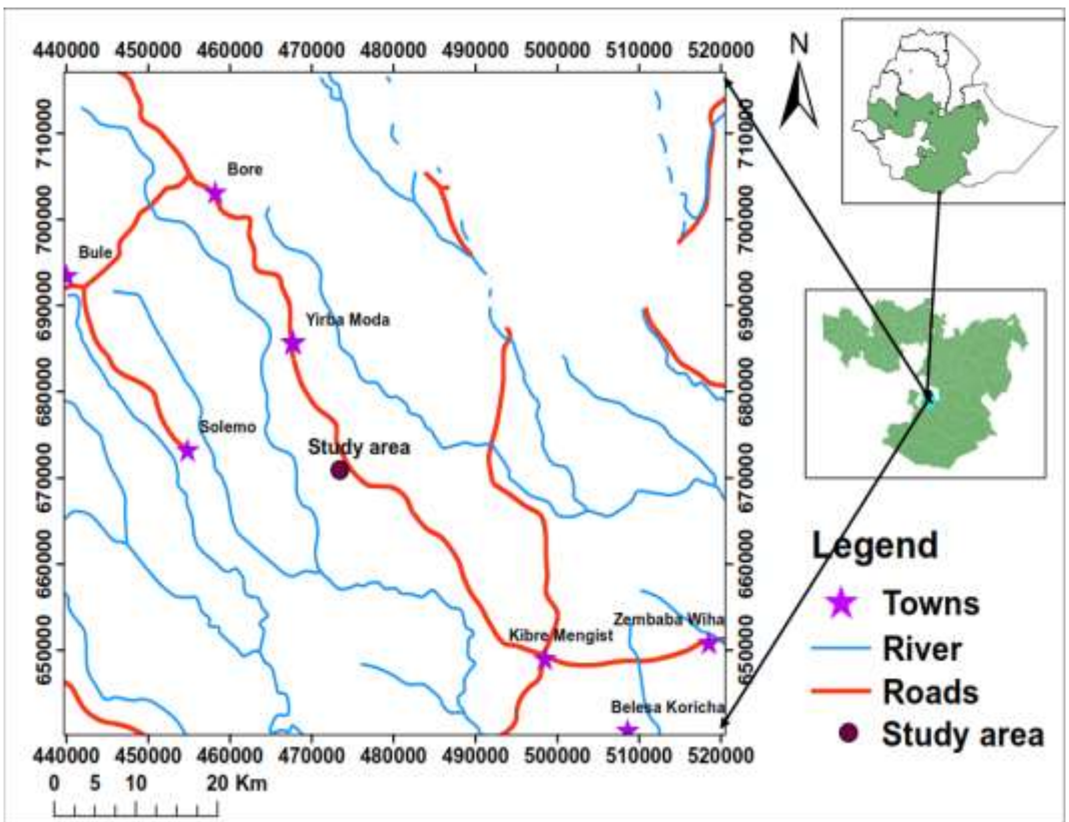


Figure 1. Location map of the study area.

METHODS AND MATERIALS

Evaluation of the mining and processing techniques started with reviewing the documents from Ethiopian Mineral Development Share Company (EMDSC) on pit design, mining method and processing technologies employed at Bombowha kaolin mine. Moreover, samples were collected from the parent rock, kaolinized granite, kaolinized pegmatite, Run-Off-Mine (R.O.M.) and processed kaolin. Samples of the kaolinized granite and pegmatite are compared to each other to explain the influence of parent rock on the quality of the kaolin deposit. The sample from the R.O.M. is used to show how quality of kaolin has been affected during mining. Moreover, the efficiency of the kaolin processing technology is evaluated by comparing the processed kaolin with the kaolin ore (from granite and pegmatite) and R.O.M. Samples were analyzed for major elements, mineralogical composition and selected physical parameters like grain size, plasticity, linear shrinkage, specific gravity, and pH.

Mineralogical analysis was conducted on four samples (3 from crude ore and one from processed kaolin) using X Ray Diffraction (XRD) method. Eight samples were selected for geochemical analysis. The samples were collected from the source granite, crude kaolin (kaolin deposit and R.O.M.) and processed kaolin. These samples were sent to Australian Laboratory Services (ALS) in Ireland and analyzed for major elements (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, MnO and P_2O_5 including Loss on Ignition - LOI) using Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma Mass spectrometry (ICP-MS).

Moreover, from the collected samples, two samples from the crude kaolin ore were selected for grain size analysis, Atterberg limits (plasticity), linear shrinkage, specific gravity and pH determination. One sample of the processed kaolin was also tested for specific gravity and pH. The grain size distribution of the samples was analyzed using sieve analysis with sieve sizes of 4.75, 2.36, 1.18, 0.6, 0.3, 0.16 and 0.063mm. During the analysis, 200g of the sample was used from each sample. This mass of the sample was allowed to pass through various sized sieve openings. Finally, the retained mass on each sieve was determined. The plasticity test was also carried out to determine the Atterberg limit or plastic limit (PL), liquid limit (LL) and plasticity index (PI) using Atterberg apparatus on the selected two samples. The plasticity index was determined by taking the arithmetic difference between the LL and PI. Shrinkage limit was also determined on the two samples.

RESULTS

Description of mining and processing activities at Bombowha Kaolin mine

The kaolin deposit at Bombowha is a surface to near surface deposit with an overburden of up to 6m thickness. Consequently, it is exploited using simple open pit mining method. The current pit depth is about 10m from the surface. The overburden constitutes about 60% (6m) of the excavated pit depth. The pit is excavated in two successive benches that have heights of 6m and 4m representing the overburden and the kaolin ore, respectively (Fig.2). The benches have 80-85° slope and 4m width. The top of the benches is used as a haulage road. Because of the high pit-wall angle, mostly the loose overburden material collapses and blends with the underlying kaolin ore (Figs.2 and 3), especially during rainy season. Moreover, there is insufficient slope stabilizing practice. Successive phase activities during mining of the kaolin ore involve (a) logging and/or clearing of the dense forest covering the mine site, (b) removal of the overburden material. The overburden material is a reddish to pinkish soil the upper most part of which is black to brownish. Thickness of the overburden varies from a maximum of 6m at the top and flat part of the ridge down to 4m in steep slope parts of the area, and (c) extraction of the kaolin ore through stripping using bulldozers. During kaolin mining, the two kaolin ore units (i.e., the one derived from the granite and the other from pegmatite) are excavated, transported to the processing plant and mixed together. Since the ore is very soft, poorly cohesive and rheologically weak, no drilling and blasting are needed. After excavation is done, the ore is loaded onto trucks using front end loaders and transported to the storage site located near the processing plant. At the storage site, the kaolin is stocked into heaps until processing starts.

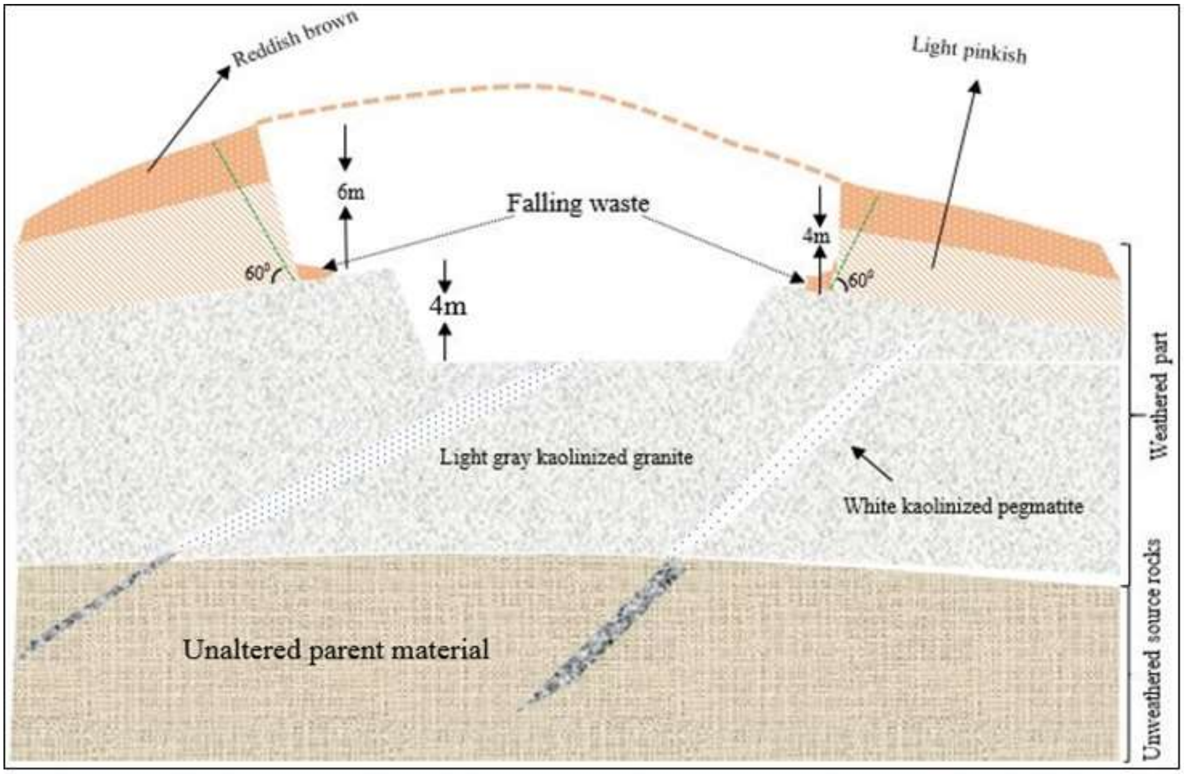


Figure 2. Sketch of the Bombowha open pit mine.

Figure 3. Section view of the open pit with the overburden material (top) and kaolin ore (bottom).

The Bombowha kaolin production uses wet processing method. The processing follows a sequence of beneficiation steps and removes different size impurities (mainly quartz, mica and iron minerals). Finally, it produces the kaolin concentrate with the desired particle size (<45μm). The beneficiation unit of the plant has a capacity to produce a kaolin product with 18% moisture content. The whole beneficiation process is working on two independent sections. The first section contains the feeding, washing, classifying and thickening activities. Section two comprises filtering, drying and stockpiling of the produced kaolin concentrate. The thickener connects the two sections and serves as a storage tank for the kaolin enriched slurry.

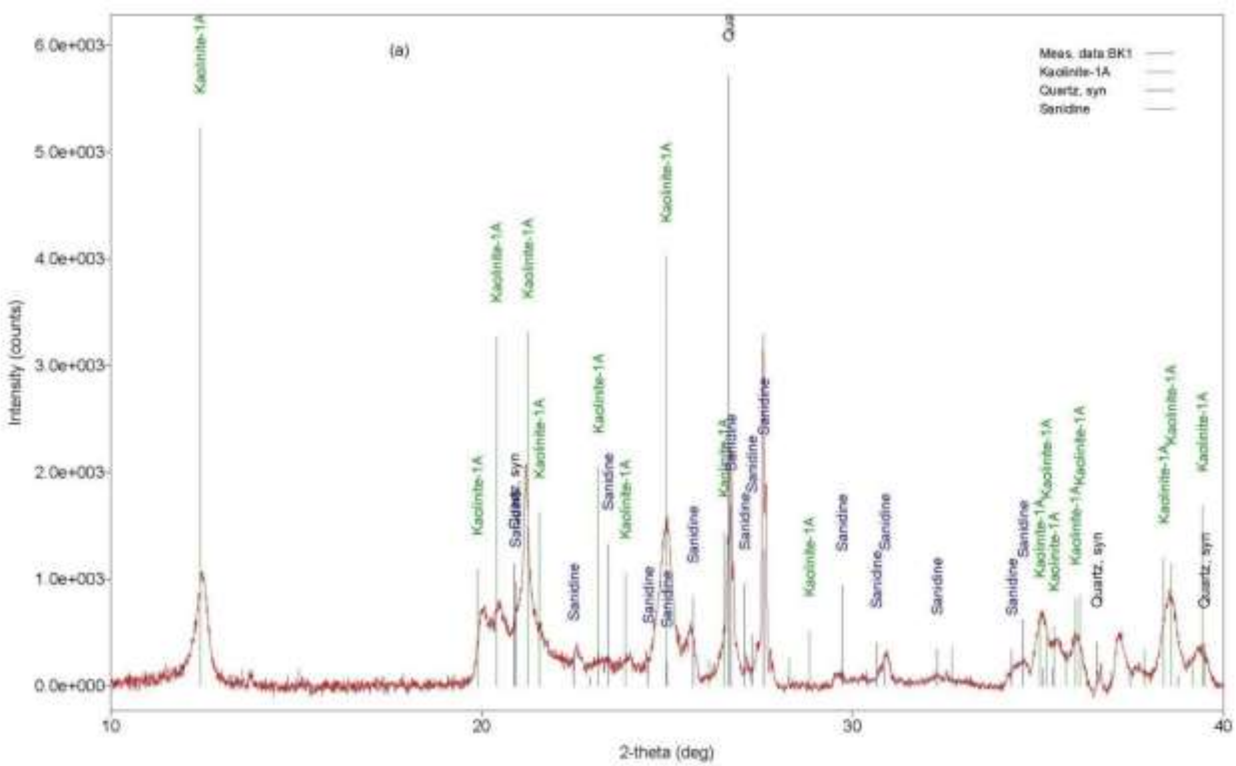
Mineralogical composition

Mineralogical composition of the kaolinized granite (2 samples), kaolinized pegmatite (1 sample) and kaolin concentrate (1 sample) were analyzed using X-Ray Diffraction method (Table 1, Fig.4). The main source rock for the kaolin (i.e., the parent granite) is also studied using petrographic microscope.

The parent granite is composed of k-feldspar, quartz, plagioclase, biotite, muscovite and opaque minerals (Fe oxide). Kaolinite and quartz are the major minerals present in the kaolin deposit. There are also other minor phases including illite, muscovite, halloysite and other unaltered feldspar minerals mainly sanidine and orthoclase.

Table 1. XRD mineralogical analysis result of kaolin at Bombowha kaolin mine site.

Sample	Major Phase	Minor Phase
Kaolinized granite	Kaolinite, Quartz	Sanidine, halloysite
Kaolinized pegmatite	Kaolinite	Illite
Processed kaolin	Kaolinite	Muscovite, Orthoclase



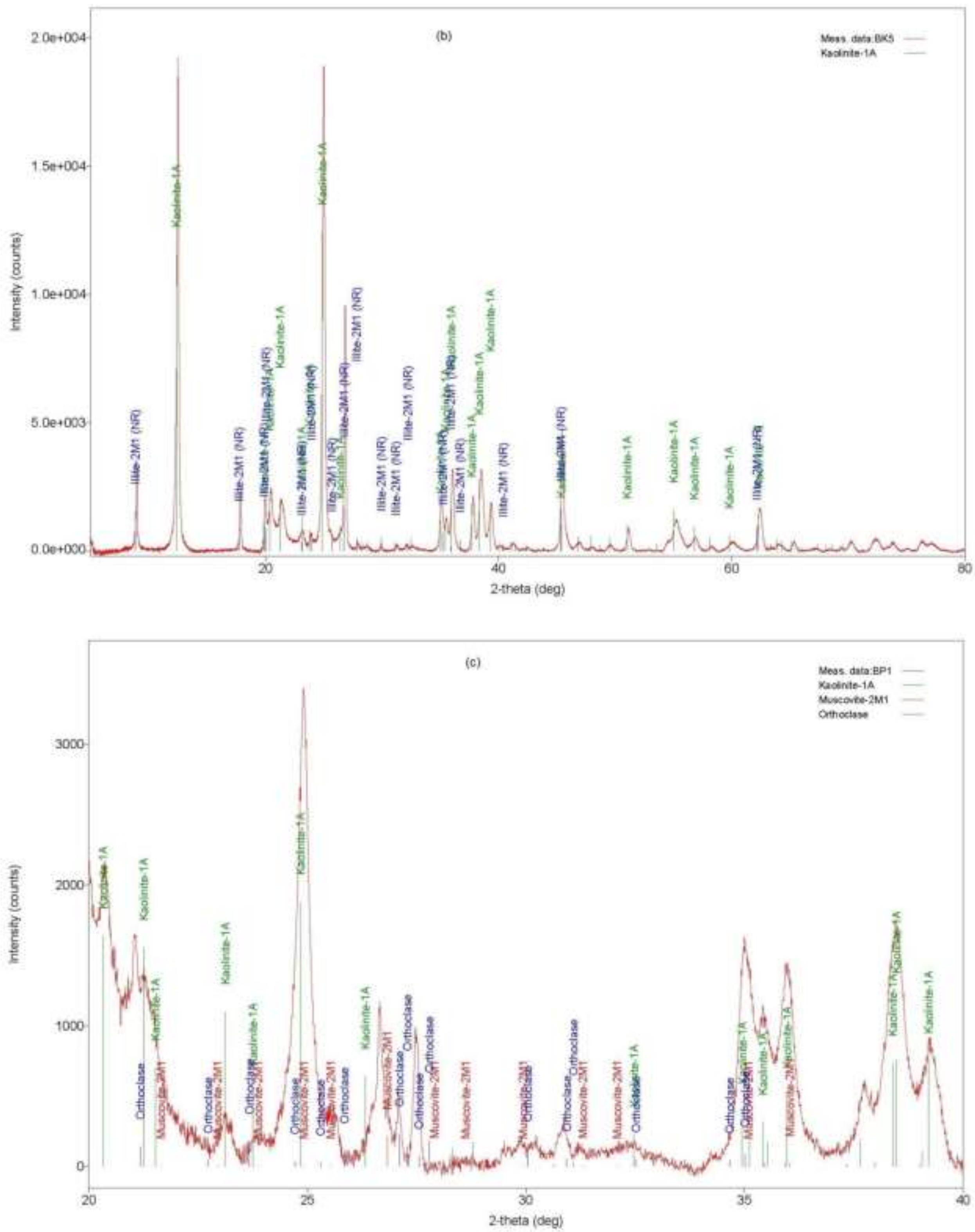


Figure 4. XRD **mineralogical analyses results of (a) kaolinized granite, (b) kaolinized pegmatite, and (c) processed kaolin.**

Geochemical compositions

The major elements analysis results are given in Table 2. The results show a distinct variation in the chemical composition of the parent granite, kaolinized granite and pegmatite, the R.O.M. and the kaolin concentrate. Even if the geochemical composition of all samples is dominated by SiO_2 and Al_2O_3 (> 85% of the bulk composition of all samples), clear distinction can be made among the different groups of samples. Silica has the highest concentration in the parent granite (72.1%) followed by the R.O.M. (71.2%). The lowest concentration of SiO_2 is in the processed kaolin (45.8%). Whereas the Al_2O_3 concentration shows inverse relation to that of SiO_2. The highest Al_2O_3 content is registered in the kaolin concentrate (35.5%) followed by the kaolinized pegmatite (33.4%), and the lowest concentration is in the parent granite (16.3%) followed by the R.O.M. (17.95%). It is notable that the parent granite and the R.O.M. have concentrations close to each other, which may be due to appreciable incorporation of the granite during mining and transportation of the mined kaolin. Compared to the kaolinite derived from granite (Al_2O_3=20.19%), the kaolinized pegmatite has better quality because it has Al_2O_3 concentration (33.4%) close to the ideal kaolin composition (39.5%).

The LOI and Al_2O_3 followed similar pattern of distribution among the different types of samples, whereas SiO_2, Fe_2O_3 and TiO_2 display similarity in their distribution pattern among samples. The other element with recognizable concentration is K_2O which has its highest concentration (5.04%) in the parent granite owing to the presence of k-feldspar followed by the R.O.M. (3.88%). The lowest concentration (1.09%) of K_2O is in the processed kaolin.

The abundance of the major coloring elements, Fe_2O_3 and TiO_2, is low ranging from 1.09-1.88% and 0.03-0.13%, respectively. The kaolin concentrate contains very low concentration of Fe_2O_3 (0.99%) and TiO_2 (0.05%).

Physical properties

Physical properties of kaolin are among the determinant factors for application in different industries. These properties are dependent on degree of kaolinization, bulk mineralogical and geochemical compositions, size ranges of individual particles in the deposit and presence and proportion of grits and coloring impurities (Murray, 2007).

The physical properties determined for the Bombowha kaolin deposit are color, grain size, plasticity, linear shrinkage, pH, and specific gravity (Tables 3 and 4). The qualitatively determined color for the raw kaolin is dominantly grey, pinkish grey to light grey. However, the kaolin derived from the pegmatite is lighter than the kaolinized granite. The processed kaolin is nearly white.

Grain size analysis was done only in the kaolinized granite and pegmatite and the result is given in Table 3 below. As can be seen from the size distribution data, the Bombowha kaolin deposit is coarse grained in which the coarse fraction (i.e., sand sized and above) constitutes from 79.9% to 96.7%. The fine size silt and clay components are very low with a range of proportion between 3.3 and 20.1%. The granite derived kaolin is coarser than the kaolinized pegmatite with coarser fractions being 96.7 and 79.9% respectively, whereas the highest proportion of fine fraction (20.1%) is found in the kaolin derived from pegmatite.

Table 2. Geochemical composition of the parent granite and kaolin samples from the Bombowha kaolin mine site.

	Granite	Kaolinized Granite				Kaolinized Pegmatite	R.O.M.	Processed Kaolin
	BR1	BK1	BK2	BK3	BK4	BK5	BM1	BP1
SiO_2	72.10	70.90	67.60	66.10	67.40	51.50	71.20	45.80
Al_2O_3	16.30	18.10	19.75	20.30	22.60	33.40	17.95	35.50
Fe_2O_3	1.88	1.89	1.92	1.61	1.18	1.09	1.88	0.99
CaO	0.15	0.02	0.02	<0.01	0.02	0.01	0.03	0.06
MgO	0.23	0.25	0.26	0.21	0.12	0.07	0.17	0.12
Na_2O	0.72	0.15	0.06	0.03	0.03	0.03	0.22	0.05
K_2O	5.04	3.73	1.69	1.12	0.99	1.53	3.88	1.09
TiO_2	0.13	0.15	0.17	0.12	0.06	0.03	0.10	0.05
MnO	0.05	0.07	0.09	0.12	0.06	0.59	0.11	0.06
P_2O_5	0.02	0.02	0.02	0.01	0.01	0.03	0.03	0.01
LOI	3.85	5.52	7.88	8.90	9.04	11.95	5.43	14.70
Total	100.47	100.80	99.46	98.52	101.51	101.23	101.00	98.43

Table 3. Grain size distribution of Bombowha kaolin deposit.

Sieve size (mm)	Kaolinized granite			Kaolinized pegmatite		
	Retained weight (g)	Retained (%)	Passing %	Retained weight (g)	Retained (%)	Passing (%)
4.75	0	0	100	0	0	100
2.36	15.4	7.7	92.3	53.6	26.8	73.2
1.18	38	19	73.3	21.6	10.8	62.4
0.6	46	23	50.3	22.6	11.3	51.1
0.3	34	17	33.3	14.8	7.4	43.7
0.16	28.8	14.4	18.9	12.2	6.1	37.6
0.063	31.2	15.6	3.3	35	17.5	20.1
Pan (<0.063)	6.6	3.3	0	40.2	20.1	0

Plasticity is another important property of kaolin and is measured based on the test results from liquid limit and plastic limit. The liquid and plastic limits for the kaolinized granite were not measured because of the coarse texture of the kaolin. Therefore, the granite derived kaolin is considered to be non-plastic. Whereas the kaolinized pegmatite has a liquid limit and plastic limit of 51% and 41%, respectively which gives a plasticity index of 10% for the pegmatite derived kaolin.

Linear shrinkage has also been determined for the two kaolin types. The kaolinized pegmatite has got 3% while the granite derived kaolin has 0 linear shrinkage. The pH values measured indicate a slightly acidic to neutral values and are found to be 6.27mol/L, 6.37mol/L and 6.46 for the kaolinized granite, kaolinized pegmatite and processed kaolin, respectively.

Table 4. Measured physical properties of kaolin at Bombowha mine site,

Color	Kaolinized granite Grey to pink	Kaolinized pegmatite White	Processed kaolin White
% fine (Silt + Clay)	3.3%	20.1%	----
Liquid Limit	-	51%	----
Plastic Limit	-	41%	----
Plasticity Index	-	10%	----
Linear Shrinkage	0	3%	
pH	6.27	6.37	6.46
Specific gravity	2.65 g/cm^3	2.53 g/cm^3	2.50 g/cm^3

DISCUSSION

Impact of parent material on quality of the kaolin ore

Parent material is the major factor determining the quality of a kaolin deposit. Among the different properties of rocks, their mineralogical composition is critical for the formation of high-quality kaolin. Minerals which are ferromanganese in composition or resistant to the kaolinization process will persist and be part of the mineralogical composition of kaolin (incomplete kaolinization, Malu *et al.,* 2013), or if decomposed may release coloring impurities such as Fe. The resistant minerals become grits (mainly quartz and mica). If the original rocks are rich in Fe bearing minerals (e.g., biotite, ilmenite etc.), these could be sources of coloring impurities like Fe. In the case of Bombowha deposit, the parent granite contains quartz (40%), k-feldspar (30%), plagioclase (15%), biotite (11%), muscovite (3%) and other opaques mainly Fe oxide minerals (1%). These minerals are potential impurities which contributed to the low quality of the kaolin, especially the high proportion of grits (quartz, mica, undecomposed feldspars) and high amount of coloring impurities (mainly iron oxide minerals). On the other hand, the pegmatite is constituted by quartz, k-feldspar and minor muscovite in which case the coloring impurities are minimum. The only impurity is the grits that come from quartz, mica and undecomposed k-feldspar. The presence of quartz, k-feldspar and mica minerals contribute to the grittiness of the kaolin and affects the quality of kaolin such as decrease plasticity and shrinkage properties. They also affect the abrasiveness and other optical and rheological properties of kaolin (AL-Shameri and Rong, 2009).The presence of halloysite in the kaolinized granite indicates the incomplete kaolinization and affects the properties of kaolin such as increasing the viscosity and lowering the dispersion properties (i.e., reflocculating effect), lowering the opacity which are the most required properties in paper industries (Siddiqui *et al*., 2005).The presence of mica (biotite and illite minerals) is a source of iron impurity during kaolinization process (Ali and Dikko, 2015).

Incomplete kaolinization of the granite is indicated by the different physical, chemical and mineralogical composition of the kaolin derived from it. The first parameter is the grain size distribution (Fig.5) in which the finer components (silt and clay) are only 3% in the kaolinized granite as opposed to 20% in the kaolinized pegmatite. Bombowha kaolin deposit is thus dominantly characterized by coarser materials. Grits result from incomplete kaolinization (Nyakairu *et al.,* 2001). These grits affect the grain size distribution, plasticity and linear shrinkage values of the kaolin. Moreover, high proportion of grits also affects the other most favorable commercial properties of kaolin such as brightness, opacity, glossiness, viscosity, abrasiveness and smoothness which are required in paper and ceramics production (Murray, 2007). A kaolin material with the highest quality is characterized by fine grain size distributions (usually >90% of grains with <2µm size) (Evans, 1993). The plasticity and linear shrinkage properties of kaolin are also affected by the grain size distribution characteristics. Bombowha kaolin deposit is characterized by a slightly plastic to non-plastic property and lower (0-3) linear shrinkage values. This is due to the presence of higher silica and silica enriched minerals (grits) such as quartz, mica and feldspar. Plasticity and linear shrinkage properties are increased by removing the coarser mineral grains, in this case mica and quartz (Siddiqui et al., 2005). Kaolinized pegmatite is slightly plastic and shows higher linear shrinkage value compared to the kaolinized granite. This is because kaolinized pegmatite has higher finer fractions (20.1%) than kaolinized granite (3.3%). The variation of pH and specific gravity values of kaolin indicates the presence of impurities mainly iron and titanium oxides (Ahmedin, 2007). However, the variation of pH (6.27-6.37) and specific gravity (2.53-2.65) in Bombowha kaolin deposits very low compared to the pH of ideal pure kaolin (7) and specific gravity (2.60) (Murray, 2007). According to Miranda-Trevino (2013) the presence of iron impurity in kaolin causes a decreasing of pH and increasing of specific gravity values.

Chemical composition of a kaolin deposit is a reflection of parent rock composition and degree of kaolinization (Murray, 2007; Kogel *et al*., 2006; Dill, 2016; Bedassa *et al*., 2019; Getnet Gezahegn and Worash Getaneh, 2020). During kaolinization process, mobile elements like the alkali and alkaline earth elements are removed and immobile components like Al_2O_3 remain behind and become concentrated in the weathering product, in this case kaolin. The chemical composition of Bombowha kaolin deposit is mainly characterized by higher SiO_2 and lower Al_2O_3. The presence of high SiO_2 and lower Al_2O_3 in kaolin deposits indicate that the deposit has high quartz and lower kaolinite minerals. This is mainly due to incomplete kaolinization and/or resistance of some mineral components in the parent rock to the alteration process (Malu *et al.,* 2013). However, the comparison of kaolinized granite and pegmatite shows the kaolinized pegmatite has higher Al_2O_3 (33.4%) and lower SiO_2 (51.5%) compared to kaolinized granite (SiO_2=68% and Al_2O_3=20.2%). The kaolinized pegmatite has more or less equal amount of Al_2O_3 to that of the processed kaolin (35.5%). The kaolinized pegmatite has also higher LOI, lower Fe_2O_3, and lower alkali and alkali earth elements.

Generally, all of the chemical, mineralogical and physical properties of the two types of kaolin (i.e., those derived from granite and pegmatite, Tables 1-3, Figs. 4 and 5) prove that the kaolin derived from pegmatite has better quality than the one derived from granite. Consequently, since the granite is volumetrically large compared to the pegmatite veins, the overall quality of the Bombowha kaolin deposit is low. It is more siliceous and less aluminous as compared to the theoretical composition of pure kaolin deposit (Al_2O_3 = 39.5%) and the world-class high-quality kaolin deposits of UK(Cornwall) and Georgia.

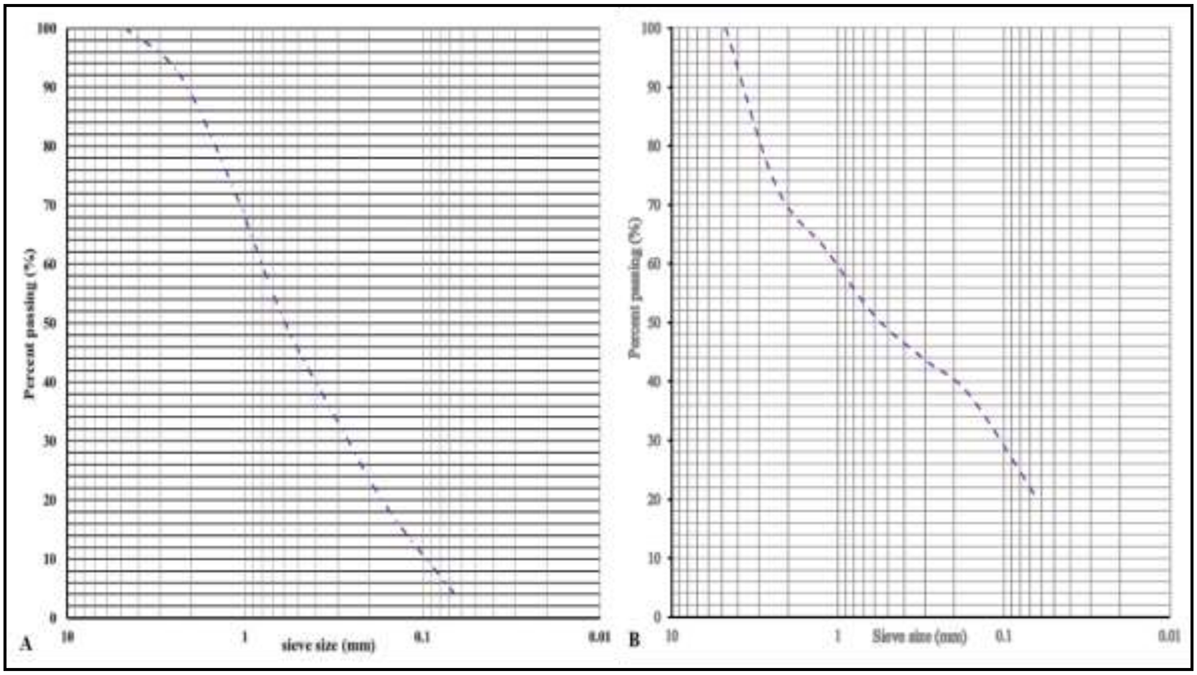


Figure 5. Grain size distribution of kaolinized granite (a) and kaolinized pegmatite (b) of Bombowha kaolin deposit.

Dilution and ore grade diminution

The geochemical analysis results of the R.O.M. clearly demonstrate the high degree of dilution because of faulty mining, haulage and stockpiling practices. As it can be seen from Fig.6 and Table 2, the R.O.M. has almost equal concentration of all elements to the parent granite, except a slightly lower TiO_2 (0.1% as opposed to 0.13% of granite) and slightly higher Al_2O_3 (17.95% as opposed to 16.3% of the granite). The composition of the kaolin deposit (both the kaolinized granite and kaolinized pegmatite) suffered dilution by considerable amount. The relative percent of decrease in quality in terms of decrease in Al_2O_3 and LOI and increase in SiO_2 and Fe_2O_3 has been calculated as follows and given in Table 5.

$\%Change = \frac{ROM-KGRN}{KGRN} * 100$ (for the kaolinized granite), and

$\%Change = \frac{ROM-KPG}{KPG} * 100$ (for the kaolinized pegmatite)

Where

KGRN= Kaolinized Granite

KPG= Kaolinized Pegmatite

Table 5. Comparison of chemical composition of the R.O.M. with kaolin ore.

Sample	% Change				
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	LOI
Kaolinized granite	4.7	-11.1	13.9	-23.1	-30.7
Kaolinized pegmatite	38.3	-46.3	72.5	233.3	-54.6

This simple calculation demonstrates that the high-quality indicators, i.e., Al_2O_3 and LOI have negative values (decreased) and the impurities (Fe_2O_3, SiO_2 andTiO_2) have positive values (increased) in the R.O.M. with respect to both types of kaolin ores. The ore feed has become essentially the parent granite, not the kaolinized ones. The fundamental source of the problem is the absence of well-designed mining plan. The extraction is conducted through simple excavation using excavators. Delineation of mineable part of the ore is conducted visually and arbitrarily without any sampling and chemical analysis. Therefore, during excavation a large amount of the parent granite is mixed with the kaolin ore. In the absence of drilling and blasting, which could fragment country rocks beyond ore limit and mix with the kaolin ore resulting in dilution, the level of dilution seen at Bombowha is unacceptably high.

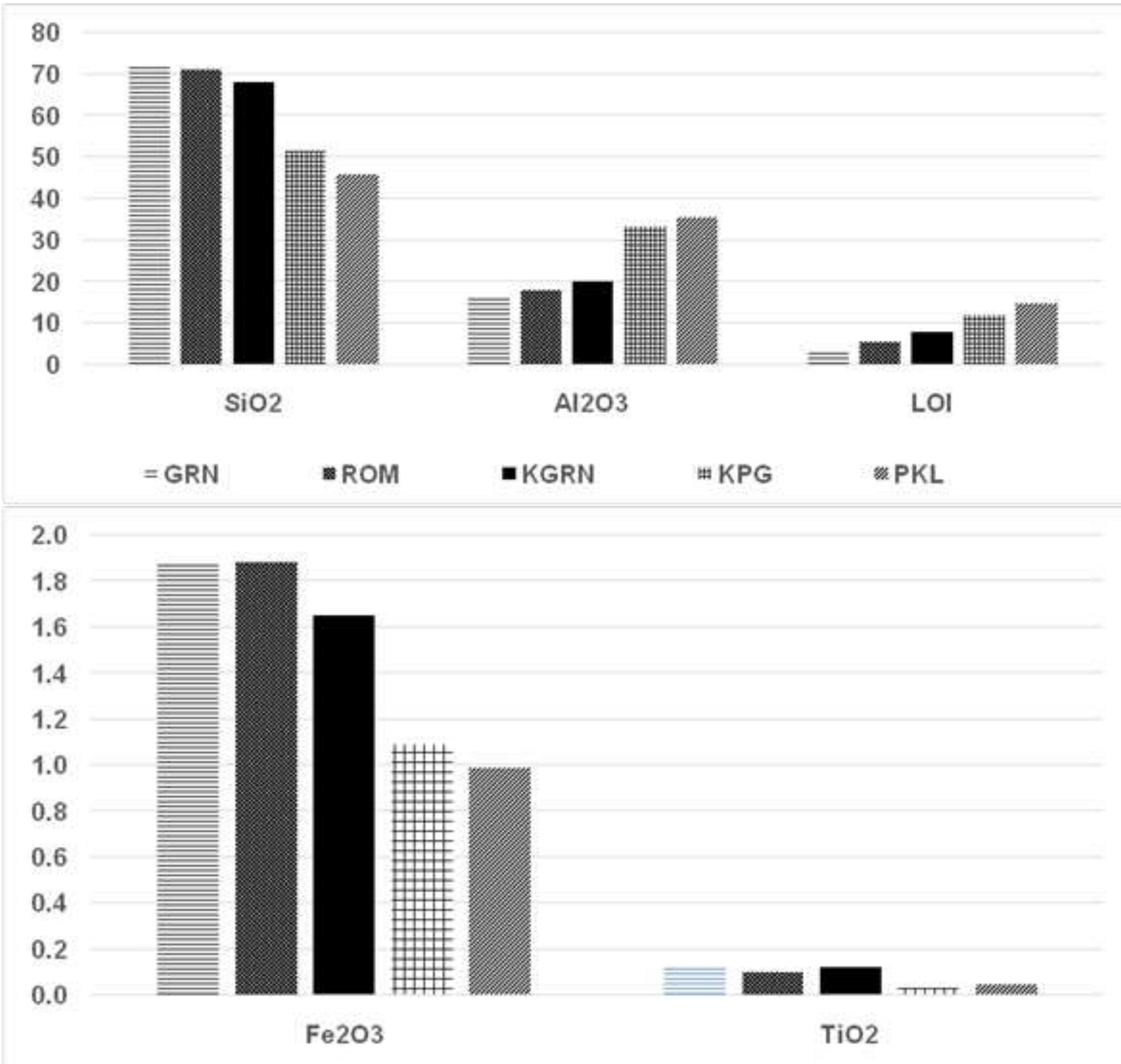


Figure 6. Concentration of selected elements and LOI in different kaolin samples (LOI=Loss on ignition; GRN=Granite; PKL=Processed kaolin).

The other source of dilution is related to the overburden. Currently the weak and thick (4-6m) overlying material is removed at one step with a face angle range of 80-85^0(nearly vertical) until the underneath kaolin ore is exposed. However, the collapse of waste material from the overburden in to the ore is observed and is very common (Figs. 2 and 3). This is because the thicker and loose overlying waste material with very steep face angle is removed continuously as one bench. The waste material sliding from the overburden causes dilution and discoloring of the kaolin ore. During rainy season, the wall failure and sliding of the waste material becomes more common and detrimental to the ore. Runoff transports the overburden and stains the kaolin into reddish brown color, of course, in addition to diluting it. Unfortunately, due to absence of proper mine design there is no systematic diversion system that can prevent runoff into the mine pit and kaolin ore. This also hinders the production rate of the ore and disturbs working sites during exploitation. The stripping of overlying waste material step by step (by more than one bench) at lower face angle (45-60^0) could have reduced the failure of waste material in to the underneath kaolin ore. Moreover, the removal, relocating and stockpiling of the overburden material from the whole deposit should have been done before starting the exploitation of the kaolin ore so that the mixing of overburden and ore would not have been as significant as it is now. Therefore, the ore dilution is the result of absence of mine design, poor delimitation of mineable portion of the ore (poor understanding of the geometry of the deposit), high pit wall angle not in accordance with the geotechnical property of the overburden, and poor operating efficiency (inability to perfectly remove each ore block).

Effectiveness of kaolin processing technology

Processing of kaolin ore is one of the fundamental activities in kaolin resource development process. It is required to enhance and control required properties within a specific range as required by the end use application. From the two major types of kaolin processing methods, the wet method is considered to be suitable to produce kaolin of high grade for the paper and filler industries while the dry processing method produces kaolin for the ceramic and similar industries (Murray, 1999, 2007; Kogel *et al*., 2006). The quality of processed kaolin product depends on the quality of crude kaolin and efficiency of processing technology. The processing system upgrades the quality of kaolin product by removing the available impurities (grits and coloring impurities). It enhances the properties of kaolin product such as grain size distribution, plasticity, linear shrinkage, brightness, viscosity and other commercial properties. The efficiency of processing system is measured by the properties of the processed kaolin products (Murray, 1999; Psyrillos *et al.,* 1999).

The SiO_2 content of the processed kaolin is significantly reduced from 71.2% to 45.8% (Table 6). The reduction of SiO_2 indicates the removal of quartz and other silica rich minerals. The Al_2O_3 and LOI values are increased from 17.95% and 5.43% to 35.5% and 14.7%, respectively. The processing system demonstrated a capacity to produce products having a high alumina yield of up to 35.5%. The LOIvalue is also enhanced by about three times from its crude state. This indicates the increasing of kaolinite concentrate due to the removal of associated impurity minerals. Increasing of the concentration of kaolinite mineral is directly related with the enhancement of refractoriness property (Mandal and Banerjee, 2004)).

The lowering of silica and increasing of alumina indicates that the processing system reduces the coarser and abrasive silicate impurities (grits) through simple screening and settling procedures. The removal of grits, mainly quartz, feldspar and mica leads to the improvements of physical parameters of kaolin including grain size distribution, brightness, viscosity, plasticity, linear shrinkage, color, abrasiveness, smoothness and fineness (Murray, 2007). The SiO_2/Al_2O_3 ratio is also reduced by 68% due to the enhancement of the alumina and reduction of the siliceous materials. The ore processing activities have reduced also the flux components (alkalis and alkali earth oxides) effectively from 4.30% to 1.32%, which is a 69% reduction, and the decrease in fluxes is indicator of removal of feldspars and mica. The reduction of the flux components enhances the refractory properties of kaolin product (Mandal and Banerjee, 2004).

The concentration of Fe_2O_3 in the processed kaolin product is also reduced from 1.88% to 0.99%. Almost half of the Fe_2O_3 content of the crude kaolin is removed from the kaolin ore. The lowering of Fe_2O_3 in the processed kaolin indicates the elimination of Fe-bearing impurities. The reduction of such coloring impurities is believed to enhance the optical properties of kaolin such as whiteness and brightness (Murray, 2007).

However, about 0.99% iron impurity is still contained in the processed kaolin products. This indicates either the iron impurity has ultrafine size (as fine as the clay minerals) or may exist as a structural iron of kaolinite mineral which have been incorporated during kaolinization and needs complex processing method for its removal (Ali and Dikko, 2015; Ramaswamy and Raghavan 2011). The presence of Fe_2O_3 more than 0.8% causes negative impact on the properties of kaolin such as whiteness, brightness and refractoriness. These properties are basic for the productions of paper and fine ceramics (white porcelain) (Mandal and Banerjee, 2004; Zegeye *et al.,* 2013; Murray, 2007; Wilson, 2004). It is, therefore required to further process and reduce the iron impurity below 0.8% and upgrade the quality.

Table 6. Comparison of the quality of processed kaolin with the kaolin ore and R.O.M.

Quality parameter	Ore		R.O.M.	Processed Kaolin	Quality enhancement with respect to		
	Kaolinized granite	Kaolinized pegmatite			Kaolinized granite	Kaolinized pegmatite	R.O.M.
Al_2O_3	20.19	33.40	17.95	35.50	76%	6%	98%
SiO_2	68.00	51.50	71.20	45.80	-33%	-11%	-36%
Fe_2O_3	1.65	1.09	1.88	0.99	-40%	-9%	-47%
TiO_2	0.13	0.03	0.10	0.05	-62%	-67%	-50%
Al_2O_3/SiO_2	0.30	0.65	0.25	0.77	157%	19%	208%
Fluxes ($CaO+MgO+Na_2O+K_2O$)	2.14	1.64	4.30	1.32	-38%	-20%	-69%
LOI	7.84	11.95	5.43	14.70	88%	23%	171%

As far as the mineralogy of processed kaolin is considered, it is characterized by high concentration of kaolinite with subordinate amount of orthoclase and muscovite. The presence of the latter two impurity minerals indicates their fine and ultrafine size which passes through the screens and hydrocyclones of the processing plant. During site visit of the processing plant, visual inspection was conducted to understand the constraints compromising the quality of the kaolin product. The processing components including screens and hydrocyclones are old and the impurity can easily pass to the kaolin product. Moreover, three hydrocyclones are available in the processing system but recently the third hydrocyclone is not functional. The presence of iron (0.99% Fe_2O_3) and minute abrasive silicate minerals including orthoclase and muscovite in the processed kaolin product may be due to the non-functioning of the third hydrocyclone of the processing system. Therefore, the incorporation of the third hydrocyclone may enable the system to reduce the undesirable trace impurities and enhance the quality of the processed kaolin. It also helps to avoid the ore loss, to increase quantity of the clay product, to upgrade the fineness properties, and to enhance the overall quality of kaolin products by enhancing the alumina/kaolinite content. Moreover, the introduction of high intensity magnetic separator will help to remove discrete iron and titanium minerals. Selective flocculation and flotation are also advised for the removal of iron and titanium impurities (Murray, 2007).

The other problem observed during field inspection is absence of selective mining and graded stockpiling of kaolin ore in which kaolin of different qualities could have been mined and stored in different stockpiles for separate processing. In kaolin deposits where there is quality difference (like the kaolinized granite and kaolinized pegmatite of the Bombowha kaolin deposit), it is advisable to mine a particular quality kaolin and stockpile it separately so that better grade quality can be produced during processing by adopting variable mixing ratio or adopting variable processing procedures (Murray, 2007). It is thus advised to build several stockpiles based on values of quality parameters such as brightness, color, viscosity, and grit percentage for possible blending of different qualities for better results. However, in the case of Bombowha mine, there is neither selective mining nor graded stockpiling as it is evidenced by the significantly low quality of the R.O.M. (Tables 2 and 6) compared to both kaolin deposit types (i.e., kaolinized granite and kaolinized pegmatite) on the ground. The bad mining practice have caused the kaolin processing to start with poor quality input (i.e., the R.O.M.) which has a chemical composition similar to non-kaolinized granite, sometimes worse than the kaolinized granite (note that the Al_2O_3 in R.O.M. is 17.95% while it is 20.19% in kaolinized granite). Had the processing started with a better-quality input (e.g., the same as the kaolinized pegmatite or even the kaolinized granite), the quality of processed kaolin would have been more than what is produced now. As it has been demonstrated by the data presented in the previous tables and diagrams, the processing method is not bad as it brought significant improvement of quality with respect to the feed (R.O.M.). A simple observation can be made using Al_2O_3 content of the processed kaolin, R.O.M., kaolinized granite and kaolinized pegmatite (Table 6). The enhancement is by 98% with respect to the feed (R.O.M.). If the 98% enhancement applies for the kaolinized granite considered as the feed, the Al_2O_3 content would have been 39.97%. The enrichment becomes more than this when we consider the kaolinized pegmatite which has higher Al_2O_3 content than the kaolinized granite. Therefore, the major hindering factor for quality enhancement of kaolin during processing kaolin ore is the poor mining practice in the kaolin mine.

CONCLUSIONS

Bombowha kaolin deposit is a primary type of deposit derived from granite and pegmatite parent rocks by weathering and hydrothermal processes. The field investigation combined with physical, chemical and mineralogical analyses results indicate that the deposit is characterized by light gray to white color, highly abrasive, lower plasticity, lower linear shrinkage and higher grits compared to the industrial specifications of other commercial kaolin deposits in the world. The presence of higher amounts of grits (coarser impurities such as quartz, mica, and feldspar), coloring impurities (mainly iron oxides and other small amounts of fluxing components) lead to lower quality of kaolin. The presence of quartz combined with minor mica and trace feldspar minerals makes the deposit to be highly gritty, with increased abrasiveness, decreased plasticity and linear shrinkage properties.

From the two sources of the kaolin deposit, kaolinized pegmatite has better physical, chemical and mineralogical properties (higher quality) than kaolinized granite. Kaolinized pegmatite has nearly white color, moderate grain size distribution, moderate plasticity, lower silica, higher alumina, higher kaolinite, lower iron and titanium impurities. On the other hand, kaolinized granite has higher grits and iron impurities. It also has light gray color, higher silica, lower plasticity, lower linear shrinkage and finer particles. Due to the volumetrically high amount of the granite, the overall quality of the kaolin deposit is low.

The open pit mining method produces a crude kaolin ore with poor quality even worse than the kaolin deposit. The absence of good design, very steep pit slope, and poor delineation of mineable ore brought very high dilution. The R.O.M. is thus characterized by higher silica and iron oxide impurities and lower contents of alumina and LOIvalues than the kaolinized granite and pegmatite. This poor-quality feed to the processing plant compromises the quality of the processed kaolin. The Bombowha kaolin processing system employed the wet processing method and includes mechanical washing and screening system. It is effective for the removal of coarser materials (grits such as quartz and mica). The processing technique enhanced the quality of kaolin product by increasing the alumina content, lowering the silica and iron content. However, because of the very poor quality of the feed, very old age and nonfunctioning of some of the processing units, the processed kaolin does not the highest quality required by paper or filler industries, especially with respect to its low Al_2O_3, high Fe_2O_3 and presence of grits (orthoclase and muscovite) in the processed kaolin. The presence of grits in the processed kaolin is ascribable to their ultra-fine size. In the present state of operation, Bombowha kaolin product can be fit for many industrial applications including ceramics (wall and floor tile, sanitary ware, bricks), paint, rubber and cement. It can also be used for the paper industry as a filler after the enhancement of the alumina and reduction of iron content using the required extra processing techniques such as high intensity magnetic separators.

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