The role of purity level in foundry silica sand on its thermal properties

Judit Svidró¹, József Tamás Svidró¹ and Attila Diószegi¹

¹Department of Materials and Manufacturing, Jönköping University School of Engineering, P.O Box 1026 SE-551 11 Jönköping, Sweden

E-mail: judit.svidro@ju.se

Abstract. Silica sand is the most commonly used mineral for molding and core making applications in foundry technology due to its availability, thermal and chemical attributes. However, there are many additional requirements foundry sands need to meet regarding their sizing, chemical purity, physical durability and thermal properties. This research studies the thermophysical properties of a foundry silica sand comprehensively. After separating one sand batch into numerous grain size ranges, the chemical composition and thermophysical properties of the fractions were investigated, respectively. By means of this approach, the chemical properties and thermal behavior can be directly linked. The silicon dioxide content shows a strong correlation with the thermal expansion properties of the various fractions. The results give a better understanding of the high temperature behavior of foundry silica sands and clarify the role of factors affecting their thermophysical properties.

1. Introduction
In the metal casting process, molten metal is poured into a mold cavity that is the negative of the cast part. Internal cavities in the cast part are produced by cores. Expendable molds and cores consist of three main components: granular aggregate material, suitable bonding agent that bonds the particles together and additives which aim to improve the performance of molds and cores and also the quality of the final product. The major component is the aggregate material, which is between 84 to 98 m/m% of the molding mixture. There are many restrictions regarding their different attributes that make natural and artificial aggregates suitable for foundry purposes. They must be chemically inert with molten metals and compatible with binder systems, dimensionally and thermally stable at elevated temperatures, evolve limited volatiles upon heating, and have consistent composition, pH and suitable granulometric properties [1]. Foundry sands consist of 2-3 major and several minor grain size fractions in the range 0.063 to 1mm. The selection for the most part is based on their average grain size. But consistent particle size distribution is crucial to achieve maximum performance and efficient operations. Its role is well known; the grain size distribution of the aggregate determines its binder demand, the compactibility and permeability of the molds, etc. The most common aggregate in use is silica sand. When referring to silica sand as molding material, we define it as the mineral quartz. Some of its many advantages are its worldwide availability and low cost. It is required to contain approx. 95% SiO₂, which composition is determined to the batch.

The relationship between grain size distribution and thermal properties like thermal expansion is commonly studied in foundry research both on unbonded and bonded sand samples [2-6]. From the metal/mold interface, the layers of the mold heat up to a range of temperatures, due to the relatively
low thermal conductivity of the porous mold. Therefore, the rate of expansion is different based on the distance from the casting. This can lead to mold deformation and can cause casting defects such as rattail, buckles, and veining [1]. Previous authors found clear connection when expansion increased as grain size increased [4, 5]. However, this correlation is generally explained purely on the basis of the physical size difference of the fractions and neglects the state of chemical composition.

The thermophysical properties of molding materials play significant role in the solidification process of the cast parts. Attributes like specific heat determine the cooling capacity of the mold, e.g. the amount of heat it can absorb and conduct from the molten metal to the surrounding [7]. The present study attempts to shed new light on the relation between chemical and thermal attributes through a comprehensive study of a foundry silica sand.

2. Materials and methods

2.1. Investigated materials

A medium spherical, sub-angular shaped foundry silica sand shown in figure 1 was studied in this work. This grade contains two major fractions in the size range of 0.18 to 0.355mm and several minor fractions spread in the whole size range between 0 and 1 mm. The exact grain size distribution is found in table 1 and the bar chart and the cumulative curve is shown in figure 2.

Figure 1. Image of the studied silica sand captured by optical microscope

Figure 2. Grain size distribution chart of the investigated silica sand

| Sieve opening (mm) | Percent retained on sieve (%) | Cumulative percent passing (%) |
|--------------------|-------------------------------|-------------------------------|
| 0,02               | 99,98                         |
| 0,71               | 99,94                         |
| 0,5                | 99,84                         |
| 0,355              | 95,85                         |
| 0,25               | 34,02                         |
| 0,18               | 9,6                           |
| 0,125              | 0,8                           |
| 0,09               | 0,15                           |
| 0,063              | 0,01                           |
| 0 (PAN)            | 0                              |
2.2. Analysis methods
All the analyses were performed on sand samples without binder. The chemical composition of the silica sand was determined by wavelength dispersive X-ray fluorescence spectroscopy. The sand samples were powdered, mixed with lithium tetraborate/metaborate mixture flux and heated to 1250°C. Glass discs were made of the melt and analyzed. The thermal expansion properties were measured in a horizontal dilatometer. The unbonded sand samples were placed in a cylindrical sample holder made of aluminum-oxide. The ends of the cylinder were closed by free-moving aluminum-oxide plugs. The sand samples were compacted by vibration. The volume change was registered while the samples were heated by 10K/min rate to 1100°C and during cooling back to room temperature with the same rate. Three test pieces were prepared and measured from each sample; the results shown are the average of the three measurements. The specific heat was determined by differential scanning calorimetry. The measurement settings were the same as those for dilatometry.

2.3. Chemical composition of the investigated silica sand
The average chemical composition, pH and loss on ignition (referred to as LOI – which represents the volatile materials lost during heating) determined regarding the sand batch presented above is found in table 2. This is a high-purity foundry sand with more than 99% silicon dioxide, 0.5% aluminum-oxide, 0.18% titanium dioxide and 0.09% iron-oxide content.

| Constituent (% | pH (%) | LOI (%) |
|----------------|--------|---------|
| SiO₂           | >99    | 0.09    |
| Fe₂O₃          | 0.500  | 0.180   |
| Al₂O₃          | 0.003  | 0.020   |
| TiO₂           | 0.005  | 0.004   |
| Na₂O           | 7.09   | 0.09    |
| K₂O            |        |         |
| CaO            |        |         |
| MgO            |        |         |

In the next step the sand was separated by sieving and the fractions were investigated respectively. Table 3 contains the chemical composition of the various grain sizes in the studied silica sand. There is a significant difference in the composition and the silicon dioxide content of the fractions. The fine range F1 contains 43.58% silicon dioxide, less than half of the average level. The purity of the samples is improving by increasing grain size, the ranges above 0.25mm contain more, than 99% SiO₂. The amount of other constituents is clearly higher in the finer ranges; titanium dioxide, aluminum oxide and iron(III) oxide have the highest levels.

| Sample ID | Grain size range (mm) | SiO₂ | Fe₂O₃ | Al₂O₃ | TiO₂ | Na₂O | K₂O | CaO | MgO | ZrO₂ |
|-----------|-----------------------|------|-------|-------|------|------|-----|-----|-----|------|
| F1        | 0.09 – 0.124          | 43.58| 11.471| 10.661| 29.718| 0.209| 0.165| 0.075| 0.531| 1.849|
| F2        | 0.125 – 0.179         | 95.34| 0.572 | 2.450 | 1.072 | 0.048| 0.057| 0.015| 0.102| 0.052|
| F3        | 0.18 – 0.249          | 98.50| 0.128 | 0.947 | 0.110 | 0.019| 0.040| 0.008| 0.039| 0.007|
| F4        | 0.25 – 0.354          | 99.53| 0.020 | 0.216 | 0.020 | 0.003| 0.026| 0.005| 0.010| 0.004|
| F5        | 0.355 – 0.49          | 99.38| 0.054 | 0.217 | 0.014 | 0.006| 0.037| 0.006| 0.062| 0.003|
| F6        | 0.5 – 0.71            | 99.24| 0.069 | 0.366 | 0.018 | 0.009| 0.048| 0.007| 0.047| 0.003|
3. Results and discussion
Properties of the original sand samples containing all the fractions were investigated first. The results of thermal expansion and specific heat measurements are shown in figure 3 and 4. Silica sand in general has high thermal expansion compared to all other types of foundry sands, like olivine, chromite or zircon. This is due to the phase transition of silicon dioxide that takes place at approx. 573°C when α-quartz transforms to β-quartz. The changes in crystallographic structure lead to changes in the specific density, so expansion of the grains occurs. [1] It means around 2,25% for the studied sand samples containing all the grain size ranges in the ratio presented in table 1. The phase transition is accompanied by heat absorption, which is indicated by the endothermic peak visible on the specific heat curve in figure 4.

![Figure 3. Average thermal expansion of the studied silica sand as a function of temperature](image)

![Figure 4. Specific heat of the studied silica sand as a function of temperature](image)

The results shown in figure 3 and 4 represent the properties of the whole sand batch as it is used for mold and core making. However, to understand how the behavior of such granular structure builds up, one needs to distinguish the attributes of each component. Thermal expansion of the various grain size ranges was measured separately and is shown in figure 5 (a)-(f). The degree and the characteristics of expansion are different for the various grain size ranges. The peak expansion caused by the phase transition of quartz is the lowest for sample F1 and increases with the increase of grain size. When looking at the peak expansion of samples F1 to F6, it is in correlation with their silicon dioxide content. Volume change during cooling may differ, since these samples consist of unbonded grains which are able to move on each other. The grains may rearrange during expansion, so their order also changes when shrinking. This phenomenon is affected by the shape and size of the grains in the system.
Figure 5. Thermal expansion of the studied silica sand fractions as a function of temperature

The specific heat of the studied silica sand fractions also shows significant differences as the samples with lower silicon dioxide level have lower peak areas. Besides the reversible transition of quartz at approx. 573°C, other reactions take place. An endothermic peak at approx. 950°C can be observed in the specific heat curves of samples F1, F2 and F3 with a tendency to decrease. On the results of samples F4, F5 and F6 it is not visible. The three constituents following the same trend are TiO$_2$ with 29.718% in F1, 1.072% in F2 and 0.110% in F3 samples, Fe$_2$O$_3$ with 11.471% in F1, 0.572% in F2 and 0.128% in F3 samples and Al$_2$O$_3$ with 10.661% in F1, 2.450% in F2 and 0.947% in F3 samples. Identifying what phase transition takes place at this temperature range requires further studies.
Figure 6. Specific heat of the studied silica sand fractions as a function of temperature

4. Summary and conclusions

Aggregates are the major components of sand molds and cores; therefore, their granulometric and thermal properties affect the quality of the final product significantly. Thermal expansion of the aggregate may result in casting surface defects and its specific heat determines the heat absorbing capacity of a mold. Latter has importance also in modeling and simulation of the solidification process. The chemical composition is usually determined with regard to the whole sand batch as it is used for mold making. However, thermal properties of foundry sands are common topics of foundry research, they are rarely connected with the purity of the aggregate material. The aim of the present research was to examine the correlation between chemical composition and thermal properties by studying the components of a silica sand separately. The investigation has identified the deviation in chemical composition of the different grain size ranges of a silica sand. The results clearly indicate direct correlation between the silicon dioxide content and the peak expansion and specific heat of the studied grain size fractions. The findings of this work complement those of earlier studies with a new understanding on the reasons behind the phenomena. This research has important practical implication as well. It points to the fact that suppliers have a wide variety of foundry sands from the same quarry, with the same average composition; the only difference is the average grain size, so the grain size distribution of the sands. However, the amount of the various size ranges is relevant not only because of their effect on the permeability or the binder demand, but also because of their effect on the thermal properties. Higher amount of fines decreases the expansion due to their lower silicon dioxide content and also changes the thermophysical properties significantly as unexpected phase changes may take place in them. A further study could clarify these transitions and assess the effects of other elements in the silica sand, also regarding other aspects of the casting manufacturing process.
Acknowledgement
The present work was co-funded by the Regional Development Council of Jönköping County, Sweden and Jönköping University. The cooperating parties in the project were Jönköping University, AB Bruzaholms Bruk, Valmet AB, Sandvik SRP AB and Sibelco Nordic AB. The participants from these institutions and companies are gratefully acknowledged.

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