Evaluation of Potential Applications of Quartzite from the Longworth Silica Project

Final Report

211613165

for

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Executive Summary

MGX is in the process of developing its Longworth Silica Property in east-central British Columbia. MGX has begun technical evaluation of the property and, as necessary, will complete a NI 43-101 compliant technical report, prepare an exploration and preliminary development plan and file a Notice of Work with the B.C. Ministry of Energy and Mines to complete diamond core drilling.

After sending approx. 1 ton of lumpy quartzite, MGX assigned ANZAPLAN in July 2018 to carry out the services proposed in quotation 211613165 "Evaluation of Potential Applications of Quartzite from the Longworth Silica Project".

The sample was subjected to processing tests targeting the evaluation of the suitability of the quartzite sample for silicon applications as well as for frac sand.

The received sample was crushed and screened into fractions 20 – 120 mm for evaluation of applicability of these fractions in MG silicon production. For fine fraction < 20 mm applicability in frac sand was evaluated.

After comminution and classification fraction 20 – 120 mm was analyzed and found to be of high initial purity of 99.5 wt.-%. This fraction is already chemically suitable as medium quality feedstock material for MG silicon production. The impurity content of all analyzed elements is well below the typical content of high quality quartz feed stock for MG silicon except titanium (TiO_2). Typically 0.006 wt.-% TiO_2 are specified for a high quality quartz feed stock for MG silicon production and 0.012 wt.-% TiO_2 for a medium quality quartz feed stock. Titanium in the feed sample slightly exceeds the specification for a high quality material and is well below the threshold for the medium quality (0.008 wt.-% TiO_2). Further improvement to high quality feedstock material for MG silicon by optical sorting has not been achieved.

Thermal stability is categorized by Heat Index (HI) and Thermal Strength Index (TSI). HI was found to be good and TSI to be poor. While the measurement of thermal stability is currently the industry standard, the importance of applying mechanical stress is discussed controversially. While most silicon producers only accept quartzite for which both, HI and TSI, are categorized as good, some silicon producers consider solely thermal stress characteristics determined in the HI as being relevant.

Fraction < 20 mm was further crushed and classified into fractions 0.1 – 0.4 mm, 0.4 – 0.8 mm and 0.8 – 2.0 mm since these are silica sand fractions used as frac sand.

All typical frac sand fractions considered (0.1 – 0.4 mm, 0.4 – 0.8 mm, 0.8 – 2.0 mm) meet the chemical specification of frac sand (SiO_2 content exceeding 99 wt.-%). A more critical parameter to the applicability of a silica sand as frac sand are the physical characteristics including roundness and sphericity. Individual silica particles of MGX´s sand sample are built up of smaller crystallites forming "agglomerates". These intra grain boundaries will form preferred fracture lines in the crushing test thus reducing the overall strength of the particle structure. Therefore the sand is not expected to meet crush resistance specifications. Further consideration of the frac sand application for this silica sand sample is not recommended.

For fraction 0.1 – 0.4 mm following possible applications were identified based on the chemical composition after different processing steps.

After classification, fraction 0.1 – 0.4 mm meets the typical chemical purity for application in container glass (colored and clear), float glass, fiberglass, borosilicate glass, pyrex, white float glass, opal glass, quartz powder (e.g. glass, ceramics and filler industry), engineered stone, silicon carbide, fused silica, and sodium/potassium silicate.

After additional attrition the iron content is further reduced from 123 mg/kg to 107 mg/kg Fe_2O_3, being beneficial for glass applications, but not resulting in additional applications.

After additional magnetic separation iron content is further reduced from 107 mg/kg to 88 mg/kg Fe_2O_3, resulting in an additional chemical suitability for solar glass.

For final approval of glass applications, the evaluation of heavy minerals is necessary, including an analysis of coloring elements (e.g. copper, chromium, cobalt and nickel). For quartz powder, grinding and application tests have to be carried out. For engineered stone, a bright and uniform color has to be achieved and for SiC, fused silica and sodium respectively potassium silicate application tests in cooperation with the potential customer may be necessary.

As next steps ANZAPLAN recommends to further evaluate alternative applications for fraction < 20 mm including test work targeting e.g. high value glass applications like borofloat glass. This covers crushing and classification, attrition, magnetic separation and flotation of fraction 0.1 – 0.5 mm. Final product will be analysed regarding chemical composition, coloring elements and heavy mineral content.

Due to the plurality of process options, resulting in a range of applications, a market research of the local market is recommended. The result of this study will be the basis for a scoping study, which will balance processing costs and expected prices for the different products in the local market to optimize the product portfolio.

MGX has indicated that additional samples are available. ANZAPLAN has therefore offered to carry out additional test work (quotation 211613293) targeting the evaluation of these samples for MG silicon production.

Table of contents

List of Tables

List of Figures

1 Introduction

The Longworth Silica Property is located approximately 85 kilometers east of Prince George in east-central British Columbia and is accessible by logging roads. The land package covers 1,084 contiguous hectares situated four kilometres from the Canadian National railroad mainline and power grid. The Property is listed as one of the top silica occurrences in the Province of British Columbia by the BCGS (Simandl, 2014).

MGX has begun technical evaluation of the property and, as necessary, will complete a NI 43-101 compliant technical report, prepare an exploration and preliminary development plan and file a Notice of Work with the B.C. Ministry of Energy and Mines to complete diamond core drilling.
After sending approx. 1 ton of lumpy quartzite, MGX assigned ANZAPLAN in July 2018 to carry out the services proposed in quotation 211613165 "Evaluation of Potential Applications of Quartzite from the Longworth Silica Project".

The sample was subjected to processing tests targeting the evaluation of the suitability of the quartzite sample for silicon applications and frac sand.

This report summarizes the processing test results.

2 Applied techniques and procedures

2.1 Mineralogical Analyses by X-ray diffraction analysis

Selected samples were characterized by X-ray diffraction (XRD) analysis (Bruker, Diffractometer D8 ADVANCE with DAVINCI design) according to DIN 13925. The crystalline phases were identified by an expert using the JCPDS data base (INTERNATIONAL CENTRE FOR DIFFRACTION DATA).

2.2 Chemical analyses by X-ray fluorescence spectroscopy

The chemical composition was analyzed by X-ray fluorescence spectroscopy (XRF, Bruker AXS Sequential X-Ray Spectrometer Type S4 Pioneer) according to DIN EN ISO 12677.

2.3 Grain size distribution

Grain size distribution of samples which consists mainly of particles ≥ 0,1 mm were analyzed according to DIN EN 933-1 by dry sieve analysis. Fine fractions with particles ≤ 0,1 mm were analyzed according to DIN EN 933-10 by air jet sieve analysis.

2.4 Mineral processing

2.4.1 Crushing and grinding

Quartzite lumps were initially crushed using a jaw crusher. In the subsequent processing steps (< 20 mm fraction), comminution of the material into frac sand fractions was also performed in a jaw crusher.

2.4.2 Classification

Dry screening was applied for all coarse separation steps at 120 mm, 50 mm and 20 mm using different types of sieving machines.

Dry screening was also applied to separate the frac sand fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm and 0.1 – 0.4 mm after further comminution and separation of the undersized fraction <0.1 mm. The tumbling screening machine was equipped with a plastic coated stainless steel frame and removable screening decks.

2.4.3 Optical sorting

Fully automated optical sorting devices employ CCD cameras for particle detection, exploiting characteristics such as color, contrast or shape differences of particles as a sorting criterion. Non specified particles are separated from the bulk flow by high pressure air jets. For the test work, an industrial sized optical sorting device was used. Figure 1 shows the principle of the optical sorting device and Figure 2 depicts details of the optical detection and separation system.

From the feed hopper the raw material is discharged to a vibration feeder which allows a constant feeding speed and adjusts a homogenous distribution of the feed material (mono layer) to the scanning line. There the feed material is scanned by two CCD cameras. The signal is then processed by a computer.

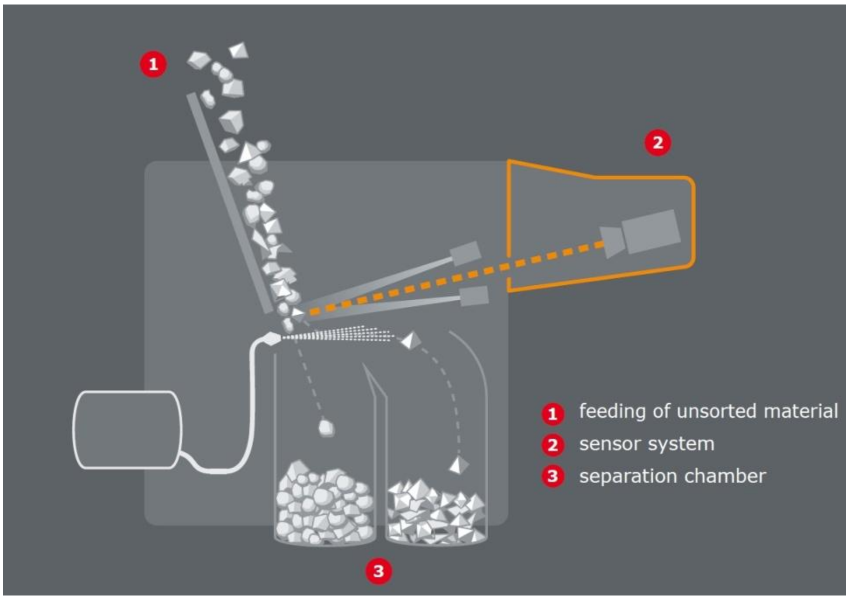

Figure 1: Operating principle of optical sorting system

For detection, the raw material is lighted by specific LED lamps to ensure a defined white light that prevents detection problems on the camera image. The sample material is scanned in a free fall sequence, so the raw material can be accessed from both sides. The computer aided information controls the pressurized air ejection system and the individual blowing valves. The ejected material is deflected from the flight path by the air blow and collected in the reject material box.

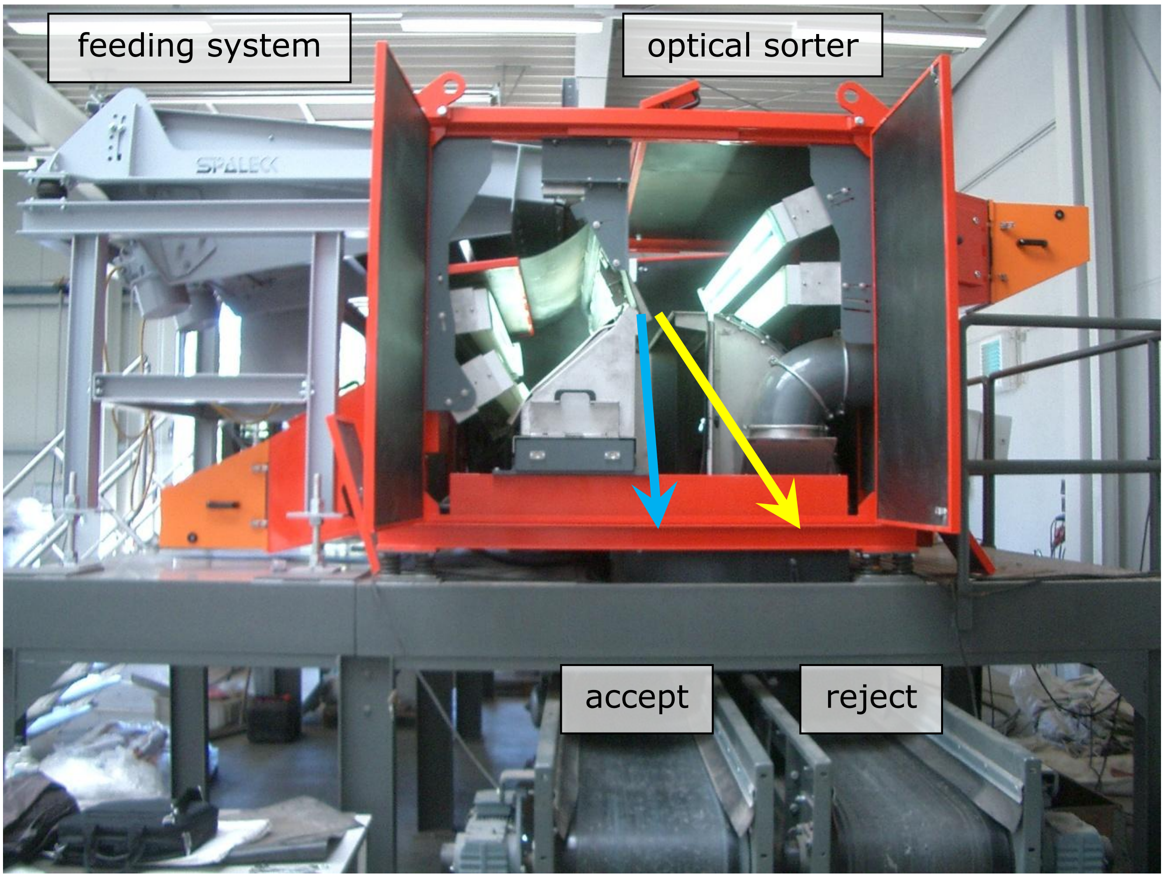

Figure 2: Details optical sorting system

2.4.4 Dry Magnetic separation via HGMS

In silica processing magnetic separation is used to separate heavy minerals from quartz. Most heavy minerals have paramagnetic or even ferromagnetic properties. Therefore a magnetic force acts on these minerals in the direction of increasing magnetic field strength. Since this force is strong in case of ferromagnetic minerals only moderate magnetic field strengths are necessary for separation. To separate paramagnetic minerals, higher field strengths are necessary. Quartz itself has diamagnetic properties. Therefore quartz particles are repelled from magnetic fields.

High gradient magnetic separation (HGMS) was carried out by a semi-technical belt magnetic separator with variable speed of the conveyer belt and variable splitter adjustment. The sand was fed to the belt by a vibration feeder ensuring a constant feed rate and homogenous distribution of the particles. The feed material was divided into two fractions during each separation step. The NONMAG fraction is identified as the material which was not affected by the magnetic field. The MAG fraction was separated by the magnetic field (waste). All tests were run in five steps, in which the speed of the conveyer belt and the splitter position were varied.

Main technical data:
Belt thickness 0.15 mm
Belt width: 150 mm
Magnetic roll configuration: 6/1.5
Manufacturer: Eriez Magnetics, UK

2.4.5 Attrition

Attrition was used to clean the surface of the quartz sand particles. Thereby fine particles attached to the surface of the quartz e.g. clay minerals or iron oxide coatings were abraded and dispersed in the added liquid. For this treatment, the quartz sand was filled in an octagonal plastic attrition cell and stirred intensely with a plastic coated multi-stage stirrer at a solid content of > 65 wt.-% for 10 minutes. Attrition may result in an additional abrasion of edges of the individual particles, resulting in more rounded shapes which are favorable for application as frac sand.

2.5 Thermal stability tests

In the carbothermic production of ferrosilicon and silicon metal, quartzite or quartz are used as silicon source.

Ideally lumpy quartzite should keep its original size throughout the reduction process until it starts to soften and melt in the lower part of the furnace. When quartzite lumps are fed into the furnace they generally experience a temperature shock which may lead to varying degrees of disintegration and generation of fines. If excess fines are generated, process stability is negatively affected causing a volume increase, lower permeability of the charge and increased slag formation in the furnace which in turn results in losses in conversion efficiency of quartz (SiO_2) into Si.

Therefore in the present test work thermal stability tests were carried out to receive an indication of the suitability of the quartzite samples for silicon / ferrosilicon production.

Part of the lumpy quartzite sample was crushed carefully via jaw crusher, equipped with carbon steel wear plates, in order to produce the required fraction for thermal stability tests in the particle size of 20 to 25 mm. For separating the fraction 20 to 25 mm a vibration screening machine was used.

For each thermal stability test 500 g of quartz/quartzite in defined particle size 20 to 25 mm is required. For thermal exposure the sample is heated in a laboratory furnace to 1,300°C and held at this temperature for 1 hour. After cooling to room temperature the particle size distribution of the sample is analyzed by screening carefully. For mechanical exposure the thermally stressed sample is tumbled with 100 rotations at 40 rpm in a Hanover Drum. Particle size distribution after tumbling is determined. The heat index (HI) and the thermal strength index (TSI) are determined based on changes in particle size distribution during heat treatment and during tumbling after heat treatment. The heat index defines the percentage of material left in original size > 20 mm after heating and before tumbling.

Thermal strength index, TSI is defined by the following formula:

$$TSI = \frac{\%(20 - 25\ mm) + \%(10 - 25\ mm) + \%(4 - 25\ mm) + \%(\ 2 - 25mm)}{4}$$

All numbers for the calculation of the TSI are based on the size distribution after tumbling.

Based on the results, quartz quality is categorized as good, medium or poor (Table 1).

Table 1: Relation between heat index, thermal strength index and quartz quality

Heat index (HI)	**Quality**
80 – 100 %	Good
70 – 79 %	Medium
< 70 %	Poor

Thermal strength index (TSI)	**Quality**
80 – 100 %	Good
70 – 79 %	Medium
< 70 %	Poor

3 Processing tests for silicon/ ferrosilicon application

3.1 Crushing and screening

For silicon production generally quartzite in particle size 20 - 120 mm is used. Processing steps are summarized in a flow sheet (cf. Figure 3).

Quartzite sample from MGX minerals was crushed (jaw crusher) and screened into fractions < 20 mm, 20 – 50 mm and 50 – 120 mm. Product fractions 20 – 50 mm and 50 – 120 mm were washed prior to sensor based sorting. Mass distribution after crushing is presented in Table 2.

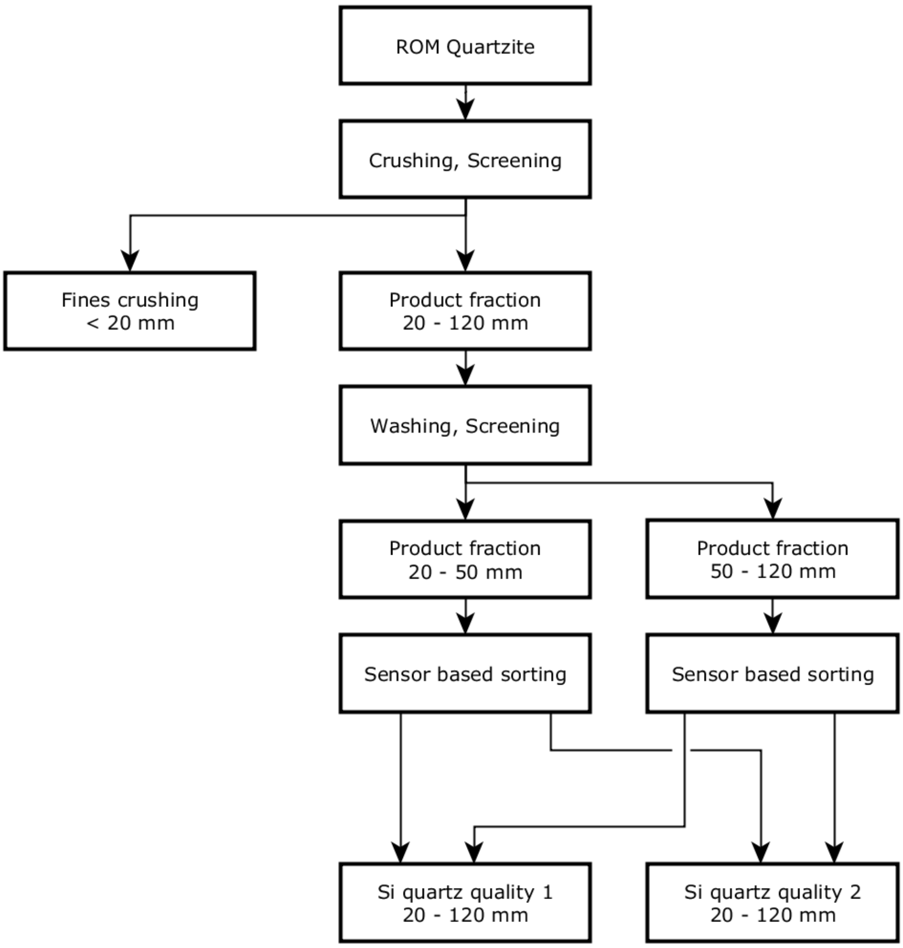

Figure 3: Flow sheet for silicon/ ferrosilicon application

Table 2: Mass distribution of product fractions 50 – 120 mm and 20 - 50 mm and fine fraction < 20 mm after crushing and classification

Sample ID	Mass [wt.-%]
Fraction 50 – 120 mm	10.4
Fraction 20 – 50 mm	45.8
Fraction < 20 mm	43.8

Crushing was carried out with standard parameter for the crushing of lumpy quartzite samples. Compared to typical mass distribution, a higher portion of fraction < 20 mm was yielded (typically approx. 20 wt.-% expected) while a lower fraction 50 – 120 mm was achieved (typically approx 40 wt.-% expected). This indicated a low resistance of the quartzite against mechanical stress. However, there is room for optimization, since crushing was not optimized yet.

3.2 Processing tests of fractions > 20 mm

Target of the processing tests of fractions > 20 mm was to determine the suitability of these fractions (20 – 50 mm and 50 – 120 mm) for silicon applications. Therefore, sensor based (optical) sorting and thermal stability testing was conducted and is described in the following.

3.2.1 Optical sorting (sensor based sorting)

Automated optical sorting exploits differences in color to sort the quartzite into different qualities. Based on visual appearance of the quartzite three sorting steps were carried out with both fractions. After each sorting step one accept (product fraction) and a reject (waste fraction) was generated with the target to improve the quality of the accept fraction from step to step. For each subsequent sorting step the accept fraction (product) from the previous step served as feed material as visualized in the flow sheet presented in Figure 4. The procedure to increase the quality step by step was applied in order to find suitable settings for receiving different mass portions for different silicon qualities. After the complete optical sorting procedure, three reject fractions and one final accept fraction were obtained for both fractions. Mass balances of the optical sorting tests are listed Table 3 including the corresponding, calculated, accept (product) fractions.

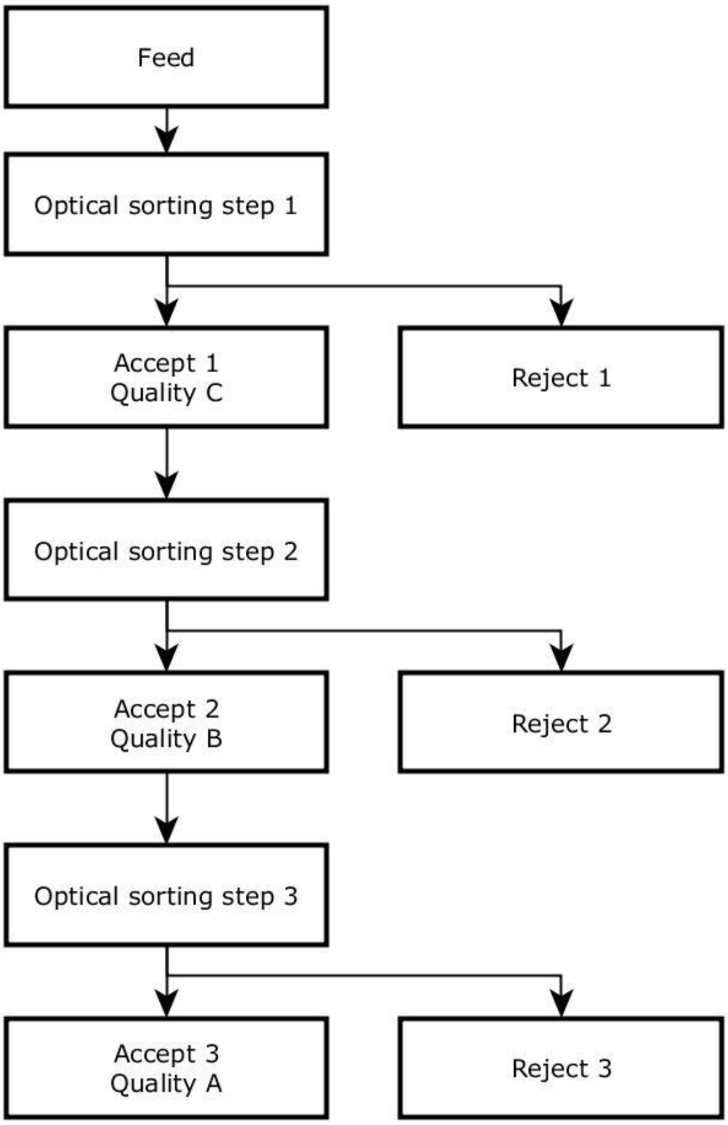

Figure 4: Flow sheet of optical sorting tests

Table 3: Results from optical sorting of fractions 20 – 50 mm and 50 - 120 mm

Sample ID	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	mass (step)
	[wt.-%]	[wt.-%]	[wt.-%]	[wt.-%]	[wt.-%]	[wt.-%]	[wt.-%]
50 - 120 mm Reject 1	99.4	0.19	0.014	0.009	0.03	0.01	23.0
50 - 120 mm Reject 2	99.6	0.12	0.012	0.007	0.03	<0.01	39.4
50 - 120 mm Reject 3	99.7	0.08	0.012	0.006	0.01	<0.01	20.1
50 - 120 mm Accept 3	99.6	0.11	0.010	0.008	0.02	<0.01	17.5
20-50 mm Reject 1	99.3	0.22	0.016	0.010	0.05	0.02	22.2
20-50 mm Reject 2	99.5	0.11	0.013	0.007	0.06	<0.01	41.1
20-50 mm Reject 3	99.6	0.11	0.011	0.007	0.03	<0.01	23.4
20-50 mm Accept 3	99.6	0.11	0.009	0.007	0.02	<0.01	13.3
Fractions after classification							
50 - 120 mm (calc.)	99.6	0.13	0.012	0.007	0.02	<0.01	10.4
20 - 50 mm (calc.)	99.5	0.13	0.013	0.008	0.05	<0.01	45.8
Accept fractions							
50 - 120 mm Accept 1 (calc.)	99.6	0.11	0.011	0.007	0.02	<0.01	77.0
50 - 120 mm Accept 2 (calc.)	99.7	0.09	0.011	0.007	0.01	<0.01	37.6
50 - 120 mm Accept 3	99.6	0.11	0.010	0.008	0.02	<0.01	20.1
20 - 50 mm Accept 1 (calc.)	99.5	0.11	0.012	0.007	0.04	<0.01	77.8
20 - 50 mm Accept 2 (calc.)	99.6	0.11	0.010	0.007	0.03	<0.01	36.7
20 - 50 mm Accept 3 (calc.)	99.6	0.11	0.009	0.007	0.02	<0.01	13.3
Typical specifications							
Quartz for MG-Si (high quality)	99.5	0.20	0.14	0.006	0.03	0.02	
Quartz for MG-Si (medium quality)				0.012	0.20		

The chemical results after optical sorting present a high responsiveness of optical sorting regarding iron oxide (Fe_2O_3) content, but iron is already below the threshold limit of 0.14 wt.-% Fe_2O_3. 0.013 wt.-% Fe_2O_3 were analyzed in the feed fractions 20 – 50 mm and 0.012 wt.-% Fe_2O_3 in fraction 50 – 120 mm.

The material is of a high initial purity of 99.5 wt.-% with all analyzed elements well below the typical content of high quality quartz feedstock for MG silicon except titanium (TiO_2). Typically 0.006 wt.-% TiO_2 are specified for a high quality quartz feed stock for MG silicon and 0.012 wt.-% TiO_2 for a medium quality quartz feed stock. Titanium in the feed sample slightly exceeds the specification for a high quality material and is well below the threshold for the medium quality (0.008 wt.-% TiO_2 for fraction 20 – 50 mm and 0.007 wt.-% TiO_2 for fraction 50 – 120 mm).

In summary fraction 20 – 120 mm after comminution and classification is already chemically suitable as medium quality feedstock material for MG silicon. No upgrading to high quality feedstock material for MG silicon by optical sorting was achieved.

3.2.2 Thermal stability testing

Besides chemical purity, thermal and mechanical strength are important parameters in evaluating quartz feed stock with regard to its potential in silicon production.

In general, the thermal stability test provides a first indication if a quartzite will offer good furnace operation or not. The thermal stability test is used to determine thermo-mechanical properties of quartz giving an indication if the material will most likely disintegrate during heating in the furnace having a negative impact on furnace operation. It is, however, not a definitive criterion for exclusion. This is stressed by the fact that a number of different testing methods producing widely different results are in use in the silicon industry for specifying thermal stability properties.

The results of the thermal stability test are listed in Table 4 and presented in Figure 5.

Table 4: Summary of results from thermal stability tests

Sample ID	**HI**		**TSI**	
	[%]	[-]		[-]
MGX TST (1)	79	medium	35	poor
MGX TST (2)	95	good	46	poor
MGX TST (3)	89	good	48	poor
MGX TST average	**88**	**good**	**43**	**poor**

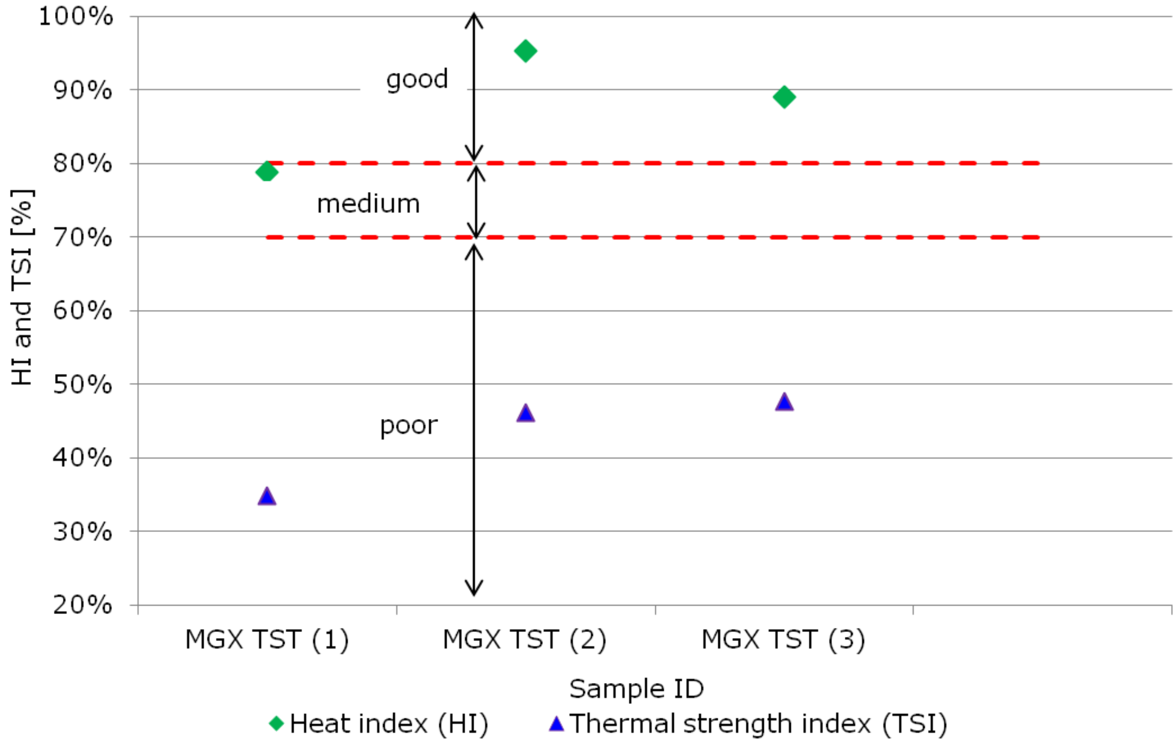

Figure 5: Summary of results from thermal stability tests

While the heat index (HI) is categorized as good, the thermal strength index is clearly categorized as poor. This means, the quartzite presents a good resistance against heat, but disintegrates when applying additional stress after thermal treatment.

In summary, the chemical composition of the quartzite is favorable for usage as feedstock material for MG silicon, but the thermal stability is categorized as poor. While the measurement of thermal stability is currently the industry standard, the importance of the mechanical stress is discussed controversially. While most silicon producers only accept quartzite for which both, HI and TSI, are categorized as good, some silicon producers consider solely thermal stress characteristics as being relevant. MGX quartzite is expected to pass such tests.

3.3 Processing tests of fraction < 20 mm

Fraction < 20 mm deriving from beneficiation tests for the silicon applications was used as feed material for the processing tests for frac sand. All processing steps applied during the beneficiation are illustrated in the process scheme in Figure 6 and further described in the following.

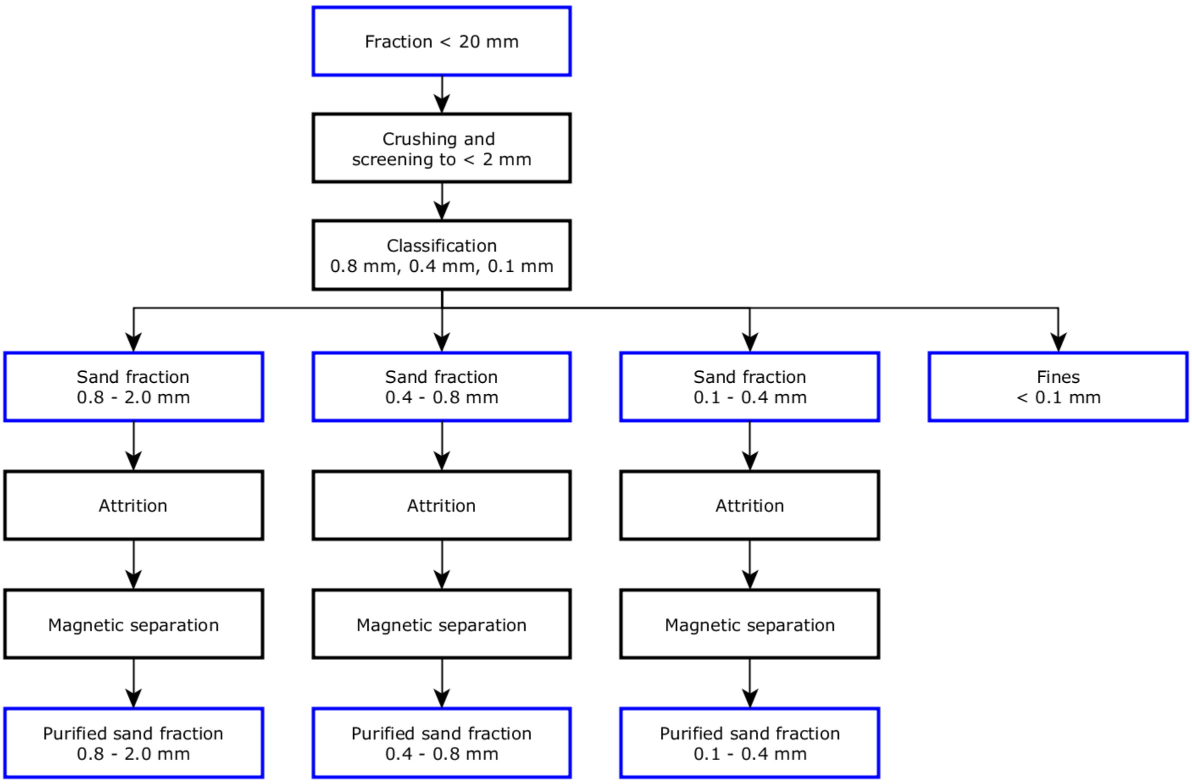

Figure 6: Mineral processing steps, applied to sample < 20 mm for flow sheet development

3.3.1 Crushing and screening of fraction

Fraction < 20 mm was further comminuted to < 2 mm using a jaw crusher. The gap between the jaws was successively narrowed in a stepwise manner.

After comminution, fraction < 2.0 mm was separated via dry screening. The coarse fraction > 2.0 mm was returned to the crusher. Subsequent to the comminution stage the sand fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm, 0.1 – 0.4 mm were separated from each other and from undersized fraction < 0.1 mm via dry screening.

The mass distribution of product fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm, 0.1 – 0.4 mm and undersized fraction < 0.1 mm is presented in Table 5. Amount of fines < 0.1 mm is in a typical range.

Particle size distributions (PSD) of fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm, 0.1 – 0.4 mm and < 0.1 mm are listed in Table 6 and presented in Figure 7.

Table 5: Mass balance after comminution and classification

Fraction [mm]	**Mass** [wt.-%]
0.8 – 2.0	23.2
0.4 – 0.8	12.6
0.1 – 0.4	51.6
< 0.1	12.6

Table 6: Particle size distribution of fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm, 0.1 – 0.4 mm and < 0.1 mm after comminution and classification of fraction < 20 mm

Particle size [mm]	0.8 - 2.0 mm [wt.-%]	0.4 - 0.8 mm [wt.-%]	0.1 - 0.4 mm [wt.-%]	< 0.1 mm [wt.-%]
< 2.24	100			
< 2.0	99.9			
< 1.8	95.3			
< 1.6	79.7			
< 1.4	56.0			
< 1.25	40.4			
< 1.0	17.9	100		
< 0.8	3.1	99.8		
< 0.71	0.9	91.8		
< 0.63		78.7		
< 0.5		46.3	100	
< 0.4		9.1	99.9	
< 0.355		1.3	93.8	
< 0.315			82.1	
< 0.25			60.1	
< 0.2			34.4	
< 0.18			25.0	
< 0.16			16.5	
< 0.125			4.5	100
< 0.1			1.8	99.9
< 0.09			0.2	99.0
< 0.071				80.4
< 0.063				72.7
< 0.04				47.9

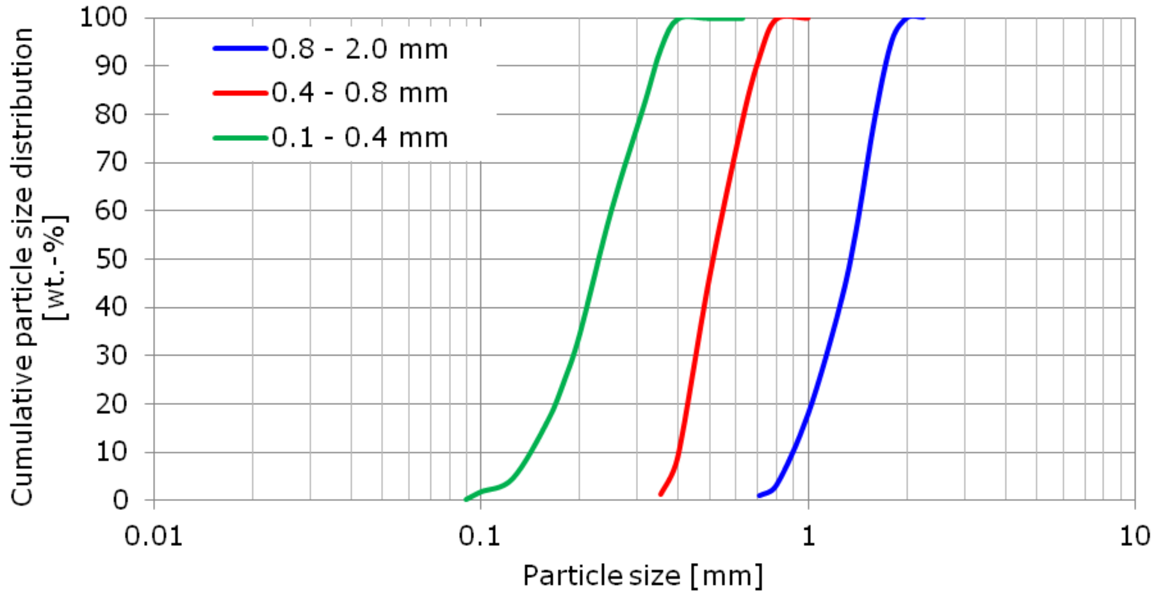

Figure 7: Cumulative particle size distribution of fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm and 0.1 – 0.4 mm after comminution and classification of fraction < 20 mm

3.3.2 Attrition

Attrition was applied in order to smooth the edges of individual particles, since sphericity and roundness are important parameters for application of quartz sand as frac sand.

The product fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm and 0.1 – 0.4 mm were scrubbed intensively in an attrition cell. Abraded fines and dissolved waste were separated by washing with tap water on a screening machine equipped with 0.8 mm / 0.4 mm / 0.1 mm screen cloth respectively. The product yield of the scrubbing tests is listed in Table 7. Product yields are in a typical range for this processing step.

Table 7: Mass yield of single attrition tests

Sample I.D.	Mass [wt.-%]
Product yield fraction 0.8 – 2.0 mm	95.7
Product yield fraction 0.4 – 0.8 mm	93.8
Product yield fraction 0.1 – 0.4 mm	92.0

3.3.3 Magnetic separation after attrition

Magnetic separation after attrition was applied for further purification of the quartz sand fractions. Since high gradient magnetic separation (HGMS), which is a dry process, was applied, the quartz sand fractions were dried prior to attrition.

Mass yield of the single HGMS tests are presented in Table 8. Dry magnetic separation (HGMS) of fractions 0.4 – 0.8 mm and 0.8 – 1.2 mm resulted in a high product yield of 97.5 wt.-% and 98.4 wt.-% respectively. In contrast, product yield of fraction 0.1 – 0.4 mm is 79.5 wt.-%, which is significantly lower than that of coarser products. The reduced product yield in fraction 0.1 – 0.4 mm is typical for this fraction and mainly based on electrostatic adhesion to the conveyor belt. Product yield was not optimized.

Table 8: Mass yield of single HGMS tests

Sample I.D.	Mass [wt.-%]
Product yield fraction 0.8 – 2.0 mm	98.4
Product yield fraction 0.4 – 0.8 mm	97.5
Product yield fraction 0.1 – 0.4 mm	79.5

3.4 Analyses of particle shape

According to API (American Petroleum Institute) frac sand specifications primary considerations are the physical aspects of the sand. The API recommends specifications on size, sphericity, roundness, crush resistance and mineralogy.

Micrographs of the fractions after attrition present the shape of individual particles. In fraction 0.1 – 0.4 mm (Figure 8) numerous particles show a sustained shape (reduced sphericity) or edges (reduced roundness). Most particles present a sphericity and roundness higher than 0.6 (cf. Figure 11), which meets the API specification.

In fraction 0.4 - 0.8 mm, most particles present a sustained shape (poor sphericity). Of specific interest are crystal boundaries which have been detected within the individual silica particles showing a reduced primary grain size (Figure 9 and 10) and particles being built up as "agglomerates". These boundaries will form preferred fracture lines in the crushing test thus reducing the overall strength of the particle structure. Therefore a poor crush resistance can be expected. Since fraction 0.4 – 0.8 mm is the most relevant size fraction for frac sand, further application tests regarding frac sand are not recommended.

The impression of fraction 0.8 – 2.0 mm (Figure 10) is similar to the impression of fraction 0.4 – 0.8 mm.

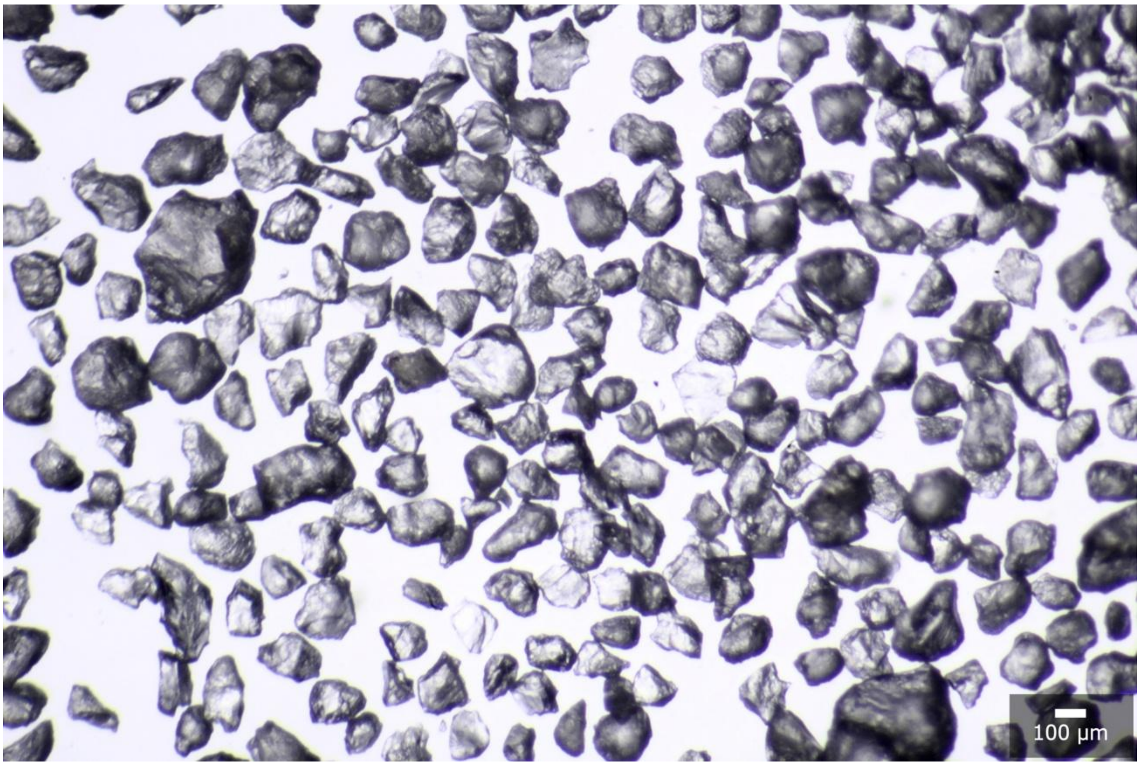

Figure 8: Micrograph of fraction 0.1 – 0.4 mm after attrition

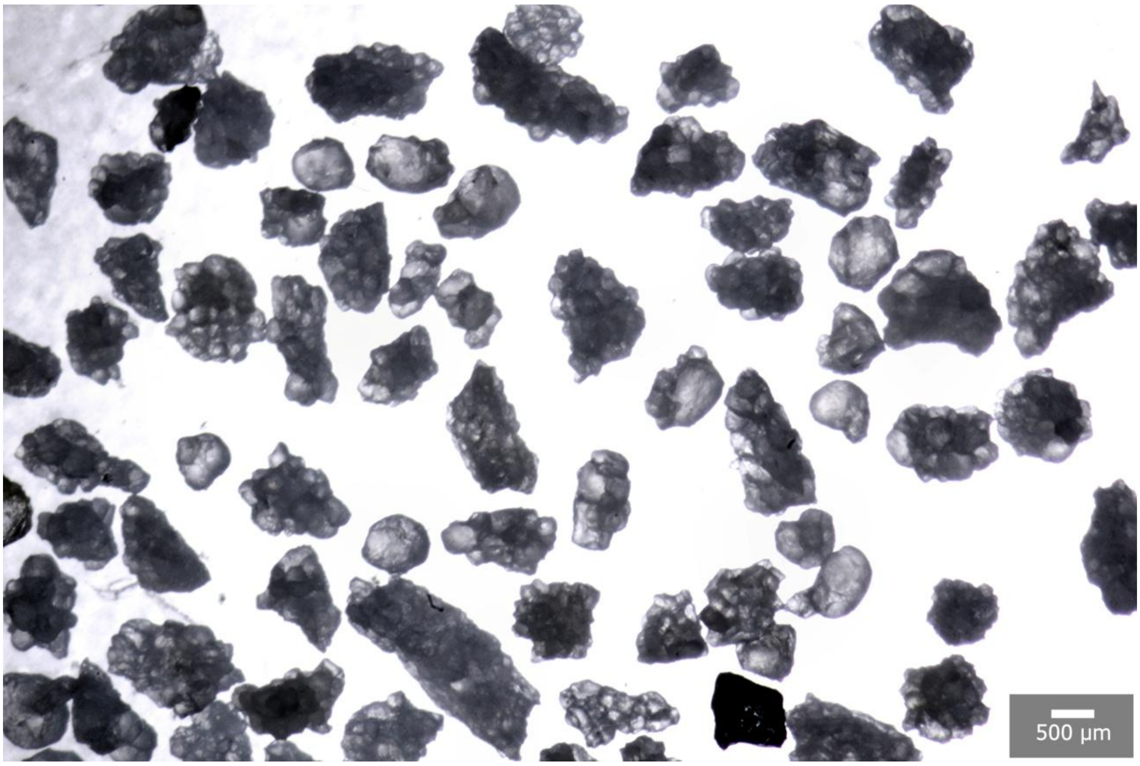

Figure 9: Micrograph of fraction 0.4 – 0.8 mm after attrition

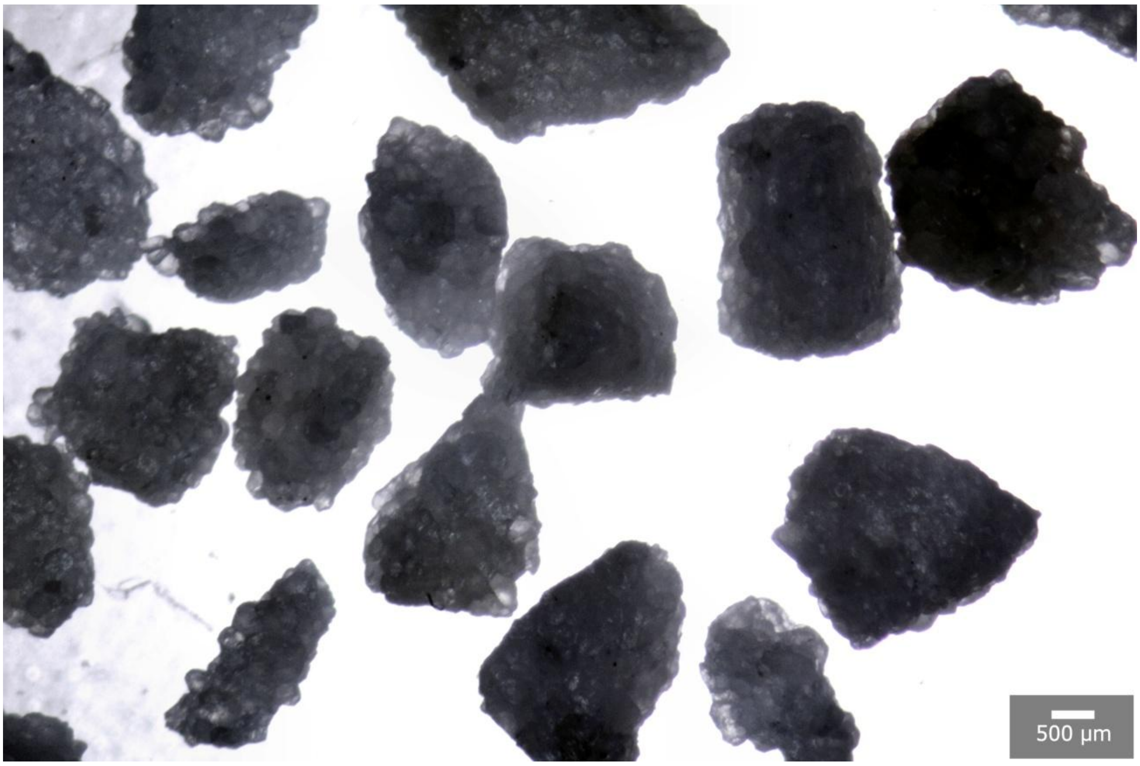

Figure 10: Micrograph of fraction 0.8 – 2.0 mm after attrition

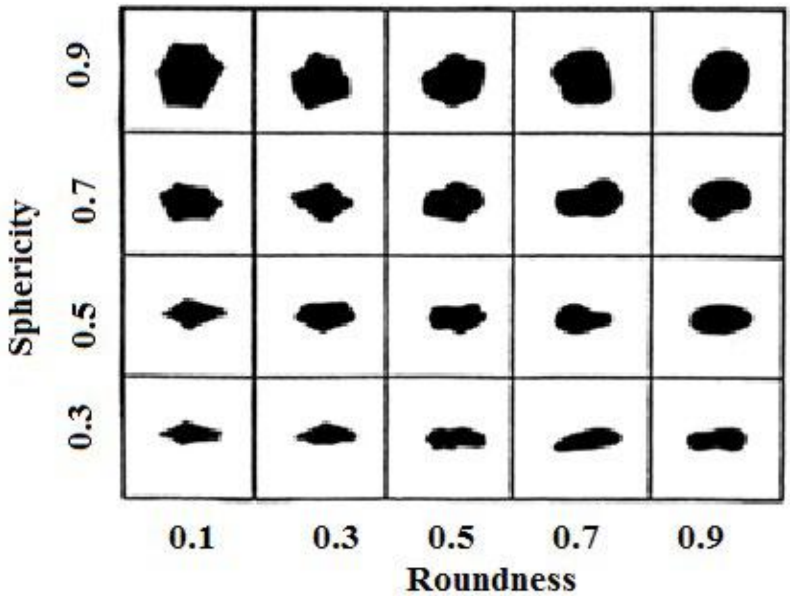

Figure 11: Roundness and sphericity chart, Krumbein and Sloss (Freeman, 1963)

3.5 Chemical analyses

The efficiency of each processing step for improving the chemical composition of the processed sample is discussed below. The sequence of processing steps is illustrated in the flow sheet presented in Figure 12.

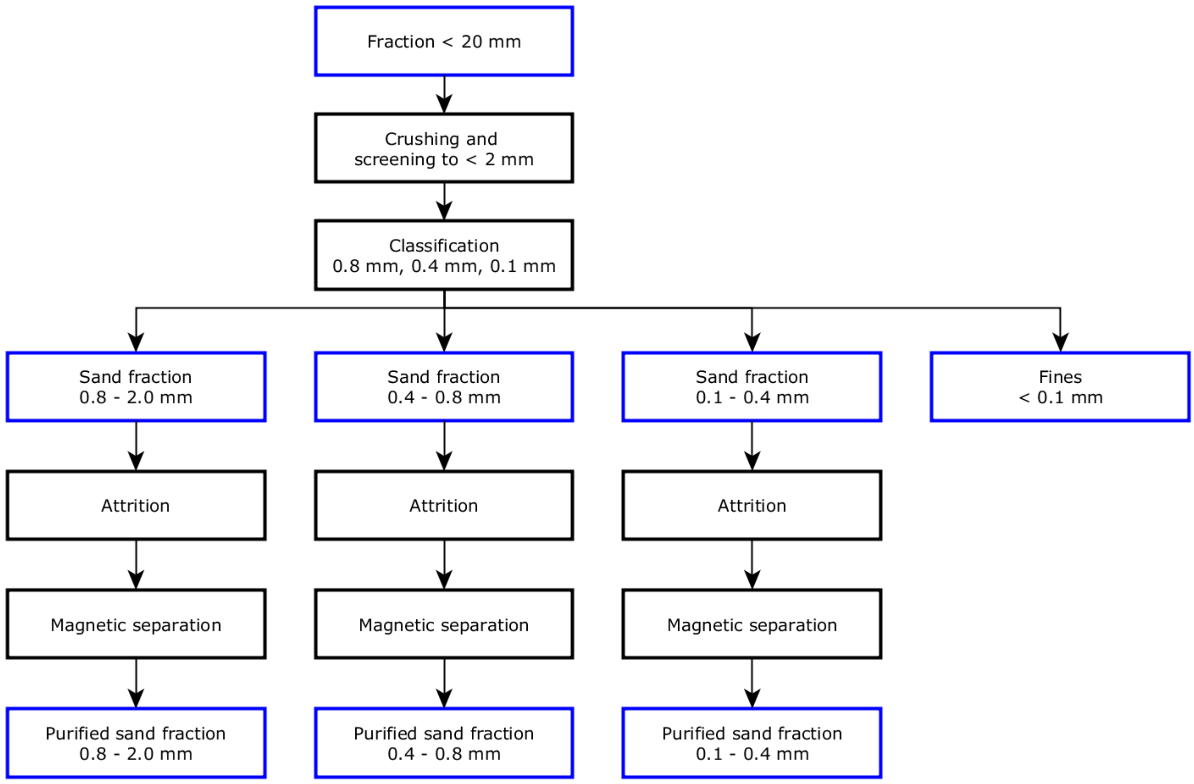

Figure 12: Mineral processing steps, applied to sample < 20 mm for flow sheet development

Chemical analyses after each refining step are listed in Table 9.

The separation cuts to produce fractions of different sizes were adjusted to the application as frac sand.

Fractions 0.8 – 2.0 mm, 0.4 – 0.8 mm and 0.1 – 0.4 mm are typical fractions for silica sand used as frac sand. All of these fractions meet the chemical specification of frac sand (SiO_2 content exceeding 99 wt.-%).

A more critical parameter to the applicability of a silica sand as frac sand are the physical characteristics including roundness and sphericity. The sand is not expected to meet crush resistance specifications for reasons discussed above. Thus, further consideration of the frac sand application for this silica sand sample is not recommended. However, MGX has indicated that additional samples are available. ANZAPLAN has therefore offered to carry out additional test work (quotation 211613293) targeting the evaluation of these samples for MG silicon production.

Other typical applications for silica sand are e.g. different glass applications, composite materials or quartz powder. Different applications require different size fractions and fraction 0.1 – 0.5 mm is a fraction usable in most applications. Chemical suitability is therefore further discussed on fraction 0.1 – 0.4 mm, being close to fraction 0.1 – 0.5 mm.

Typical chemical specifications are presented in Table 10 for different applications. After classification, fraction 0.1 – 0.4 mm meets the typical purity for application in container glass (colored and clear), float glass, fiberglass, borosilicate glass, pyrex, white float glass, opal glass, quartz powder, engineered stone, silicon carbide, fused silica, and sodium/potassium silicate (cf. Table 11).

After additional attrition the iron content is further reduced from 123 mg/kg to 107 mg/kg Fe_2O_3, being beneficial for glass applications, but not resulting in additional applications.

After additional magnetic separation iron content is further reduced from 107 mg/kg to 88 mg/kg Fe_2O_3, resulting in an additional chemical suitability for solar glass.

For final approval of glass applications, the evaluation of heavy minerals is necessary, including an analysis of coloring elements (e.g. copper, chromium, cobalt and nickel). For quartz powder, grinding and application tests have to be carried out. For engineered stone, a bright and uniform color has to be achieved and for SiC, fused silica and sodium respectively potassium silicate application tests in cooperation with the potential customer may be necessary.

Table 9: Chemical analyses, frac sand fractions after classification, attrition and magnetic separation

Sample ID	SiO_2 [wt.-%]	Al_2O_3 [wt.-%]	Fe_2O_3 [wt.-%]	TiO_2 [wt.-%]	K_2O [wt.-%]	Na_2O [wt.-%]	CaO [wt.-%]	MgO [wt.-%]	BaO [wt.-%]	LOI 1,025°C [wt.-%]
Fractions after classification										
Fr. 0.8 - 2.0 mm after classification	99.5	0.15	0.0138	0.01	0.04	<0.02	0.03	<0.01	<0.01	0.17
Fr. 0.4 - 0.8 mm after classification	99.5	0.10	0.0145	0.01	0.03	<0.02	0.03	<0.01	<0.01	0.17
Fr. 0.1 - 0.4 mm after classification	99.6	0.08	0.0123	0.01	0.03	<0.02	0.02	<0.01	<0.01	0.15
Fr. <0.1 mm after classification	99.2	0.21	0.0240	0.01	0.07	<0.02	0.09	0.02	0.01	0.29
Fractions after attrition										
Fr. 0.8 - 2.0 mm after attrition	99.5	0.14	0.0135	0.01	0.04	<0.02	0.02	<0.01	<0.01	0.15
Fr. 0.4 - 0.8 mm after attrition	99.6	0.09	0.0133	0.01	0.02	<0.02	0.02	<0.01	<0.01	0.13
Fr. 0.1 - 0.4 mm after attrition	99.7	0.05	0.0107	0.01	0.02	<0.02	0.01	<0.01	<0.01	0.10
Fractions after magnetic separation										
Fr. 0.8 - 2.0 mm after attr. and mag. sep.	99.5	0.12	0.0118	0.01	0.04	<0.02	0.03	0.01	<0.01	0.20
Fr. 0.4 - 0.8 mm after attr. and mag. sep.	99.5	0.09	0.0110	0.01	0.03	<0.02	0.02	0.01	<0.01	0.25
Fr. 0.1 - 0.4 mm after attr. and mag. sep.	99.7	0.05	0.0088	0.01	0.02	<0.02	<0.01	<0.01	<0.01	0.15

Table 10: Standard specifications for quartz sand applications

Application	SiO_2 [wt.-%]	Al_2O_3 [wt.-%]	Fe_2O_3 [wt.-%]	TiO_2 [wt.-%]	Notes [-]
Container glass (colored)	> 98.9	< 0.15	< 0.15	< 0.10	Analysis of heavy minerals
Container glass (clear)	> 99.5	< 0.10	< 0.035	< 0.02	Analysis of heavy minerals
Float glass (window, automotive)	> 99.5	< 0.15	< 0.04	< 0.04	Analysis of heavy minerals
Fiberglass (insulation)	> 98.1	< 0.52	< 0.50	< 0.05	
Fiberglass (fabrics)	> 99.2	< 0.60	< 0.04	< 0.05	
Borosilicate glass, pyrex	> 99.0	< 0.20	< 0.015	< 0.01	Analysis of heavy minerals
White float glass, opal glass, Crystal glass	> 99.0	< 0.20	< 0.0125	< 0.01	Analysis of heavy minerals
Solar glass	> 99.0		< 0.01	< 0.02	Analysis of heavy minerals
Borofloat			< 0.007		Analysis of heavy minerals
Quartz powder	> 98.5		< 0.25		Grinding and application tests
Engineered stone	> 99.5				Uniform color
Silicon carbide	> 99.0	< 0.2	< 0.1		Application tests
Fused silica	> 99.5		< 0.02		Application tests
Sodium/ Potassium silicate	> 99.0		< 0.02		Application tests
Frac sand	> 98.0	< 0.8	< 0.5		Grain size, Sphericity, Roundness, Permeability
Filtration sand	> 96.0				Specific surface area, Permeability

Table 11: Suitability of fractions 0.1 – 0.4 mm after beneficiation steps with regard to chemical composition

Fraction 0.1 – 0.4 mm	Container glass (colored)	Container glass (clear)	Float glass (window, automotive)	Fiberglass (insulation)	Fiberglass (fabrics)	Borosilicate glass, pyrex	White float glass, opal glass, crystal glass	Solar glass	Borofloat	Quartz powder	Engineered stone	Silicon carbide	Fused silica	Sodium/ Potassium silicate
after classification	+	+	+	+	+	+	+	-	-	+	+	+	+	+
after attrition	+	+	+	+	+	+	+	-	-	+	+	+	+	+
after magnetic separation	+	+	+	+	+	+	+	+	-	+	+	+	+	+

+ Suitable with regard to chemical composition

- Not suitable with regard to chemical composition

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