An Investigation into

THE METALLURGICAL TESTWORK TO REMOVE IMPURITIES FROM THREE SILICA SAND SAMPLES

prepared for

MINISTRY OF ENERGY AND MINERAL RESOURCES, JORDAN

Project 19097-03 – DRAFT – Final Report
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NOTES

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Executive Summary

A total of five silica sands samples from the Jordan Ministry of Energy and Mineral Resources were received at SGS Lakefield for a metallurgical testwork program. The test scope included sample preparation, head assays, particle size analysis, attrition scrubbing, dry-belt magnetic separation, wet high-intensity magnetic separation (WHIMS) and acid leaching tests. The objectives of the program were to remove any impurity elements and produce a silica sand concentrate grading at least 99.9% SiO_2.

The chemical assays of the five silica samples are presented in Table I. The SiO_2 grades of the samples were high, at 95~98% by the XRF method. The silica sand assays of samples GSB-03, GSB-04 and GSB-06 were confirmed by gravimetric method, which yielded results of 98.50, 98.67, and 98.05% SiO_2, respectively. The major trace impurity elements were alumina (0.5-1.8% Al_2O_3), iron (0.02-0.08% Fe_2O_3), calcium (0.02-0.27% CaO), titanium (0.07-0.25% TiO_2) and cobalt (710-806 g/t Co). A previous mineralogy study (SGS project# 19097-01) on a similar silica sand sample indicated kaolinite was the major impurity mineral, with trace amount of other minerals including chlorite, Fe-oxides, carbonates (calcite and dolomite), rutile/anatase, etc.

Table I: Head Assays of Silica Sand Samples

Head Assays on Silica Sand Samples											
WRA, %	GSB-01	GSB-02	GSB-03	GSB-04	GSB-06	ICP, g/t	GSB-01	GSB-02	GSB-03	GSB-04	GSB-06
SiO_2	95.9	97.2	98.3	98.4	98.1	Ag	< 200	< 200	< 200	< 200	< 200
Al_2O_3	1.80	1.20	0.64	0.47	1.01	As	< 1200	< 1200	< 1200	< 1200	< 1200
Fe_2O_3	0.08	0.03	0.02	0.05	0.03	Ba	< 30	< 30	< 30	< 30	< 30
MgO	0.03	< 0.01	< 0.01	< 0.01	< 0.01	Be	< 3	< 3	< 3	< 3	< 3
CaO	0.27	0.14	0.02	0.11	0.01	Bi	< 400	< 400	< 400	< 400	< 400
Na_2O	0.06	0.03	0.03	0.03	0.03	Cd	< 40	< 40	< 40	< 40	< 40
K_2O	0.02	< 0.01	< 0.01	< 0.01	< 0.01	Co	776	722	806	816	710
TiO_2	0.25	0.10	0.07	0.07	0.08	Cu	< 40	< 40	< 40	< 40	< 40
P_2O_5	0.02	0.01	0.01	0.02	0.02	Li	< 800	< 800	< 800	< 800	< 800
MnO	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Mo	< 300	< 300	< 300	< 300	< 300
Cr_2O_3	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Ni	< 300	< 300	< 300	< 300	< 300
V2O5	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Pb	< 800	< 800	< 800	< 800	< 800
LOI	1.21	0.74	0.45	0.46	0.63	Sb	< 400	< 400	< 400	< 400	< 400
Sum	99.6	99.5	99.6	99.6	99.9	Se	< 2000	< 2000	< 2000	< 2000	< 2000
Gravimetric SiO_2, %			98.50	98.67	98.05	Sn	< 800	< 800	< 800	< 800	< 800
						Sr	93	69	40	56	65
						Tl	< 2000	< 2000	< 2000	< 2000	< 2000
						U	< 400	< 400	< 400	< 400	< 400
						Y	< 8	< 8	< 8	< 8	< 8
						Zn	< 300	< 300	< 300	< 300	< 300

The particle size distributions were similar, with K_{80} sizes ranging from 477 to 601 µm, for the five silica sand samples at a crush size of -3.35 mm. Size by size analyses indicated that the impurity elements, such as alumina, calcium, and titanium, were mainly distributed in the -38 micron fraction, which can likely be removed by desliming.

Silica sand samples GSB-03, GSB-04, and GSB-06 were selected for the subsequent metallurgical testwork to remove impurity elements and improve SiO_2 grade, as per confirmation from the Jordan Ministry. The three samples were dry screened at 16 mesh (1.18 mm) to remove the oversized material. The -1.18 mm fraction of each sample was submitted for chemical assays and testwork. The WRA assays of the -1.18 mm fraction of each sample are shown in Table II.

Table II: WRA Assays on the -1.18 mm Fraction of GSB-03, GSB-04, and GSB-06

-1.18 mm Fractional Assays			
WRA, %	GSB-03	GSB-04	GSB-06
SiO_2	98.4	98.6	97.7
Al_2O_3	0.56	0.45	1.01
Fe_2O_3	0.03	0.03	0.02
MgO	< 0.01	< 0.01	< 0.01
CaO	0.01	0.09	< 0.01
Na_2O	0.02	< 0.01	< 0.01
K_2O	< 0.01	< 0.01	< 0.01
TiO_2	0.06	0.06	0.07
P_2O_5	0.01	0.01	0.02
MnO	< 0.01	< 0.01	< 0.01
Cr_2O_3	< 0.01	< 0.01	< 0.01
V2O5	< 0.01	< 0.01	< 0.01
LOI	0.56	0.42	0.78
Sum	99.6	99.7	99.6

Attrition scrubbing tests were carried out on the three samples at moderate or intensive conditions. This was followed by magnetic separation on the scrubbed material (after removal of the -38 µm fraction), using either a dry-belt magnetic separator or an Eriez WHIMS unit. Three-stage attrition scrubbing, desliming, and magnetic separation was also compared to one-stage attrition scrubbing and desliming processing.

The test results indicated that three-stage intensive attrition scrubbing at 900 rpm for 10 minutes with 60% pulp density was very effective in breaking down the gangue minerals and having them deport to the -38 micron fraction. About 88-94% of the aluminum, 69-74% of the iron, 53-81% of the calcium and 67-84% of the titanium could be removed by screening out the -38 micron fraction from the scrubbed silica sands.

WHIMS yielded better results than dry-belt magnetic separation in generating a cleaner non-magnetic silica sand. The non-magnetics generated by attrition scrubbing, desliming, and WHIMS assayed 98.8-99.0% SiO_2, 0.04-0.05% Al_2O_3, and ≤0.01% Fe_2O_3.

Acid leaching tests were performed on the non-magnetic WHIMS products. Tests L1 to L3 were carried out on silica sand GSB-03 to investigate HCl and H_2SO_4 as the lixiviant and the effect of feed size. Under the best conditions estabished (20% HCl, 10% solid (w/w), 80°C, and 6 hour reaction time), impurity elements such as Al, Fe, and Co were effectively removed from stage-pulverized (K_{80} of 53-58 µm) silica sands. The final leach residue of GSB-03, GSB-04, and GSB-06 contained 99.66, 99.80, and 99.58% SiO_2, respectively, by gravimetric method (ASTM-C146), slightly below the 99.9%SiO_2 target. Impurity elements such as alumina, titanium, and calcium and sodium assayed 407-450, 74-99 and 20-31 ppm, respectively. The chemical assays of the final silica sand products are shown in Table III.

Table III: Gravimetric SiO_2 Assay and Impurity Elements by Neutron Activation Analysis on Final Silica Sand Products

Product	SiO_2, % ASTM C-146	Neutron Activation Analysis, ppm								
		Al	Ca	Cr	Fe	Mg	Mn	K	Na	Ti
L3 residue, GSB-03	99.66	412	31	<10	<1000	<30	0.830	<110	22.0	74.0
L4 residue, GSB-04	99.80	450	27	<10	<1000	<30	0.830	<111	74.0	99.0
L5 residue, GSB-06	99.58	407	20	<10	<1000	<30	0.650	<112	19.0	89.0

Introduction

Mr. Yahya Alhazaimeh of SGS Jordan on behalf of the Ministry of Energy and Mineral Resources of Jordan, contacted SGS Lakefield in July 2022, with a request for metallurgical testwork to remove impurities from three silica sand samples.

The scope of the testwork included sample preparation, head assays, size by size analysis, attrition test, magnetic separation, and acid leaching. The technical objective of this testwork program was to remove any impurity elements and produce a silica sand concentrate grading 99.9% SiO_2.

During the development of the testwork, progress was discussed with Mr. Yahya Alhazaimeh, Mr. Hisham Alzyood, Mr. Saleem Saleem, Mr. Saleh Al-Kharabsheh, Mr. Asmaa Alqurneh, Mr. Mohamad Abweny, and Mr. Ali Alsmadi through emails, and all results were provided to them as they became available.

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Report preparation by: Hao Li
Reviewed by: Cheryl Mina, Chris Fleming, Dan Imeson

Testwork Summary

1. Sample Receipt and Preparation

1.1. Sample Receipt

Two shipments containing a total of five boxes of samples were received at the SGS Lakefield site on August 11 and 15, 2022. Each box contained a high-grade silica sand sample in a rice bag. The sample deposit information was not known/received. The internal receipt numbers of 0159-AUG22 and 0191-AUG22 were assigned to the five samples, which were designated as GSB-01, GSB-02, GSB-03, GSB-04, and GSB-06.

All the samples were received, inventoried, and weights recorded. The sample list is shown in Table 1.

Table 1: Sample Inventory List As-received

Sample #	GSB-01	GSB-02	GSB-03	GSB-04	GSB-05
Net Weight, kg	19.9	18.7	18.5	18.9	17.3

1.2. Sample Preparation

Each of the five as-received silica sand samples was screened at 3.35 mm to remove coarse particles and/or aggregates. The oversize material was further crushed to -3.35 mm and blended with undersize material to ensure 100% passing -3.35 mm. Each of the samples was fully homogenized before being rotary split into 1-kg test charges.

Later, the 1-kg test charges of GSB-03, GSB-04 and GSB-06 were recombined into bulk samples and dry screened to remove the +1.18 mm fraction as per instructions from the Jordan Ministry. The -1.18 mm fraction of each silica sand sample was further homogenized and re-split into 1 kg charges for subsequent metallurgical testwork.

2. Sample Characterization

2.1. Head Assays

Table 2 shows the head chemical assays of five silica sands. The SiO_2 grade of the silica sands was high, at 95~98% by the borate fusion XRF method. The major trace impurity elements were alumina (0.5-1.8% Al_2O_3), iron (0.02-0.08% Fe_2O_3), calcium (0.02-0.27% CaO), titanium (0.07-0.25% TiO_2), and cobalt (710-806 g/t Co).

The silica sand GSB-03, GSB-04, and GSB-06 samples were further analyzed by the gravimetric method, which yielded grades of 98.50, 98.67, and 98.05% SiO_2, respectively

A previous mineralogical test program (SGS project number 19097-01) on a similar silica sand sample indicated that kaolinite was the major impurity mineral, with trace amount of other minerals including chlorites, Fe-oxides, carbonates (calcite and dolomite), rutile/anatase, etc.

Table 2: Head Assays of Five Silica Sand Samples

Head Assays on Silica Sand Samples											
WRA, %	GSB-01	GSB-02	GSB-03	GSB-04	GSB-06	ICP, g/t	GSB-01	GSB-02	GSB-03	GSB-04	GSB-06
SiO_2	95.9	97.2	98.3	98.4	98.1	Ag	< 200	< 200	< 200	< 200	< 200
Al_2O_3	1.80	1.20	0.64	0.47	1.01	As	< 1200	< 1200	< 1200	< 1200	< 1200
Fe_2O_3	0.08	0.03	0.02	0.05	0.03	Ba	< 30	< 30	< 30	< 30	< 30
MgO	0.03	< 0.01	< 0.01	< 0.01	< 0.01	Be	< 3	< 3	< 3	< 3	< 3
CaO	0.27	0.14	0.02	0.11	0.01	Bi	< 400	< 400	< 400	< 400	< 400
Na_2O	0.06	0.03	0.03	0.03	0.03	Cd	< 40	< 40	< 40	< 40	< 40
K_2O	0.02	< 0.01	< 0.01	< 0.01	< 0.01	Co	776	722	806	816	710
TiO_2	0.25	0.10	0.07	0.07	0.08	Cu	< 40	< 40	< 40	< 40	< 40
P_2O_5	0.02	0.01	0.01	0.02	0.02	Li	< 800	< 800	< 800	< 800	< 800
MnO	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Mo	< 300	< 300	< 300	< 300	< 300
Cr_2O_3	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Ni	< 300	< 300	< 300	< 300	< 300
V2O5	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	Pb	< 800	< 800	< 800	< 800	< 800
LOI	1.21	0.74	0.45	0.46	0.63	Sb	< 400	< 400	< 400	< 400	< 400
Sum	99.6	99.5	99.6	99.6	99.9	Se	< 2000	< 2000	< 2000	< 2000	< 2000
Gravimetric SiO_2, %			98.50	98.67	98.05	Sn	< 800	< 800	< 800	< 800	< 800
						Sr	93	69	40	56	65
						Tl	< 2000	< 2000	< 2000	< 2000	< 2000
						U	< 400	< 400	< 400	< 400	< 400
						Y	< 8	< 8	< 8	< 8	< 8
						Zn	< 300	< 300	< 300	< 300	< 300

It should be noted that the SiO_2 assay by GC_XRF76V borate fusion XRF has a relative +/- 2% uncertainty at the concentration levels reported here. The ASTM_C146 is a wet chemistry gravimetric method that is more suitable for SiO_2 analysis on samples over 90% SiO_2, with an absolute uncertainty of +/- 0.25%. In consultation with the Jordan Ministry and SGS Jordan, it was decided to use the borate fusion XRF SiO_2 assay as a qualitative indicator for metallurgical mass balance evaluation given that it is quicker and less expensive. The gravimetric method was only used to determine the head and final product (leach residues) of GSB-03, GSB-04, and GSB-06 samples.

2.2. Particle Size Analysis and Size x Size Analysis

The particle size distribution plots of the five silica sands at a crush size of 100% passing -3.35 mm are presented in Figure 1. Detailed PSA results of each sample are listed in Appendix A.

The particle size distributions were similar for all samples, with K_{80} sizes ranging from 477 to 601 µm.

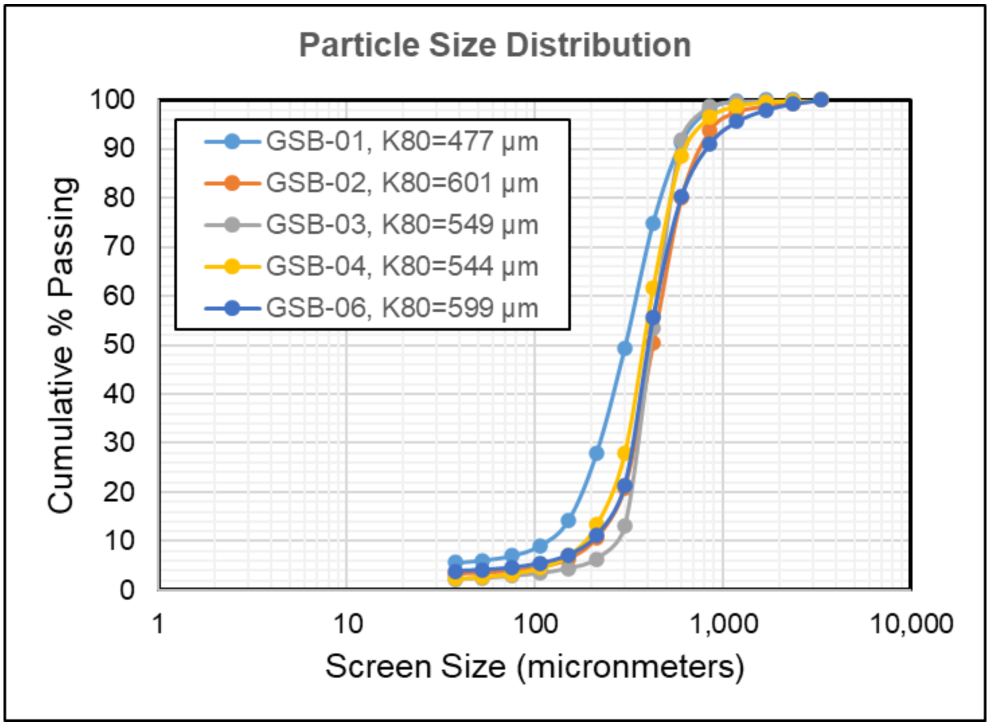

Figure 1: Particle Size Distribution of Five Silica Sand Samples

2.3. Size by Size Analysis

The trends of key element assays in each size fraction of the five silica sands are presented in Figure 2 with assay details in Appendix B. The mass balance of the -38 µm and cumulative +38 µm fractions is summarized in Table 3.

The SiO_2 grades of -850/+150 µm fractions were consistently high across all five samples, at 98-99% SiO_2. Lower SiO_2 grades were observed at finer size fractions (i.e., -150 µm), which was due to higher content of Al, Ca, and Ti gangue minerals in the slimes. As illustrated in Table 3, the Al_2O_3, CaO and TiO_2 assays and their corresponding distributions reporting to the -38 µm fraction were exceptionally high. As a result, the silica grade was only 55-77% SiO_2 in this fraction, which accounted for only 2-3% of the total silica distribution. Therefore, removing the -38 µm fraction will reject significant impurities and improve SiO_2 grades.

The silica content in the +850 µm fraction of the GSB-01, GSB-02, and GSB-03 samples were slightly lower, in the range of 95-97% SiO_2, mainly due to Fe and Ca-bearing gangue minerals.

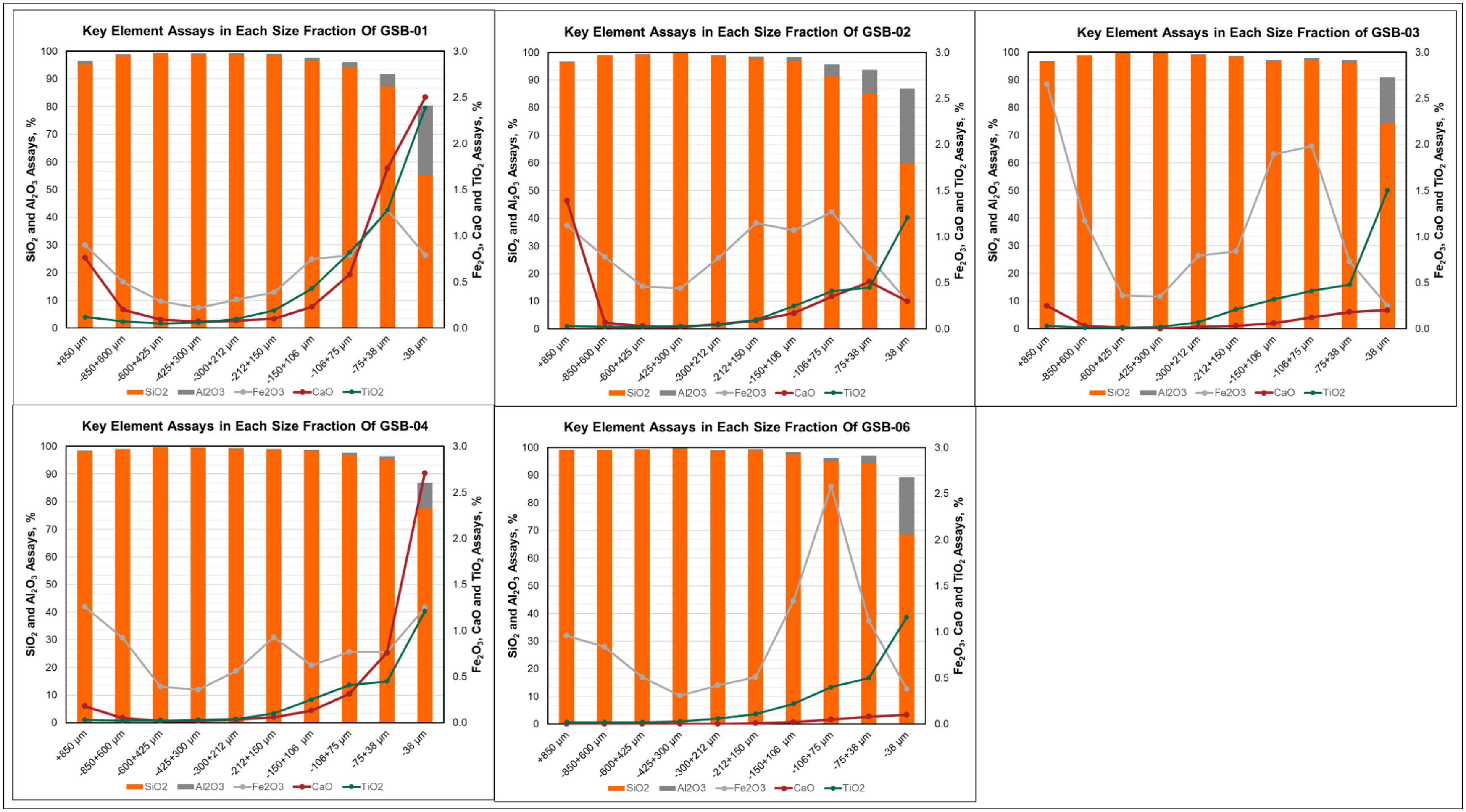

Figure 2: Trend of Key Element Assays in Each Size Fractions of Five Silica Sand Samples

Table 3: The Mass Pull, Assays, and Distributions of Five Silica Sand Samples in +38 µm and -38 µm Fractions

Sample ID	Size Fraction	Weight	Assays, %						Distribution, %					
		%	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	TiO_2	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	TiO_2
GSB-01	+38 µm frac.	94.4	98.3	0.58	0.37	0.15	0.04	0.14	96.8	28.1	88.7	50.0	90.4	50.1
	-38 µm frac.	5.6	55.3	25.1	0.79	2.50	0.08	2.39	3.2	71.9	11.3	50.0	9.6	49.9
	Feed (calc.)	100	95.9	1.96	0.39	0.28	0.05	0.27	100	100	100	100	100	100
GSB-02	+38 µm frac.	96.7	98.7	0.41	0.62	0.13	0.03	0.05	98.0	30.5	98.4	92.8	97.1	54.4
	-38 µm frac.	3.3	59.7	27.2	0.30	0.30	0.03	1.34	2.0	69.5	1.6	7.2	2.9	45.6
	Feed (calc.)	100	97.4	1.30	0.61	0.14	0.03	0.10	100	100	100	100	100	100
GSB-03	+38 µm frac.	97.8	99.3	0.24	0.51	0.02	0.03	0.03	98.3	38.6	98.9	79.9	98.7	47.5
	-38 µm frac.	2.2	74.2	16.8	0.25	0.20	0.02	1.5	1.7	61.4	1.1	20.1	1.3	52.5
	Feed (calc.)	100	98.8	0.61	0.50	0.02	0.03	0.06	100	100	100	100	100	100
GSB-04	+38 µm frac.	97.6	99.2	0.23	0.53	0.05	0.03	0.05	98.1	49.1	94.5	40.9	91.9	61.2
	-38 µm frac.	2.4	77.4	9.47	1.25	2.71	0.10	1.21	1.9	50.9	5.5	59.1	8.1	38.8
	Feed (calc.)	100	98.6	0.45	0.55	0.11	0.03	0.07	100	100	100	100	100	100
GSB-06	+38 µm frac.	96.2	99.1	0.29	0.55	0.01	0.04	0.04	97.3	25.9	97.3	73.6	92.9	47.7
	-38 µm frac.	3.8	68.5	20.8	0.38	0.10	0.07	1.16	2.7	74.1	2.7	26.4	7.1	52.3
	Feed (calc.)	100	97.9	1.07	0.54	0.01	0.04	0.08	100	100	100	100	100	100

3. Metallurgical Testwork on GSB-03, GSB-04, and GSB-06

After reviewing the head assays and discussing with the Jordan Ministry, samples GSB-03, GSB-04, and GSB-06 were selected for metallurgical testwork to remove impurities and upgrade the SiO_2 grade, with a technical objective of 99.9+% SiO_2 purity.

3.1. WRA Assays of the -1.18 mm fraction of GSB-03, GSB-04, and GSB-06

Samples GSB-03, GSB-04, and GSB-06 were dry screened at 16 mesh (1.18 mm) to remove the oversize material. The WRA assays of the -1.18 mm fractions are presented in **Error! Reference source not found.**. The mass balances of the +1.18 and -1.18 mm fractions of three silica sands are summarized inTable 5.

Owing to the low mass in the +1.18 mm fractions, the SiO_2 upgrading by rejecting this fraction was negligible, but impurity rejection was apparent: since about 28% of the calcium was discarded from GSB-03 in the +1.18 mm fraction, along with 9.4% calcium and 4.9% iron rejection from GSB-04 and 5.4% iron rejection from GSB-06.

Table 4: -1.18 mm Fractional Assays of GSB-03, GSB-04, and GSB-06

-1.18 mm Fractional Assays			
WRA, %	GSB-03	GSB-04	GSB-06
SiO_2	98.4	98.6	97.7
Al_2O_3	0.56	0.45	1.01
Fe_2O_3	0.03	0.03	0.02
MgO	< 0.01	< 0.01	< 0.01
CaO	0.01	0.09	< 0.01
Na_2O	0.02	< 0.01	< 0.01
K_2O	< 0.01	< 0.01	< 0.01
TiO_2	0.06	0.06	0.07
P_2O_5	0.01	0.01	0.02
MnO	< 0.01	< 0.01	< 0.01
Cr_2O_3	< 0.01	< 0.01	< 0.01
V2O5	< 0.01	< 0.01	< 0.01
LOI	0.56	0.42	0.78
Sum	99.6	99.7	99.6

Table 5: The Mass Pull, Assays, and Distributions of GSB-03, GSB-04 and GSB-06 in +1.18 and -1.18 mm Fractions

Sample ID	Size Fraction	Weight	Assays, %						Distribution, %					
		%	SiO_2	Al_2O_3	Fe_2O_3	CaO*	Na_2O*	TiO_2	SiO_2	Al_2O_3	Fe_2O_3	CaO*	Na_2O*	TiO_2
GSB-03	+1.18 mm frac.	0.4	96.8	0.37	0.03	0.99	0.01	0.09	0.4	0.3	0.4	27.5	0.2	0.6
	-1.18 mm frac.	99.6	98.4	0.56	0.03	0.01	0.02	0.06	99.6	99.7	99.6	72.5	99.8	99.4
	Head (calc.)	100	98.4	0.56	0.03	0.01	0.02	0.06	100	100	100	100	100	100
	Head (dir.)		98.3	0.64	0.02	0.02	0.03	0.07						
GSB-04	+1.18 mm frac.	1.0	96.4	0.89	0.15	0.90	0.02	0.07	1.0	2.0	4.9	9.4	2.0	1.2
	-1.18 mm frac.	99.0	98.6	0.45	0.03	0.09	< 0.01	0.06	99.0	98.0	95.1	90.6	98.0	98.8
	Head (calc.)	100	98.6	0.45	0.03	0.10	0.01	0.06	100	100	100	100	100	100
	Head (dir.)		98.4	0.47	0.05	0.11	0.03	0.07						
GSB-06	+1.18 mm frac.	3.7	98.5	0.29	0.03	< 0.01	0.02	0.02	3.7	1.1	5.4	3.7	7.1	1.1
	-1.18 mm frac.	96.3	97.7	1.01	0.02	< 0.01	< 0.01	0.07	96.3	98.9	94.6	96.3	92.9	98.9
	Head (calc.)	100	97.7	0.98	0.02	0.01	0.01	0.07	100	100	100	100	100	100
	Head (dir.)		98.1	1.01	0.03	0.01	0.03	0.08						

* Element Distribution was calculated assuming assay is 0.01% when below detection limit

3.2. Attrition Scrubbing Testwork

Attrition scrubbing, which utilizes strong friction forces between particles under controlled machine turbulence, can effectively break down clay particles from silica sands and assist in scouring of loosely adhering iron oxide particles to produce a higher-purity silica sand product.

Four attrition scrubbing tests were carried out on full size (without removing +1.18 mm fraction) silica sand samples GSB-03, GSB-04, and GSB-06. An image of the scrubbing unit used in the test is shown in Figure 3. Attrition tests A1 and A2 were completed on GSB-06 at scrubbing intensities of 400 and 900 rpm, each for 10 minutes. Attrition test A3 and A4 were carried out on GSB-04 and GSB-03, using the most effective attrition condition established in test A1 or A2. Each sample was scrubbed at 60% solid density in 1 kg batches in a baffled stainless steel container. A ~200 g subsample from each batch of scrubbed material was screened from its top size down to 38 µm, followed by WRA assay of ten (10) selected size fractions. The effect of attrition scrubbing and scrubbing intensity on upgrading of silica sand sample GSB-06 is presented in

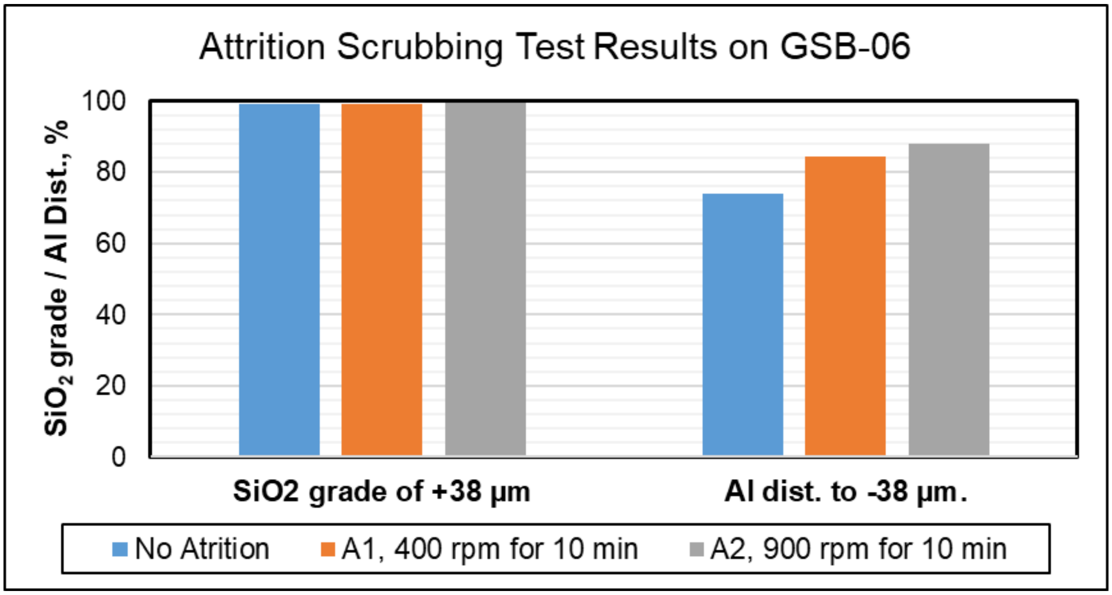

Figure 4. The size by size assays and distributions of three scrubbed silica sands are listed in Table 6. More detailed particle size distributions and size by size mass balances are included in Appendix A and Appendix B.

Figure 3: An Image of Multi-blade High Intensity Scrubbing Unit

As can be seen from

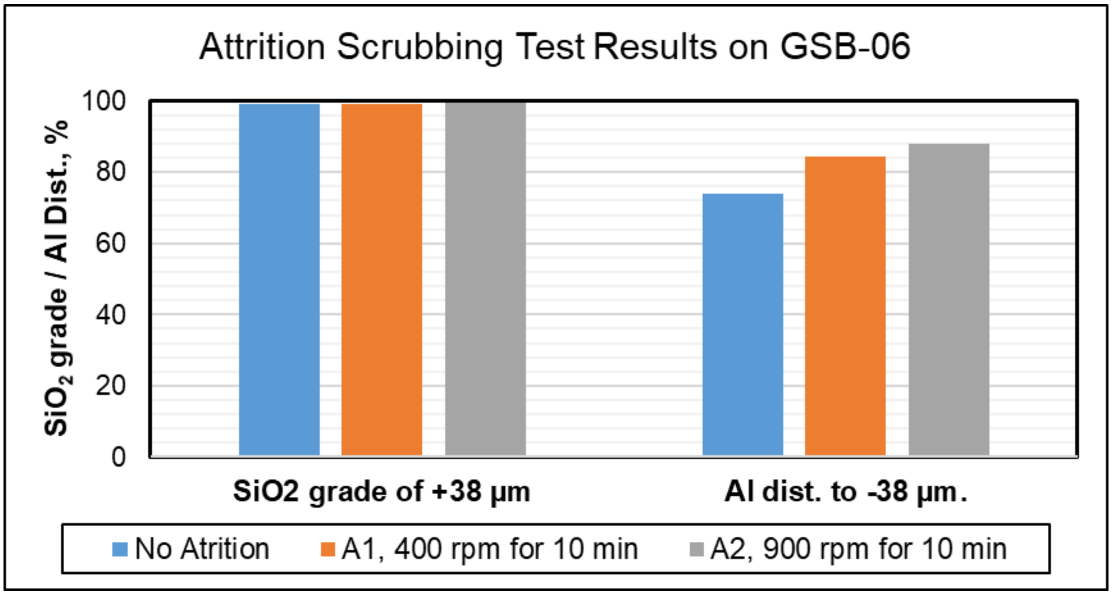

Figure 4 and Table 6, high-intensive attrition scrubbing can effectively remove impurity elements without compromising the SiO_2 grade of the combined +38 micron fraction of silica sand GSB-06. The major impurity element, Al-bearing minerals (most likely kaolinite clay), can be easily released and washed from the silica sand by intensive attrition conditioning. The alumina reported to -38 micron fraction increased from 74.1% without scrubbing, to 84.5% with moderate scrubbing at 400 rpm, and further enhanced to 88.1% with intensive conditioning at 900 rpm. Therefore, more intensive attritioning was desired for a better impurity removal efficiency for these silica sand samples.

Attrition scrubbing tests on silica sands GSB-03 and GSB-04 were completed using the test A2 conditions (i.e., 900 rpm, 10 min, 60% solid). Similarly, most of the alumina reported to the -38 micron fraction of GSB-03 and GSB-04, which increased by 17.2% and 20.5%, respectively, as a result of attritioning and scrubbing.

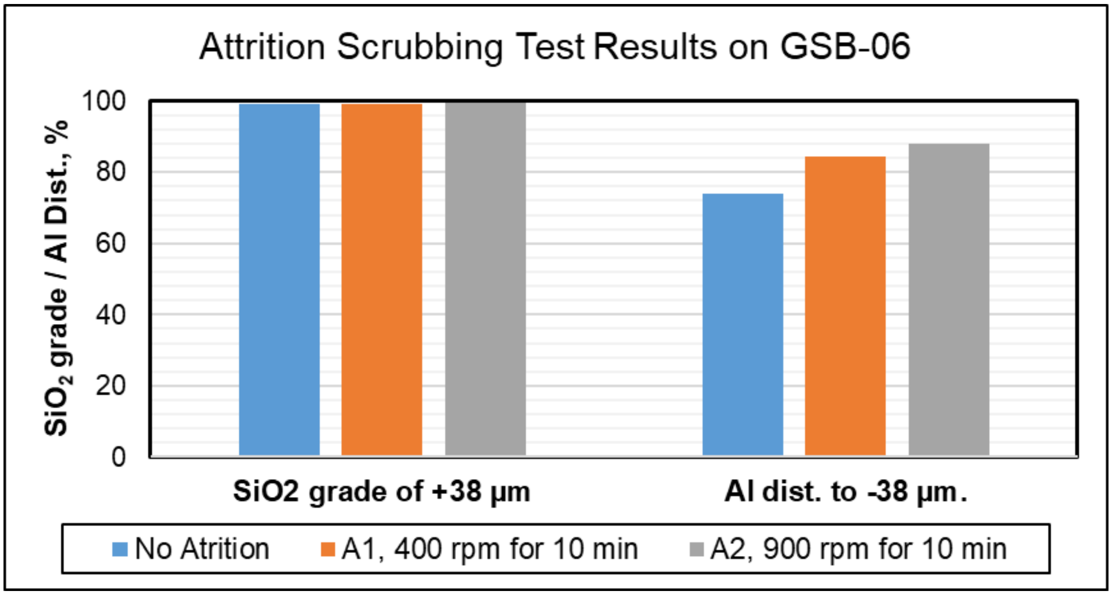

Figure 4: Attrition Scrubbing Test Result Summary on Silica Sand GSB-06 Sample

Table 6: Size by Size Assays and Distributions of Scrubbed Silica Sands

Test#	Size Fraction	Weight	Assays, %						Distribution, %					
condition		%	SiO_2	Al_2O_3	Fe_2O_3	CaO*	Na_2O*	TiO_2*	SiO_2	Al_2O_3	Fe_2O_3	CaO*	Na_2O*	TiO_2*
A1	+850 µm	8.3	99.1	0.19	0.78	0.02	0.05	0.01	8.4	1.3	12.2	10.4	13.4	1.0
GSB-06	-850+600 µm	10.5	99.4	0.13	0.63	0.01	0.03	0.01	10.7	1.2	12.5	6.6	10.2	1.2
	-600+425 µm	25.4	99.7	0.14	0.37	< 0.01	0.02	0.02	25.9	3.0	17.7	15.9	16.3	5.9
	-425+300 µm	33.3	99.3	0.16	0.28	< 0.01	0.03	0.02	33.9	4.6	17.6	20.9	32.2	7.7
	-300+212 µm	10.2	98.8	0.22	0.65	< 0.01	0.03	0.04	10.3	1.9	12.5	6.4	9.9	4.7
	-212+150 µm	4.1	98.5	0.33	1.12	< 0.01	0.04	0.09	4.1	1.1	8.6	2.6	5.2	4.2
400 rpm 10 min	-150+106 µm	1.8	97.3	0.50	1.83	0.02	0.04	0.17	1.8	0.8	6.2	2.2	2.3	3.5
	-106+75 µm	0.9	95.4	0.78	2.94	0.04	0.06	0.31	0.9	0.6	5.0	2.2	1.7	3.2
	-75+38 µm	0.9	95.3	1.21	2.61	0.07	0.05	0.41	0.9	1.0	4.6	4.1	1.5	4.5
	-38 µm	4.6	67.2	21.7	0.39	0.10	0.05	1.21	3.1	84.5	3.3	28.6	7.3	64.0
	Head	100	97.7	1.17	0.53	0.02	0.03	0.09	100	100	100	100	100	100
A2	+850 µm	8.6	99.1	0.09	0.91	< 0.01	0.04	0.01	8.7	0.7	14.7	5.7	11.2	1.0
GSB-06	-850+600 µm	10.3	99.3	0.07	0.80	< 0.01	0.03	0.02	10.5	0.6	15.5	6.9	10.1	2.3
	-600+425 µm	24.5	99.4	0.09	0.38	< 0.01	0.04	0.02	24.9	2.0	17.5	16.3	32.0	5.5
	-425+300 µm	32.6	99.6	0.11	0.28	< 0.01	0.02	0.02	33.2	3.2	17.1	21.6	21.3	7.2
	-300+212 µm	10.6	99.7	0.14	0.54	< 0.01	0.03	0.03	10.8	1.3	10.7	7.0	10.4	3.5
	-212+150 µm	4.3	99.7	0.21	0.99	< 0.01	0.04	0.08	4.3	0.8	7.9	2.8	5.6	3.8
900 rpm 10 min	-150+106 µm	2.0	98.0	0.34	1.43	0.02	0.03	0.13	2.0	0.6	5.3	2.6	1.9	2.8
	-106+75 µm	1.0	96.7	0.73	2.09	0.04	0.04	0.23	1.0	0.6	3.8	2.6	1.3	2.5
	-75+38 µm	1.0	94.0	2.42	1.51	0.06	0.04	0.33	0.9	2.1	2.8	3.9	1.3	3.6
	-38 µm	5.1	70.6	19.4	0.48	0.09	0.03	1.19	3.7	88.1	4.6	30.6	5.0	67.8
	Head	100	97.9	1.13	0.53	0.02	0.03	0.09	100	100	100	100	100	100
A3	+850 µm	3.1	97.9	0.32	0.05	0.12	0.05	0.02	3.0	2.1	2.3	3.6	8.5	0.9
GSB-04	-850+600 µm	7.6	99.0	0.10	0.03	0.04	< 0.01	0.01	7.6	1.7	3.4	3.0	4.2	1.2
	-600+425 µm	26.6	99.6	0.13	0.02	0.02	< 0.01	0.01	26.9	7.6	7.9	5.2	14.8	4.1
	-425+300 µm	33.2	99.5	0.09	0.02	0.02	< 0.01	0.01	33.5	6.5	9.9	6.5	18.5	5.1
	-300+212 µm	14.8	99.1	0.12	0.03	0.02	0.02	0.02	14.9	3.9	6.6	2.9	16.5	4.5
	-212+150 µm	6.4	98.6	0.19	0.04	0.04	0.02	0.06	6.4	2.6	3.8	2.5	7.1	5.9
900 rpm 10 min	-150+106 µm	2.6	98.3	0.26	0.06	0.08	0.03	0.14	2.6	1.5	2.4	2.1	4.4	5.7
	-106+75 µm	1.5	97.1	0.37	0.10	0.15	0.06	0.25	1.5	1.2	2.2	2.2	5.0	5.7
	-75+38 µm	1.2	97.0	0.54	0.22	0.29	0.06	0.24	1.2	1.5	4.1	3.5	4.1	4.6
	-38 µm	3.0	76.3	10.8	1.28	2.33	0.10	1.35	2.3	71.4	57.5	68.7	16.8	62.4
	Head	100	98.5	0.46	0.07	0.10	0.02	0.07	100	100	100	100	100	100
A4	+850 µm	1.3	95.6	0.41	0.06	0.38	0.11	0.02	1.2	1.0	1.7	18.1	7.9	0.4
GSB-03	-850+600 µm	7.2	99.0	0.11	0.02	0.02	0.01	< 0.01	7.3	1.5	3.2	5.4	4.0	1.1
	-600+425 µm	38.7	99.2	0.09	0.02	< 0.01	0.02	0.02	39.0	6.5	17.0	14.4	43.3	11.9
	-425+300 µm	38.5	99.5	0.10	0.02	< 0.01	0.01	0.02	38.9	7.2	16.9	14.4	21.5	11.8
	-300+212 µm	6.8	98.7	0.19	0.03	0.02	0.02	0.04	6.8	2.4	4.5	5.1	7.6	4.2
	-212+150 µm	2.1	98.0	0.27	0.06	0.03	0.03	0.10	2.1	1.1	2.8	2.3	3.5	3.2
900 rpm 10 min	-150+106 µm	1.0	97.5	0.38	0.09	0.05	0.06	0.15	1.0	0.7	2.0	1.9	3.4	2.4
	-106+75 µm	0.7	96.9	0.37	0.12	0.08	0.05	0.17	0.7	0.5	1.8	2.0	1.9	1.8
	-75+38 µm	0.6	95.3	0.42	0.18	0.14	0.05	0.20	0.6	0.5	2.4	3.1	1.7	1.8
	-38 µm	3.1	77.7	13.6	0.71	0.29	0.03	1.30	2.4	78.6	47.9	33.2	5.2	61.4
	Head	100	98.5	0.53	0.05	0.03	0.02	0.07	100	100	100	100	100	100

* mass balance was calculated assuming assays were 0.01% when below detection limits

3.3. One-Stage Attrition Scrubbing, Desliming, and Magnetic Separation Testwork

Four magnetic separation tests were carried out on silica sand samples GSB-03, GSB-04, and GSB-06 to reject any magnetic-susceptible particles (such as iron oxides and/or iron silicates) and improve the SiO_2 grade. These samples were attrition scrubbed at 900 rpm for 10 min at 60% solid density, and wet screened to remove the -38 micron fraction, which was considered as an effective cut-off particle size for removing gangue minerals without significant silica losses. The resulting +38 micron fractions were submitted for magnetic separation testwork.

3.3.1. Dry-Belt Magnetic Separation *vs.* Wet High-Intensity Magnetic Separation (WHIMS)

Due to the relatively coarse particle sizes, magnetic separation on a deslimed silica sand GSB-06 was assessed using a High-Force® dry belt magnetic separator and an Eriez wet high-intensity magnetic separator. The images of the lab testing equipment are shown in Figure 5.

The dry belt magnetic separator was equipped with a magnetic roller, with an expected magnetic intensity of 20,000 Gauss. Testing was completed by adjusting the belt speed, roll speed, and splitter for visual differences of the optimal trajectory of magnetic and non-magnetic streams. WHIMS testing was completed by passing the material through a coarse-expanded metal matrix at a pulp density of 20-30% solids, at 5,000 Gauss intensity. The non-magnetic fraction was repassed at 20,000 Gauss intensity for maximum magnetics rejection.

Figure 5: Exhibition of Dry Magnetic Separator (left) and Eriez WHIMS Lab Unit (right)

The results of the dry and wet magnetic separation with the GSB-06 sample are presented in Table 7. Both units removed iron effectively from the GSB-06 sample. The iron content in the two non-magnetics was very low, at or below the lower XRF detection limit of 0.01% Fe_2O_3. However, the WHIMS non-magnetic product assayed 99.6% SiO_2 and 0.06% Al_2O_3, better than the non-magnetics from dry belt magnetic separation, which was assayed 98.8% SiO_2 and 0.08% Al_2O_3. Therefore, WHIMS is preferred over a dry-belt magnetic separator for the application of silica sand upgrading and impurity removal in this project.

Table 7: Dry and Wet Magnetic Separation Test Results on Silica Sand GSB-06

Test#	Mag Sep Product GSB-06, full size	Weight %	Assays, % SiO_2	Al_2O_3	Fe_2O_3*	CaO*	Na_2O*	TiO_2	Distribution, % SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	TiO_2
M1	Dry Mag Sep, Non-mag	91.6	98.8	0.08	< 0.01	< 0.01	< 0.01	0.02	92.9	7.0	22.1	71.0	79.4	22.0
	Dry Mag Sep, Mag	3.5	98.9	0.51	0.16	0.01	0.04	0.20	3.6	1.7	13.7	2.7	12.2	8.5
Dry Mag Sep	-38 micron fraction	4.8	70.1	19.7	0.55	0.07	0.02	1.20	3.5	91.2	64.2	26.2	8.4	69.5
	Head Sample(calc.)	100	97.4	1.04	0.04	0.01	0.01	0.08	100	100	100	100	100	100
	Head Sample (dir.)		98.1	1.01	0.03	0.01	0.03	0.08						
M2	WHIMS, 20K Gauss, Non-mag	90.7	99.6	0.06	0.01	< 0.01	0.01	0.01	92.1	5.3	21.0	69.8	83.5	12.6
	WHIMS, 20K Gauss, Mag	3.5	98.8	0.17	0.13	0.01	0.01	0.09	3.6	0.6	10.6	2.7	3.3	4.4
	WHIMS, 5K Gauss, Mag	0.9	97.0	0.69	0.31	0.02	0.05	0.16	0.9	0.6	6.8	1.5	4.4	2.1
WHIMS	-38 micron fraction	4.8	70.1	19.7	0.55	0.07	0.02	1.20	3.5	93.4	61.5	26.0	8.9	80.8
	Head Sample(calc.)	100	98.1	1.02	0.04	0.01	0.01	0.07	100	100	100	100	100	100
	Head Sample (dir.)		98.1	1.01	0.03	0.01	0.03	0.08						

* Element Distribution was calculated assuming assay is 0.01% when below detection limit

3.3.2. WHIMS Testing on Silica Sands GSB-03 and GSB-04

WHIMS testing was completed on the -1.18 mm fraction of samples GSB-03 and GSB-04, after attrition scrubbing and desliming. The mass balances are listed in Table 8.

WHIMS was shown to be very effective for removal of both alumina and iron from silica sands. Only 0.08% Al_2O_3 and 0.02% Fe_2O_3 remained in the non-magnetic portion of sample GSB-03 and 0.06% Al_2O_3 and <0.01% Fe_2O_3 in the non-magnetic product of sample GSB-04.

Table 8: WHIMS Testwork Results on Silica Sand GSB-03 and GSB-04, -1.18 mm Fraction

Test#	Mag Sep Product	Weight %	Assays, % SiO_2	Al_2O_3	Fe_2O_3*	CaO	Na_2O*	TiO_2	Distribution, % SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	TiO_2
M3	WHIMS, 20K Gauss, Non-mag	95.2	98.8	0.08	0.02	0.02	< 0.01	0.01	96.0	12.4	44.4	65.7	90.2	16.3
	WHIMS, 20K Gauss, Mag	0.7	97.1	0.40	0.25	0.12	0.03	0.30	0.7	0.4	3.8	2.7	1.9	3.4
GSB-03,	WHIMS, 5K Gauss, Mag	1.0	96.2	0.88	0.36	0.11	0.05	0.28	1.0	1.5	8.8	4.0	5.0	5.0
-1.18 mm	-38 micron fraction	3.1	72.8	17.1	0.60	0.26	0.01	1.43	2.3	85.7	43.0	27.6	2.9	75.3
Frac.	Head Sample (calc.)	100	98.0	0.61	0.04	0.03	0.01	0.06	100	100	100	100	100	100
	Head Sample (dir.)		98.4	0.56	0.03	0.01	0.02	0.06						
M4	WHIMS, 20K Gauss, Non-mag	95.9	98.4	0.06	< 0.01	0.01	< 0.01	0.01	96.7	13.7	19.2	11.2	80.8	17.2
	WHIMS, 20K Gauss, Mag	0.6	97.1	0.51	0.15	0.04	0.02	0.24	0.6	0.7	1.8	0.3	1.0	2.5
GSB-04,	WHIMS, 5K Gauss, Mag	0.8	96.1	1.32	0.53	0.04	0.07	0.30	0.8	2.4	8.1	0.4	4.5	4.1
-1.18 mm	-38 micron fraction	2.7	71.7	12.9	1.31	2.77	0.06	1.57	2.0	83.2	71.0	88.1	13.7	76.2
Frac.	Head Sample (calc.)	100	97.6	0.42	0.05	0.09	0.01	0.06	100	100	100	100	100	100
	Head Sample (dir.)		98.6	0.45	0.03	0.09	< 0.01	0.06						

* Element Distribution was calculated assuming assay is 0.01% when below detection limit

3.4. Three-stage Attrition Scrubbing, Desliming, and WHIMS Testwork

To maximize the alumina and iron rejection and improve SiO_2 grade, a three-stage attrition scrubbing, desliming, followed by WHIMS magnetic separation was tested on the -1.18 mm fraction of samples GSB-03, GSB-04, and GSB-06. The pulp pH was adjusted to 12 with caustic soda to aid in the dispersion of fine clay particles that were broken down from coarse silica sand particles. This was different from the attrition scrubbing procedure described in Section 3.2 and Section 3.3. WHIMS testing was also completed on samples that had been separated into three size fractions (+600 micron, -600/+300 micron, and -300 micron), which was believed to improve the magnetic separation efficiency, compared with passing the material in one size. The block flowsheet diagram is presented in Figure 6 and the results are summarized in Table 9. .

The three-stage process removed >80% of the iron and >90% of the alumina from all three silica sands samples and recovered 95-96% of the silica in a final non-magnetic product that assayed ~99% SiO_2. The major impurities in the non-magnetics fraction of GSB-03, GSB-04, and GSB-06 were 0.04-0.05% Al_2O_3 and ≤0.01% Fe_2O_3, lower than the trace impurity levels achieved in the one-stage process. The SiO_2 of the non-magnetics (99.0%, 98.8%, and 98.9%) were performed by borate fusion XRF, which, as stated previously has a relative error of +/-2% when above 90%.

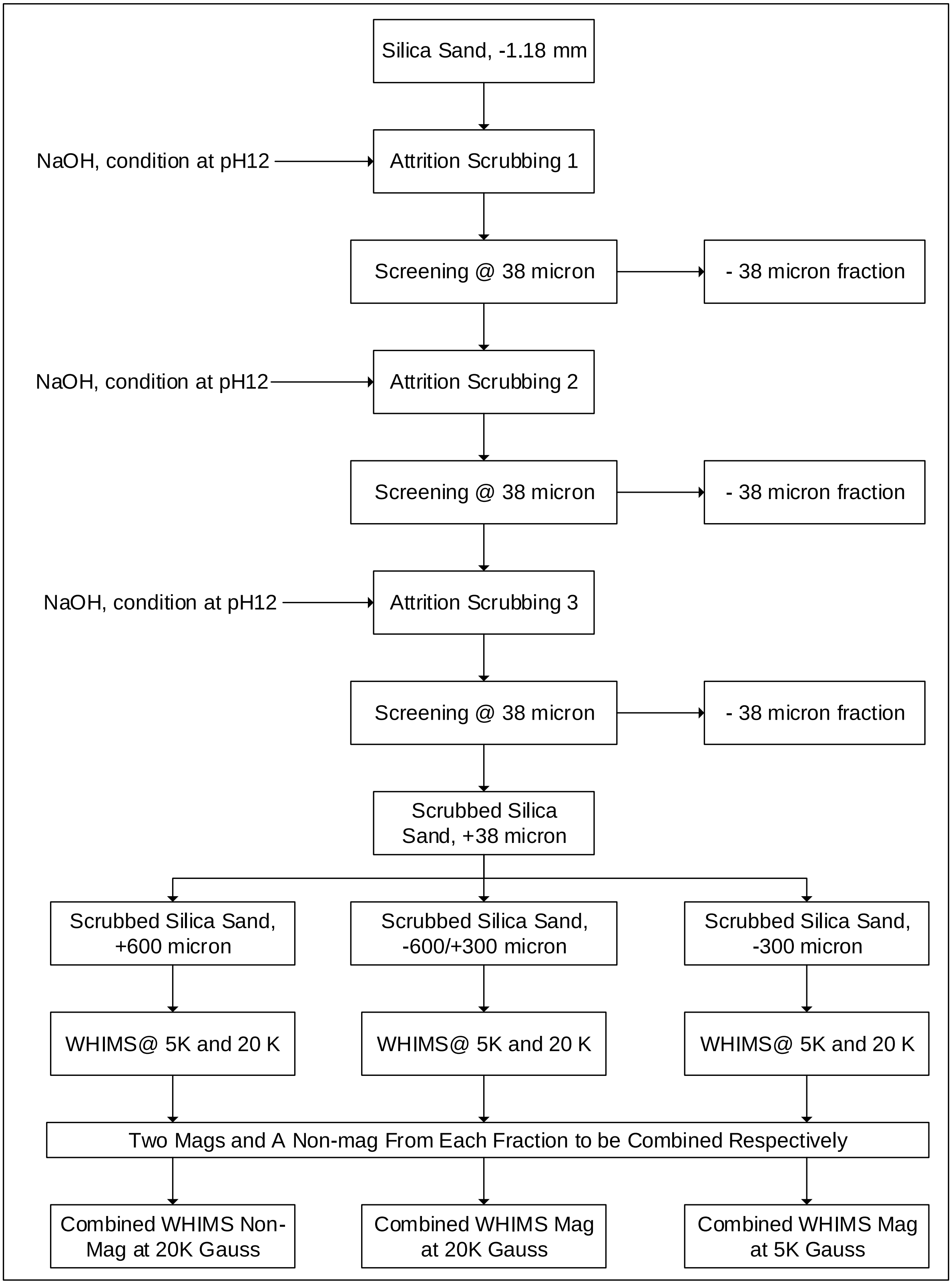

Figure 6: Block Flow Diagram of Three-Stage Attrition Scrubbing and WHIMS Testing

Table 9: Test Summary of Three-stage Attrition Scrubbing and WHIMS on the -1.18 mm Fraction of Silica Sand GSB-03, GSB-04, and GSB-06 Samples

Sample ID	Product	Weight	Assays, %						Distribution, %					
		%	SiO_2	Al_2O_3	Fe_2O_3*	CaO*	Na_2O*	TiO_2	SiO_2	Al_2O_3	Fe_2O_3*	CaO*	Na_2O*	TiO_2*
GSB-03	WHIMS, 20K Gauss, Non-mag	95.3	99.0	0.05	0.01	< 0.01	< 0.01	< 0.01	96.2	7.8	18.7	42.0	86.0	15.7
	WHIMS, 20K Gauss, Mag	0.5	96.7	0.63	0.47	0.03	0.06	0.21	0.4	0.5	4.2	0.6	2.5	1.6
	WHIMS, 5K Gauss, Mag	0.5	93.6	2.18	0.83	0.10	0.11	0.34	0.5	1.8	8.2	2.2	5.0	2.8
	-38 micron fraction, 3rd Scrub	0.2	94.0	1.18	2.52	0.16	0.01	0.4	0.2	0.5	12.0	1.7	0.2	1.6
	-38 micron fraction, 2nd Scrub	0.3	91.7	2.44	2.57	0.20	0.02	0.57	0.3	1.3	16.3	2.8	0.6	3.0
	-38 micron fraction, 1st Scrub	3.2	72.9	17.0	0.65	0.36	0.02	1.43	2.4	88.2	40.7	50.6	5.8	75.2
	Head Sample (calc.)	100	98.1	0.61	0.05	0.02	0.01	0.06	100	100	100	100	100	100
	Head Sample (dir.)		98.1	1.01	0.03	0.01	0.03	0.08						
GSB-04	WHIMS, 20K Gauss, Non-mag	95.8	98.8	0.04	< 0.01	0.02	< 0.01	0.02	96.6	9.3	16.6	17.6	77.2	28.3
	WHIMS, 20K Gauss, Mag	0.7	97.3	0.56	0.33	0.09	0.04	0.25	0.6	0.9	3.7	0.5	2.1	2.4
	WHIMS, 5K Gauss, Mag	0.5	94.7	1.65	0.67	0.11	0.1	0.34	0.5	1.9	5.5	0.5	3.8	2.4
	-38 micron fraction, 3rd Scrub	0.2	93.5	1.03	1.72	0.76	0.08	0.54	0.2	0.5	6.0	1.4	1.3	1.6
	-38 micron fraction, 2nd Scrub	0.4	89.0	3.14	2.08	1.23	0.05	0.89	0.4	3.4	15.9	5.0	1.8	5.8
	-38 micron fraction, 1st Scrub	2.5	68.8	14.2	1.23	3.34	0.07	1.64	1.7	84.1	52.3	75.0	13.8	59.5
	Head Sample (calc.)	100	98.0	0.41	0.06	0.11	0.01	0.07	100	100	100	100	100	100
	Head Sample (dir.)		98.6	0.45	0.03	0.09	< 0.01	0.06						
GSB-06	WHIMS, 20K Gauss, Non-mag	93.2	98.9	0.05	< 0.01	< 0.01	< 0.01	0.01	94.7	4.5	18.2	44.4	86.9	12.8
	WHIMS, 20K Gauss, Mag	0.8	98.4	0.29	0.16	0.02	0.03	0.13	0.8	0.2	2.4	0.7	2.2	1.4
	WHIMS, 5K Gauss, Mag	0.5	94.2	1.87	0.65	0.06	0.09	0.27	0.5	0.9	6.6	1.5	4.4	1.9
	-38 micron fraction, 3rd Scrub	0.3	95.0	1.31	1.94	0.06	0.06	0.4	0.3	0.4	12.2	0.9	1.8	1.8
	-38 micron fraction, 2nd Scrub	0.5	91.2	3.37	2.08	0.08	< 0.01	0.58	0.5	1.7	21.2	2.0	0.5	4.1
	-38 micron fraction, 1st Scrub	4.6	68.7	20.7	0.44	0.23	< 0.01	1.24	3.2	92.2	39.4	50.4	4.3	78.0
	Head Sample (calc.)	100	97.4	1.03	0.05	0.02	0.01	0.07	100	100	100	100	100	100
	Head Sample (dir.)		97.7	1.01	0.02	< 0.01	< 0.01	0.07						

* Element Distribution was calculated assuming assay is 0.01% when below detection limit

SiO_2 assay by borate fusion XRF method has a relative error of 2%

3.5. Acid Leaching Testwork

Five acid leaching tests were completed on the non-magnetic products generated in the three-stage attrition scrubbing, desliming and WHIMS flowsheet. Extreme leaching conditions were used in these scoping leach tests, with no attempt at process optimization. The purpose was to extract any remaining impurity elements while leaving silica behind in the leach residue, at a target gade of 99.9% SiO_2.

The standard procedure involved placing 200 g of the leach feed, either as-is or stage-pulverized to 100% passing 75 µm, in a glass reactor followed by DI water and acid addition to the desired solid content and acidity, with temperature maintained at approximately 80°C under atmospheric condition. The leaching time was either four or six hours. At the end of the test, the pulp was filtered and washed. The leach residue was dried and submitted for WRA or gravimetric SiO_2. Selected leach residues were submitted for trace impurity assays by neutron activation analysis and the wash solution was also submitted for ICP analysis. The acid consumption was based on the difference between acid added and acid remaining in solution at the end of the test.

Tests L1 to L3 were carried out on WHIMS non-magnetic product of silica sand GSB-03. Tests L1 and L2 compared the extraction performance of HCl and H_2SO_4 as the lixiviant, while test L3 investigated the effect of feed particle size. Test L4 and L5 were carried out on silica sand GSB-04 and GSB-06, respectively, using the pre-optimized test conditions. A summary of each test condition is presented in Table 10 and full test details are in Appendix C.

Table 10: Conditions for Acid Leaching Tests L1-L5

Test ID	L1	L2	L3	L4	L5
Feed	GSB-03, WHIMS Non-mag	GSB-03, WHIMS Non-mag	GSB-03, WHIMS Non-mag	GSB-04, WHIMS Non-mag	GSB-06, WHIMS Non-mag
%solids	10	10	10	10	10
Feed Size (K_{80}, µm)	As is	As is	53.1	57.9	54.9
Temp, °C	80	80	80	80	80
Leach Time, hr	4	4	6	6	6
Reagent	HCl	H_2SO_4	HCl	HCl	HCl
Target Acidity, w/w %	20	20	20	20	20
Acid added, tonne/tonne	1.81	1.81	1.79	1.80	1.81
Acid Cons, kg/tonne	3	18	595	615	663

The extraction of impurities in leach tests L1-L5 is shown in Table 11. Photographs of PLS solutions and acid leach residues are presented in Figure 7 and Figure 8.

It should be noted that most of the impurity elements in the feed solids were already below or around the analytical detection limits of the borate fusion XRF and ICP-MS techniques and were expected to be even lower in the leach residues, which led to an incomplete mass balance. Therefore, the amount of extracted metal units in the leach solution (in milligrams per 200 g of leach feed) was used to estimate the purity of the SiO_2 in the leach residue to provide an indication of the leach performances.

Table 11: Result Summary of Acid Leaching Tests L1-L5

Test ID	Leach Feed	Residue, %	SiO_2 % in Feed XRF_76V	SiO_2 % in Residue		Extracted Metals, mg		
				XRF_76V	ASTM-C146	Al	Fe	Co
L1	GSB-03, WHIMS Non-mag	100	99.0	99.5	-	3	6	-
L2	GSB-03, WHIMS Non-mag	99.3	99.0	99.3	-	1	3	-
L3	GSB-03, WHIMS Non-mag	96.7	99.0	-	99.66	n/a	n/a	n/a
L4	GSB-04, WHIMS Non-mag	94.5	98.8	-	99.80	15	27	99
L5	GSB-06, WHIMS Non-mag	97.5	98.9	-	99.58	12	15	110

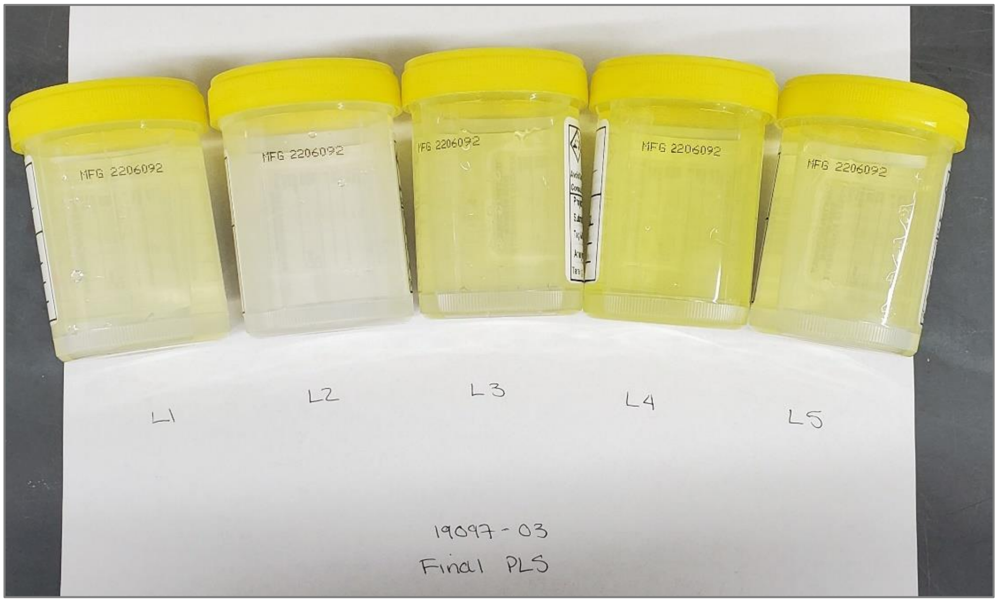

Figure 7: Images of PLS solutions of Acid Leaching Tests L1-L5

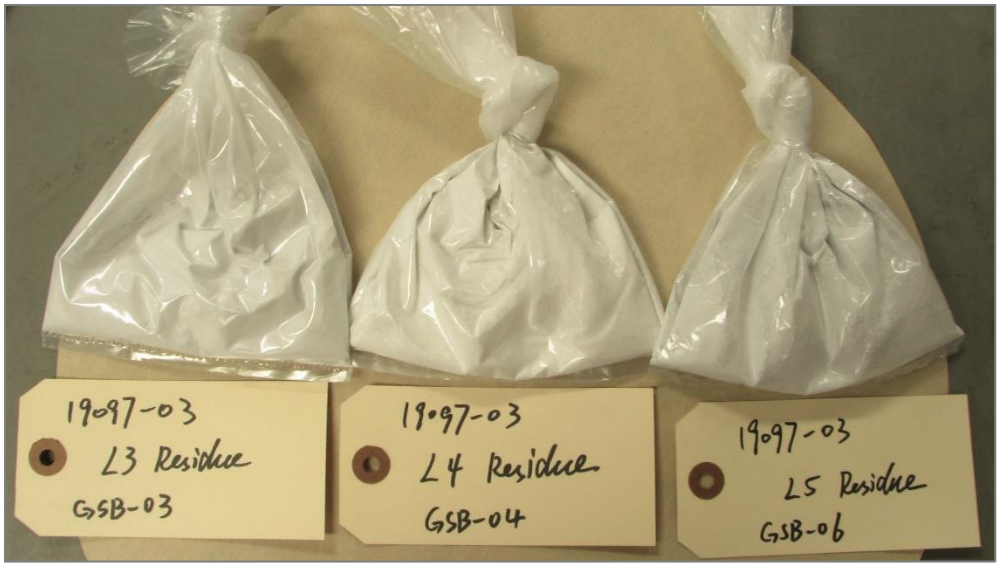

Figure 8: Images of Residues of Acid Leaching Tests L3-L5

Based on the test results and observations, the following conclusions can be made:

- Negligible impurity metals were extracted from as-received silica sand samples by HCl or H_2SO_4. HCl showed slightly better leaching performance than H_2SO_4 at same acidity strength.
- Fine grinding to K_{80} of 53-58 µm significantly improved Al, Fe, and Co impurtity removal efficiency.
- Finer grinding as well as stronger HCl or longer leach time should all be investigated to see whether the target purtity of 99.9% SiO_2 can be achieved.

It should be mentioned that test L3 only reported residue assays without quantifying the extracted metals from PLS and wash solution, which were disgarded accidently before subsampling was to occur. The extractive performance in test L3, however, should be similar to test L4 or L5, juding from the purity of leach residues and colour of PLS solutions as presented in Figure 7 and Figure 8.

3.4. Final Silica Sand Products Assays

The gravimetric SiO_2 and impurity element assays of the leached residues from the -1.18 mm fraction of silica sand GSB-03, GSB-04, and GSB-06 samples after acid washing are presented in Table 12. The assay certificates are attached in Appendix D.

The final leach residue of GSB-03, GSB-04, and GSB-06 graded 99.66, 99.80, and 99.58% SiO_2 by a gravimetric method (ASTM-C146), slightly lower than the 99.9% SiO_2 target.

The alumina remained as the major impurity element in the leach residue of GSB-03, GSB-04, and GSB-06, followed by titanium and calcium, which assayed 407-450, 74-99, and 20-31 ppm, respectively,

Table 12: Gravimetric SiO_2 Assay and Impurity Elements by Neutron Activation Analysis on Final Silica Sand Products

Product	SiO_2, % ASTM C-146	Neutral Activation Analysis, ppm								
		Al	Ca	Cr	Fe	Mg	Mn	K	Na	Ti
L3 residue, GSB-03	99.66	412	31	<10	<1000	<30	0.830	<110	22.0	74.0
L4 residue, GSB-04	99.80	450	27	<10	<1000	<30	0.830	<111	74.0	99.0
L5 residue, GSB-06	99.58	407	20	<10	<1000	<30	0.650	<112	19.0	89.0

Conclusions and Recommendations

The following conclusions can be drawn based on the testwork results:

- The five silica sand samples assayed 95~98% SiO_2 by borate fusion XRF. The major impurity elements were alumina (0.5-1.8% Al_2O_3), iron (0.02-0.08% Fe_2O_3), calcium (0.02-0.27% CaO), titanium (0.07-0.25% TiO_2), and cobalt (710-806 g/t Co).

- The particle size distributions were similar, with K_{80} sizes ranging from 477 to 601 µm, for the five silica sand samples at a crush size of -3.35 mm. Size by size analyses indicated that the impurity elements, such as alumina, calcium, and titanium, were mainly distributed in the -38 micron fraction, which can likely be removed by desliming.

- Silica sand samples GSB-03, GSB-04, and GSB-06 were selected for the metallurgical testwork as a proof-of-concept purpose, with techncial objectives of removing impurity elements and improve SiO_2 grade to 99.9+% purity.

- Intensive attrition scrubbing and desliming/washing out the -38 µm fine particles was a cost-effective beneficiation method capable of scrubbing out most of the impurity gangue minerals. Three-stage intensive attrition scrubbing and desliming also produced cleaner silica sands than one-stage intensive attrition scrubbing and desliming.

- Magnetic separation was capable of removing >80% of the residual iron and >90% of the residual alumina remaining in the silica sand after intensive scrubbing and desliming and increased the purity of the silica sand to ~99.0%. Eriez wet high-intensity magnetic separation (WHIMS) was more effective than a dry-belt magnetic separator in this role. The non-magnetic fractions of WHIMS test graded 98.8-99.0% SiO_2 by borate fusion XRF, with its major impurities assayed 0.04-0.05% Al_2O_3 and ⩽0.01% Fe_2O_3.

- Leaching with hydrochloric acid under best established test conditions (20% HCl, 10% solid (w/w), 80°C, and 6 hour reaction time) further improved the silica grade to 99.6% - 99.8%, assayed by ASTM_C146 method. This was still slightly below the 99.9%SiO_2 target, which was not achieved in this testwork.

The following recommendations are made for the future testing:

- Further optimize the attrition scrubbing conditions, such as higher solid density, longer scrubbing time, with/without dispersant addition.
- Further optimize the WHIMS test conditions on stage-ground scrubbed silica sands to maximize iron and aliumina rejection

- Investigate the effect of temperature, acidity, solids density, and feed particle size to optimize the acid leaching condition.

Appendix A – Particle Size Distributions

Appendix B – Size x Size Analysis Results

Appendix C – Acid Leaching Results

Appendix D – Assay Certificate of Acid Leach Residues of Silica Sands