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Comparing the Durability of Saudi Silica Sands for Use in Foundry Processing

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***Abstract*—**This paper was developed to investigate two types of sands from the Kingdom of Saudi Arabia (KSA) for potential use in the global metal casting industry. Four types of sands were selected for study, two of the sand systems investigated are natural sands from the KSA. The third sand sample is a heat processed synthetic sand and the last sample is commercially available US silica sand that is used as a control in the study. The purpose of this study is to define the durability of the four sand systems selected for foundry usage. Additionally, chemical analysis of the sand systems is presented before and after elevated temperature exposure. Results show that Saudi silica sands are durable and can be used in foundry processing.

***Keywords*—**Alternative molding media, foundry sand, reclamation, silica sand, specialty sand.

I. INTRODUCTION

A. Background

SILICA sand is no longer consider as cheap and easily available for use in the foundry. Competition for this granular media from industries like construction, glass, and most recently from energy for fracking, led to increasing prices and promoted environmental causes to restrict sources. More constraining is certain factors that are becoming increasingly significant as more health and environmental regulations are disseminated. The US Occupational Safety and Health Administration (OSHA) has implemented a rule to safeguard foundry workers from exposure to respirable crystalline silica which could cause lung cancer, silicosis, chronic obstructive pulmonary disease and kidney disease [1], [2].

Silica is a relatively weak mineral such that phase change during heating and cooling can cause grains to embrittle and breakdown into fines. This makes the casting process more complicated and increases the disposal [1]. When reclamation processes are used in foundry sand recycling systems, a further breakdown can be expected, increasing the total reclamation cost.

Notwithstanding the concerns for silica sand, it remains the most widely used granular media for metal casting processes. Foundries have used alternative materials for decades [1]-[3]. Natural minerals such as chromite, zircon, olivine, and aluminum oxide have been used to solve operating problems and also developed their precise niches in the foundry materials inventory and are usually referred to as specialty sands. Research conducted in the early 1990's pointed out these natural sands sand can breakdown with foundry processing [1]-[3]. Today, there are both natural and synthetic substitutes to silica sand, such as fused alumina, sintered bauxite, and ceramic sands. These alternative media can be readily tailored in composition and shape for reclamation affording materials management that is sustainable [1]. However, when compared to silica sand the alternative granular media are neither as available nor as economical for use in the metal casting industry. The metal casting industry outside the US requires clean and durable silica sand.

KSA has abundant reserves of natural granular media throughout the country. This study examines the durability of Saudi Silica Sand (SSS) for use in the metal casting industry, since SSS is mainly used in their construction, ceramic (glass), oil and gas industries.

Four types of sands were selected for study, the two from KSA are natural silica sands, and the other two are commercially available foundry sands. One commercial sand is considered a synthetic ceramic because the original media was heat processed; the other was a natural US silica sand identified as a control. The candidate media was selected such that the sands should represent the size used in a typical cast iron green sand system and targeted 50 AFS-GFN with no more than four screens. Table I is used to identify the granular media used in this study by letter and color coding. In addition, the manufacturer's documented chemical analysis, properties, and characteristics are shown. Fig. 1 is used to depict sphericity and roundness to describe the typical grain shape that is pictured in Table I. Table II provides the sand distribution and standard AFS-GFN data measured. Table III provides additional particle analysis showing the size, shape, surface area, and fines in the granular media used in this study.

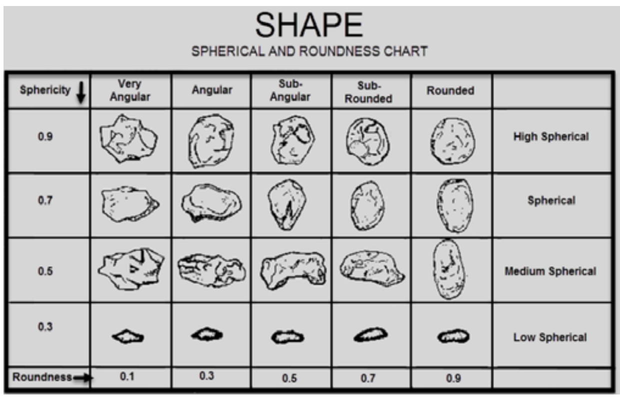

Fig. 1 Sphericity and Roundness Chart

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It is important to point out that sand samples B and C are processed for industrial use, so these have been washed and screened. In contrast, the Saudi desert sands SSS-1 and SSS-2 contained a greater percentage of fines. Foundry sand processing issues associated with fines can be reduce permeability and a greater bond requirement to achieve strength (Table II).

TABLE I
TYPES OF GRANULAR MEDIA, DOCUMENTED COMPOSITION, PROPERTIES AND CHARACTERISTICS

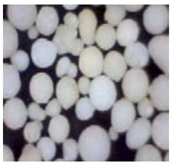
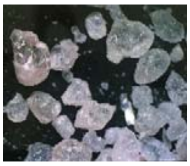
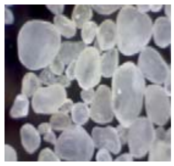
Granular Media / Chemical Analysis (%)	B	SSS-1	SSS-2	C (Control)
Al_2O_3	60.8	.81	0.25	0.13
SiO_2	35.7	98.1	99.58	99.7
Fe_2O_3	1.2	<.05	0.17	0.11
TiO_2	0.9	.22	-	< 0.01
CaO + MgO	0.4	-	-	<0.02
$Na_2O + K_2O + P_2O5$	0.9	-	-	-
Properties	B	SSS-1	SSS-2	C
AFS Grain Fineness	40 - 170	40	49	46.3 - 108.7
pH	7.2	6.7	6.9	6.8
Bulk Density (g/cm^3)	1.69	1.66	1.61	1.9
Shape	Rounded	Angular	Rounded	Rounded
Fusion/Melt Pt (°C)	1825	-	-	1710
Pictures (100X)				
Base Material	Fired mullite crystals	Natural	Natural	Natural
Color	Light Tan/ Light Brown	White/ Light Tan	Brown	White/ Light Tan
Surface of Grain	Uneven	Smooth	Smooth	Smooth

Table I was developed from a review of technical literature e.g. Control System G was developed from [12].

TABLE II
SAND DISTRIBUTION AND AFS-GFN

SAND STD.	SCREEN #	B	SSS-1	SSS-2	C
3.35 mm	6	0.0	0.0	0.0	0.0
1.70 mm	12	0.0	0.6	5.5	0.0
850 µm	20	0.0	4.5	11.3	0.0
600 µm	30	1.0	12.2	15.5	0.0
425 µm	40	10.0	26.0	22.2	9.0
300 µm	50	34.0	31.6	13.0	26.0
212 µm	70	30.0	17.5	8.6	30.0
150 µm	100	21.0	4.6	8.0	24.0
106 µm	140	5.0	1.6	6.4	9.0
75 µm	200	0.2	0.7	5.2	0.9
53 µm	270	0.0	0.4	4.0	0.1
Pan	Pan	0.0	0.3	0.3	0.0
Total		100	100	100	100
AFS-GFN		51	40	49	56

Percent Retained on USA Std. Sieves with ASTM Specification E-11-86 and I.S.O

Potential alternative molding media must possess similar or superior sand control characteristics to silica sand before they will be seriously considered for use by foundry engineers. The information a foundry engineer uses for sand control is derived from years of testing and research on silica sands [4]-[7]. This experience base serves as a starting point for determining if an alternative granular media will function satisfactorily in either the green or the chemically bonded sand casting process.

TABLE III
SIZE, DISTRIBUTION, SHAPE AND SURFACE AREA MEASUREMENTS

Sand	B	SSS-1	SSS-2	C
AFS/GFN [screens]	51 [4]	40 [4]	49 [4]	56 [3]
Mean Sphericity	0.93	0.54	0.75	0.89
Mean Symmetry	0.92	0.70	0.88	0.90
Surface Area cm^2/g (AFS/GFN & Shape Calculator)	154	94	126	201
% Fines	0.2	1.4	9.5	1.0

Any alternative molding media must offer the foundry industry benefits which can be measured in terms of cost, availability, environmental compliance and casting quality [4]-[7]. Sand suppliers were reluctant to divulge pricing, so economics was not a consideration in this work. It takes little imagination to realize that few minerals can compete with silica sand based on price and availability [4]. Thus, the benefits will not be realized if the functionality of an alternative media is not considered in terms of its durability.

B. Need & Purpose

The problem with granular media used in the foundry industry is that ultimately it will depreciate due to thermomechanical and thermochemical stresses involved in the processes and in reclamation. The AFS has no standard tests for evaluating this problem and there is limited knowledge regarding the related issues and laws facing the foundry industry [1], [2], [8].

The purpose of this study is to determine the durability of four types of sands in thermomechanical testing aimed at mimicking molding, melting, filling, shakeout and reclamation. Further, independent chemical analysis of the granular media requires documentation before and after elevated temperature exposure. Results provide information regarding the durability of granular media that is beneficial to reclamation and/or the use of granular media for foundry processing.

II. Methodology

There was neither foundry equipment like mullers for mixing and blending nor thermomechanical reclamation systems used in this study. The researchers developed a new set of techniques for evaluating the durability of granular media because no standard testing procedures exist. To represent the stresses experienced by foundry sand during processing, the researchers developed a set of novel testing procedures. The testing considered a compressive-shear force exhibited during the mulling of green sand and the abrasive rubbing of sand grains together and against the muller wheels and walls. Elevated temperatures treatment of the granular media was conducted in a reduced atmosphere furnace (1350 ˚C) representing a cast irons mold metal interface. Additionally, potential impact and heat stresses during shakeout and reclamation was considered. The ultimate aim of testing was to develop a measure of durability for granular media used in the foundry industry and that is being reclaimed. Still, there are impediments in developing durability test for granular media.

Previous work by Gulchelaar et al., used ball milling techniques to break down sand particles in a distribution has identified the conundrum [3]. No two distributions of sands are exactly the same; further complicating matters are particle type, size and shape. The differences maybe subtle but variability in the rate of breakdown of a sand distribution is always the result. Moreover, in a distribution of sand, the larger particles tend to deteriorate first and faster. In this manner, the larger particles offer protection to smaller particles. This becomes especially difficult to access in wide distributions. Fig. 2 shows the distribution skews as coarser particle breakdown and move onto finer screens in greater proportions from one ball mill cycle to the next.

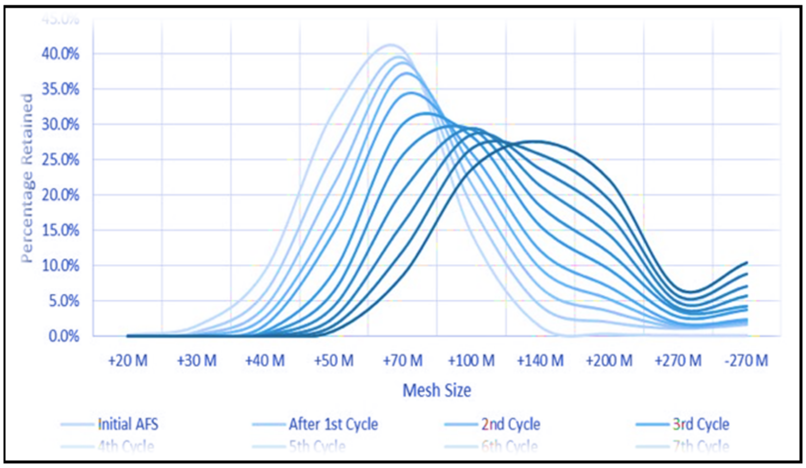


Fig. 2 Screens and Size Changing Simultaneously during Ball Milling of a Sand Distribution

Even more confounding regarding durability in granular media, the attrition rate from abrasion is different from the attrition rate caused by impact. In other words, a hard material is usually brittle but there can be exceptions. This factor was not considered in previous studies.

Laboratory testing to measure the durability of the various granular media was developed to mimic or represent stresses ensued during foundry processing and reclamation. To compare the granular media used in this study, the researchers considered a single screen distribution for a granular media in abrasion and in toughness at ambient and elevated temperature.

The methodology consisted of six major steps:

1. Collecting samples targeting a 55-60 GFN with no more than a three screen distribution from suppliers of the granular media.
2. Samples were split and sized for ambient and elevated temperature treatment.
3. X-ray Diffraction (XRD) chemical characterization of samples as-received and after elevated temperature treatment.
4. Ball Mill Testing (at ambient and at elevated temperature).
5. Abrasion Testing (at ambient and at elevated temperature).
6. Calculating a Pulverization Index

Note: All granular media samples were delivered to WMU in sealed 5 gallon buckets. Sand samples were stored and tested in laboratory conditions. Ambient conditions were controlled: temperature at 20 ± 1 °C and relative humidity at

50 ± 2%.

A. Elevated Temperature Treatment

- Materials: Granular media identified in Table I.
- Equipment: Furnace, Paragon Industries, Part # 50639
- Procedure:

1. 50 g samples of granular media were placed into an alumina crucible.
2. Set furnace to 1300 ˚C.
3. Place samples into the furnace at set temperature for 45 minutes.
4. Samples were cooled to ambient before observations were recorded.

B. X-Ray Diffraction (XRD)

- Materials: Granular media identified in Table I.
- Equipment: Granular media analysis was performed on a Malvern-PANalytical Empyrean XRD instrument (NSF Award # 1626276) in the Materials Science Laboratory, WMU [9]-[11].
- Procedure: XRD was used to ascertain the phase makeup of the granular media as-received and to study the change in compounds that may have occurred at elevated temperatures during heat treatment. XRD is one of the primary techniques used to examine the phase make-up of unknown solids. The experimental data represented as a graph of diffracted intensity vs. angle is compared to the ICSD database [10]. In the XRD powder diffraction technique, a sample is placed in a holder that has zero background and holds the powder securely in place. An incident beam of X-rays with a fixed wavelength (λ=0.1541 nm in this case) is directed at the sample, and the intensity of the diffracted beam is recorded using an X-ray detector. This data is then analyzed for the reflection angle to calculate the inter-atomic spacing (d value in nm, 10^{-9} m). The I vs. 2θ graph is used to compare with the ICSD database and determine the phases present [9]-[11].

Fig. 3 Ball Mill

C. Ball Mill Test

The ball mill testing was used to measure the toughness of the granular media prior to and after the elevated temperature treatment. Foundry sands can experience impact energy during handling, pouring, shakeout and reclamation.

- Materials: Granular media identified in Table I.
- Equipment: Ball Mill, Fig. 3 shows a schematic of the operation if one imagines the jar rotating counterclockwise. Ro-Tap machine with AFS standard sieves and balance accurate to ± 0.01g.
- Procedure:

i. Granular media (50g) - one screen size (e.g. 50 mesh – through 40 on 50 mesh)
ii. Place sample in a ball mill jar with steel balls and seal
– (6) ½” steel ball bearings (28.2 g each)
– (6) ¼” steel ball bearings (7 g each)
iii. Ball mill on high speed for 1 hour
iv. Sieve the pulverized sample for five minutes using the control sieve and a fine pan (e.g. 50 mesh).
v. Record the weight retained on the 50 mesh screen.
vi. Calculate: Pulverization Index (PI) (1):

$$\frac{\text{wt.retained on 50 mesh screen}}{\text{50g}} * 100 = PI \quad (1)$$

vii. Report the pulverizing index for ball milling (PI_B).

D. Abrasion Test

Abrasion testing was used to measure the granular media’s resistance to wear while in contact (rubbing) with other granules and with an abrasive material prior to and after the elevated temperature treatment. Foundry sands can experience abrasion during mulling, shakeout and reclamation.

- Materials: Granular media identified in Table I.
- Equipment: Abrasion Tester, Fig. 4 shows a SWECO Grinding Mill, Model M18-5 equipped with six jars. Ro-Tap machine with AFS standard sieves and balance accurate to ± 0.01g.

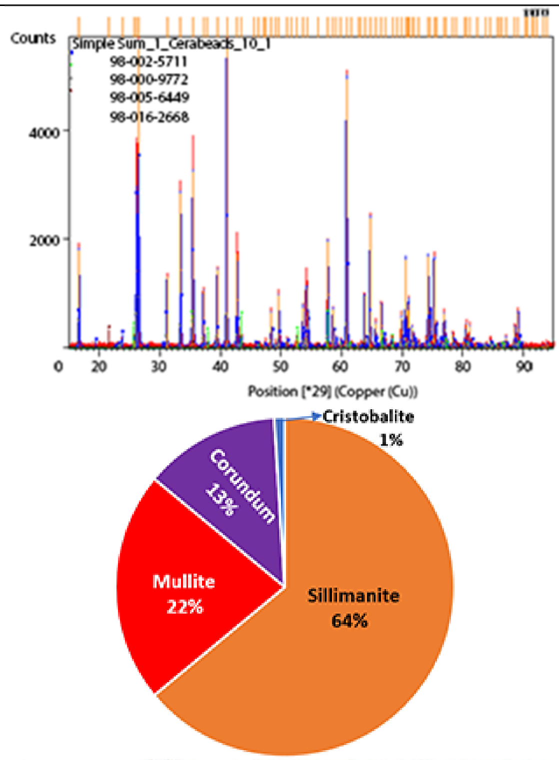
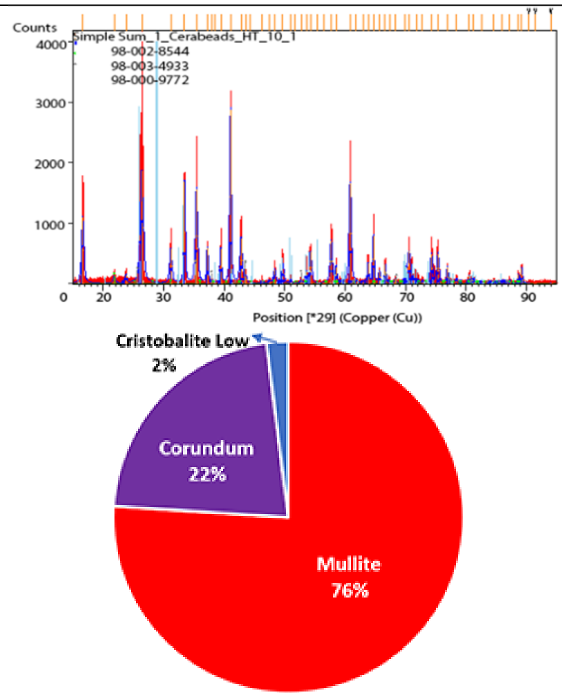
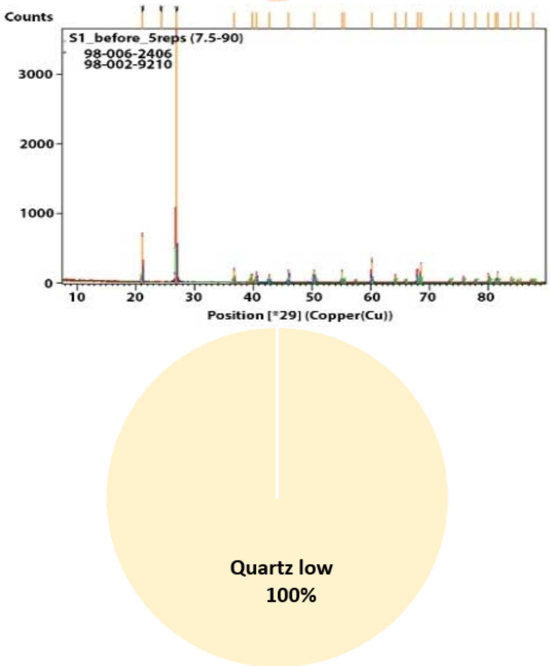
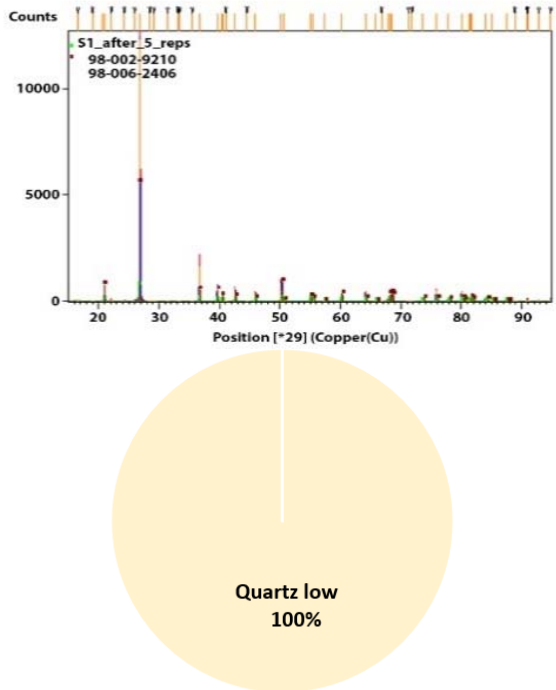
Fig. 4 Abrasion Tester

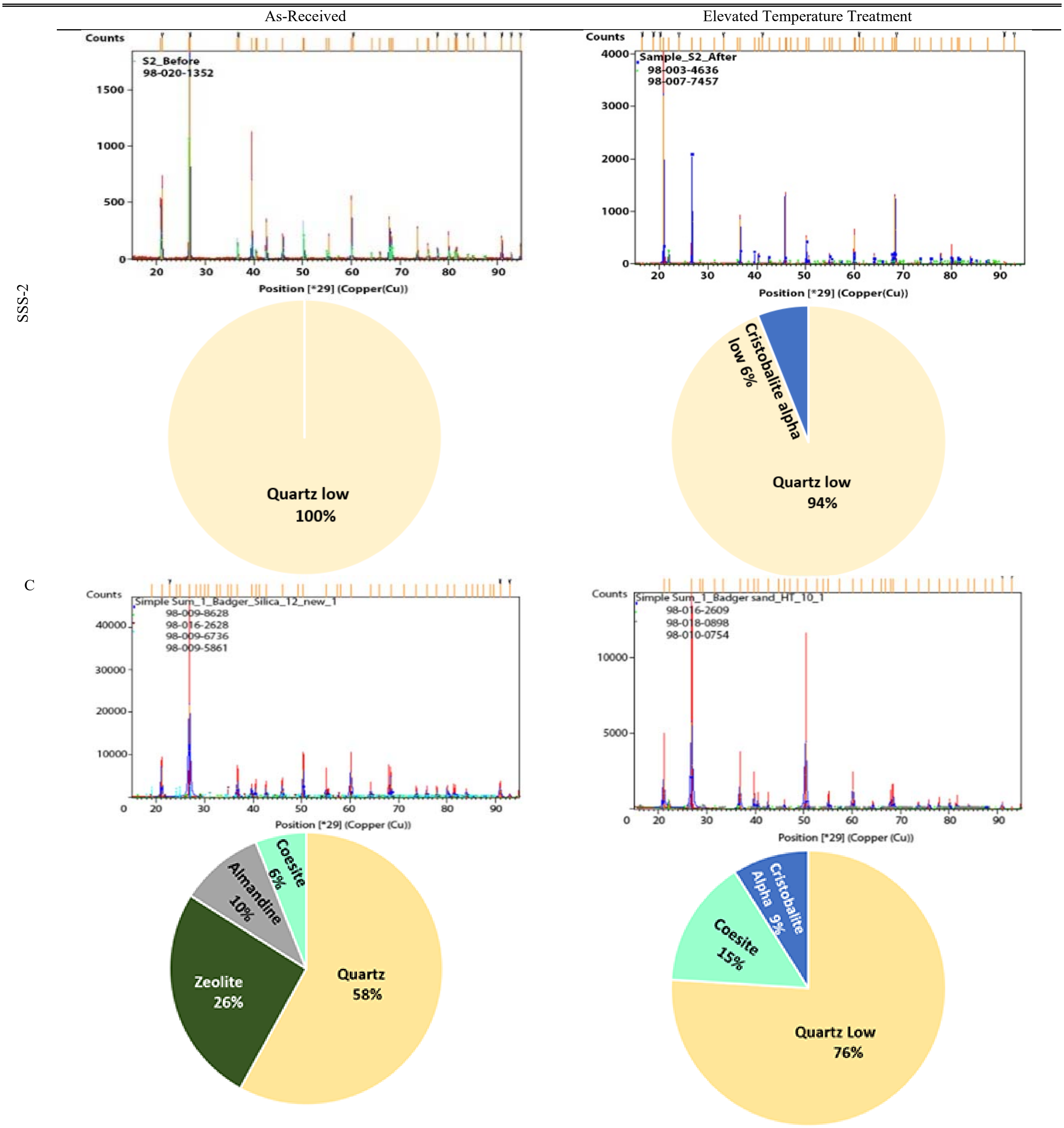
- Procedure:

i. Granular media (50g) - one screen size (e.g. 50 mesh – through 40 on 50 mesh)
ii. Place the sample into the jar (6) with ceramic charge (triangles and cylinders (DURAMEDIA 10, Washington Mills)) (1.36 kg =3 pounds each) and seal.
iii. Vibrate the jars (6) on the machine for 12 hours.
iv. Empty the charge and samples through a coarse screen to separate the charge stone abrasive. Brush the jar and abrasive to ensure complete recovery of test sample.
v. Sieve the pulverized sample on Ro-Top for five minutes using the control sieve and a fine pan (e.g. 50 mesh).
vi. Record the weight retained on the 50 mesh screen.
vii. Calculate: Pulverization Index (PI) (1).
viii. Report the percent passing the specified mesh sieve as the

pulverizing index for abrasion testing (PI_A).

TABLE IV
XRD RESULTS

	As-Received	Elevated Temperature Treatment
B		
SSS-1		



E. Pulverization Index

A durable foundry media must possess both superior toughness and superior wear resistance at both ambient and elevated temperatures. Certain media may be weak in one property and strong in another or vice versa. A mean was used to access the durability of the granular media in both ball milling and abrasion testing and is termed the Pulverization Index. A higher Pulverization Index indicates greater durability and is desirable. The researchers placed no particular weighting on either PI_B or PI_A (at ambient or elevated temperature), but this can be considered by changing the constants in (2).

Calculation of the Pulverization Index (2):

$$(0.25PI_B + 0.25PI_A + 0.25PI_{B^\wedge} + 0.25PI_{A^\wedge}) * 100 \qquad (2)$$

where: PI_B = pulverizing index for ball milling (ambient); PI_A = pulverizing index for abrasion testing (ambient); $PI_{B^\wedge}$ =

pulverizing index for ball milling (elevated temperature); $PI_{A^\wedge}$ = pulverizing index for abrasion testing (elevated temperature)

III. Results

A. XRD

Table IV shows the chemical makeup in the granular media as-received and after elevated temperature treatment. More specifically, diffraction plots pinpointing chemistries and pie charts identifying the predominant compounds by percentages for each granular media are presented as-received and after elevated temperature treatment. Interestingly, for certain granular media studied different compounds formed after an elevated temperature treatment. The majority of resulting compounds formed in the various granular media after elevated temperature treatment are renowned for hardness (Corundum, Mullite, Cristobalite). It was interesting to see that SSS-1 and SSS-2 showed the least change in chemical composition from ambient to elevated temperature treatment.

TABLE V
PULVERIZATION INDEX

	Ambient Temperature		Elevated Temperature Treatment		
Granular Media	Abrasion Test (PI_A)	Ball Mill Test (PI_B)	Abrasion Test (PI_A*)	Ball Mill Test (PI_B*)	Pulverization Index
B	95	22	91	22	58
SSS-1	86	12	84	10	48
SSS-2	96	15	96	16	56
C	96	17	80	23	54

B. Pulverization Index

Table V shows that various granular media performed differently in wear and toughness at both ambient and after elevated temperature treatment. At ambient, the control silica sand C and SSS-2 had superior wear resistance but was weaker in toughness compared to B. Interestingly, the control sand C showed lowest abrasion resistance and highest toughness after elevated temperature treatment. SSS-2 maintained superior wear resistance after elevated temperature treatment. Table V shows the Pulverization Index determined for all granular media; with a higher Pulverization Index indicating greater durability. The durability among B, SSS-2 and C are similar.

IV. Limitations

This study focused on just four granular media that can be used in the foundry industry, while there are many more media that can be investigated.

V. Conclusion and Recommendations

The Pulverization Index of foundry granular media is not sufficient information to make decisions concerning foundry processing. Apart from material cost, factors involving the sand moldability, sand casting quality and surface finish need to be considered. An elevated temperature treatment of 1300˚C affected the chemical composition of certain granular media studied as predominately harder compound formed. This research reinforces that casting process temperature and reclamation process temperature significantly affects granular media. This study shows that the durability among a synthetic ceramic sand (B), a US foundry silica sand (C) and a Saudi silica sand (SSS-2) are similar in durability for foundry processing and reclamation. The Saudi silica sands can compete with contemporary granular media for foundry processing, should they be washed and screened for removal of fines.

Acknowledgments

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