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Characterization of Silica in sandstone rocks for Advanced Energy Applications

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Abstract – *Silica (SiO_2), represents a main component used in various applications such as the manufacture of photovoltaic cells and fiberglass. Despite this importance, the use of silica in Algeria remains limited due to the quality of the material or unknown for some deposit. In this work, we carried out an in-depth characterization of the siliceous sandstone samples, using various advanced qualitative and quantitative characterization techniques of metallographic microscope, granulometric analysis, DRX and XRF. The results showed that the different characterized samples have a fairly silicon dioxide (SiO_2) purity of 89.15 % at 250-400 µm of size with the presence of different types of defects, namely mineral inclusions of clay and oxide minerals. The presence of impurities, in particular iron and aluminum, limit the use of this silica for the production of advanced materials.*

Keywords: Silica, sandstone, characterization, photovoltaic, energy.

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I. Introduction

Quartz sandstone, a widely distributed sedimentary rock, is gaining attention as a potential raw material for high-value industrial applications due to its significant silica (SiO_2) content. Silica serves as the cornerstone for producing silicon, a critical component in advanced technologies such as photovoltaic (PV) solar cells. However, for sandstone to be considered viable in these applications, stringent requirements must be met, including ultra-high silica purity and minimal impurity content. The studied sandstone, characterized by its 89.15% silica content in specific granulometric fractions, presents a promising foundation for exploration. This research investigates the material's properties, its potential for refinement, and its suitability for contributing to emerging technologies, particularly in the solar energy sector, where material efficiency and purity are paramount.

The demand for high-quality raw materials is increasingly critical for advancing modern technologies and transitioning to sustainable energy solutions. Among these materials, high-purity quartz holds particular significance due to its applications in high-tech industries, including the manufacturing of photovoltaic (PV) solar cells, semiconductors, and optical fibers. Crystalline silicon, derived from silica (SiO_2), remains the foundation of PV technology, driving global efforts to identify and enhance natural silica resources to meet the stringent purity standards for solar-grade silicon (SoG-Si). Typically found in quartz, sandstone, and sand deposits, silica undergoes a carbothermal reduction process to produce metallurgical-grade silicon, which is then refined for PV applications [1].

Recent research has explored silica-rich materials from various geological sources, including Hoggar quartz, Bechar sand, and Jijel sandstone, reporting promising purity levels ranging from 89% to 99.4% SiO_2. While these materials show potential for silicon production, enrichment processes are essential to achieve the ultra-high purity required for PV-grade applications. Advanced analytical techniques such as X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM) have proven invaluable in assessing the mineralogical and chemical properties of these materials. These methods facilitate the detection of impurities and morphological defects, providing insights into their suitability for further processing [2,3].

This study aims to characterize quartz sandstone as a potential raw material for silicon production. By examining its physical, chemical, and mineralogical properties, we evaluate its suitability for PV applications and propose enrichment strategies to meet industry requirements [4].

The optimization of oil recovery techniques is a cornerstone of modern energy production, addressing the challenges posed by declining reservoir performance and increasing global demand. Low-salinity water (LSW) injection has emerged as an effective enhanced oil recovery (EOR) technique. However, interactions between LSW and sandstone formations can lead to issues such as fines migration and formation damage. To counteract these drawbacks, incorporating silica nanoparticles (SiNPs) into LSW injection has shown significant promise. SiNPs enhance adsorption, stabilize the rock matrix, and minimize mineral dissolution, thereby improving recovery efficiency and reservoir integrity [5].

The role of silica nanoparticles extends further into surfactant-enhanced recovery. By improving the adsorption behavior of surfactants on sandstone surfaces, nanosilica-based formulations increase adsorption density and stabilize chemical stimulation processes. This synergy between nanotechnology and traditional EOR methods is particularly beneficial in conventional oil reservoirs, where adsorption isotherm modeling aids in optimizing the process [6].

Silica nanofluids have also demonstrated their potential as a tertiary recovery method, particularly in post-primary recovery scenarios. Experimental studies highlight their effectiveness in improving oil recovery after water flooding, with optimal performance achieved at specific SiNP concentrations. These environmentally friendly solutions represent a critical step forward in sustainable oil recovery [7].

In geotechnical and structural applications, sandstone formations continue to play a pivotal role. For instance, weathered sandstone used in climbing geosites has been studied for its interaction with expansion rock anchors. The physical degradation of sandstone due to weathering necessitates frequent maintenance to ensure anchor safety, emphasizing the importance of understanding rock integrity under variable conditions [8].

The convergence of nanotechnology and material science has significantly impacted well integrity. Nano-silica (NS) incorporation into cementitious materials for oil and gas wells has resulted in enhanced mechanical performance, particularly in the interfacial transition zone (ITZ). This densification improves tensile strength and ensures long-term stability under challenging downhole conditions [9].

Moreover, insights into the interactions between coal seams and neighboring tight sandstone reservoirs have expanded the understanding of unconventional gas resource development. Organic acids generated during coal hydrocarbon formation enhance the pore structure and reservoir quality of tight sandstones through dissolution and precipitation processes. These findings pave the way for more efficient development of coal measure gas fields [10].

Lastly, advancements in seismic prediction techniques have linked elastic properties to the diagenetic facies of tight sandstone formations. Sensitive seismic parameters such as p-wave impedance and porosity are now recognized as critical for distinguishing diagenetic facies, enabling more precise reservoir characterization and exploration in sparsely drilled regions [11].

This work is initially focused on the optical and mineralogical characterization of studied sandstone. In another part, a series of XRD and X-ray fluorescence tests was carried out on sandstone samples in order to evaluate and determine the impurities found in the rock.

II. Materials and Methods

The present study involved comprehensive investigations employing a range of advanced characterization techniques to analyze the siliceous sandstone samples [2]. These techniques included metallographic microscopy, X-ray fluorescence (XRF) using a RIGAKU instrument supported by the Centre de Recherche et d’Analyses Physico-Chimiques (CRAPC), X-ray diffraction (XRD) with a PANalytical instrument supported by the Centre d’Études et de Services Technologiques de l’Industrie des Matériaux de Construction (CETIM), and granulometric analysis through sieving, conducted at the École Nationale Supérieure des Sciences de la Mer et de l’Aménagement du Littoral (ENSSMAL).

X-rays, a form of electromagnetic radiation with wavelengths between 0.01 and 10 nanometers, were central to the XRF and XRD techniques used in this study. Their ability to penetrate solid materials and interact with matter at the atomic level makes them indispensable for material characterization.

Metallographic microscopy was used to observe the microstructural features of the samples, revealing key physical attributes such as surface characteristics and potential defects.

X-ray fluorescence (XRF) measured the characteristic secondary X-rays emitted by the samples upon excitation, providing quantitative data on their elemental composition and impurity levels. This analysis was performed using a RIGAKU instrument at CRAPC.

X-ray diffraction (XRD) analyzed diffraction patterns generated when X-rays interacted with the atomic lattice of the samples, offering insights into their crystalline structure and phase composition. The PANalytical instrument used for this analysis was supported by CETIM.

Granulometric analysis, conducted at ENSSMAL, determined the particle size distribution through sieving. This method provided information about specific size fractions, enabling the identification of optimal size ranges for potential industrial applications.

III. Result and discussion

This study focuses on the characterization of silica sandstone from the Kabylian region. The results reveal significant details regarding the mineralogical and chemical composition of the rock, which are crucial for determining its suitability for various industrial applications.

III.1. Macroscopic Study

The silica sandstone collected from the Kabylian region is massive and very hard, with a grayish color. The grains that make up the rock are small in size but visible, and predominantly consist of vitreous quartz grains. It associates of some iron oxide minerals with a reddish hue (Figure.1).

Figure 1. Studied quatzose silica of sandstone

III.2. Mineralogical Characterization (Microscopy and X-ray Diffraction)

Microscopic analysis of the siliceous sandstone samples revealed that the primary mineral constituent is quartz, which dominates the overall composition. The quartz grains exhibit varying degrees of angularity, indicative of moderate transport and sedimentary processes. Alongside quartz, the analysis identified notable inclusions, including oxidized biotite (Figure 2.a) and iron oxides (Figure 2.b). These inclusions provide evidence of secondary processes, such as chemical alteration and oxidation, likely resulting from prolonged exposure to environmental factors, including moisture and oxygen over time.

Trace amounts of metallic minerals were also observed, typically occurring in well-defined cubic forms, suggesting their crystallization under specific geological conditions. Additionally, accessory minerals such as muscovite and zircon were identified in minor quantities. Muscovite, a silicate mineral, adds to the textural complexity of the rock, while zircon, known for its resistance to weathering, serves as a geological marker, indicating the sandstone's provenance and thermal history.

The rock’s evidence of alteration and oxidation reflects its dynamic geological history, including potential exposure to oxidizing conditions during diagenesis or surface weathering. This mineralogical diversity and alteration further underscore the sandstone's complexity and offer insights into its formation processes and potential applications.

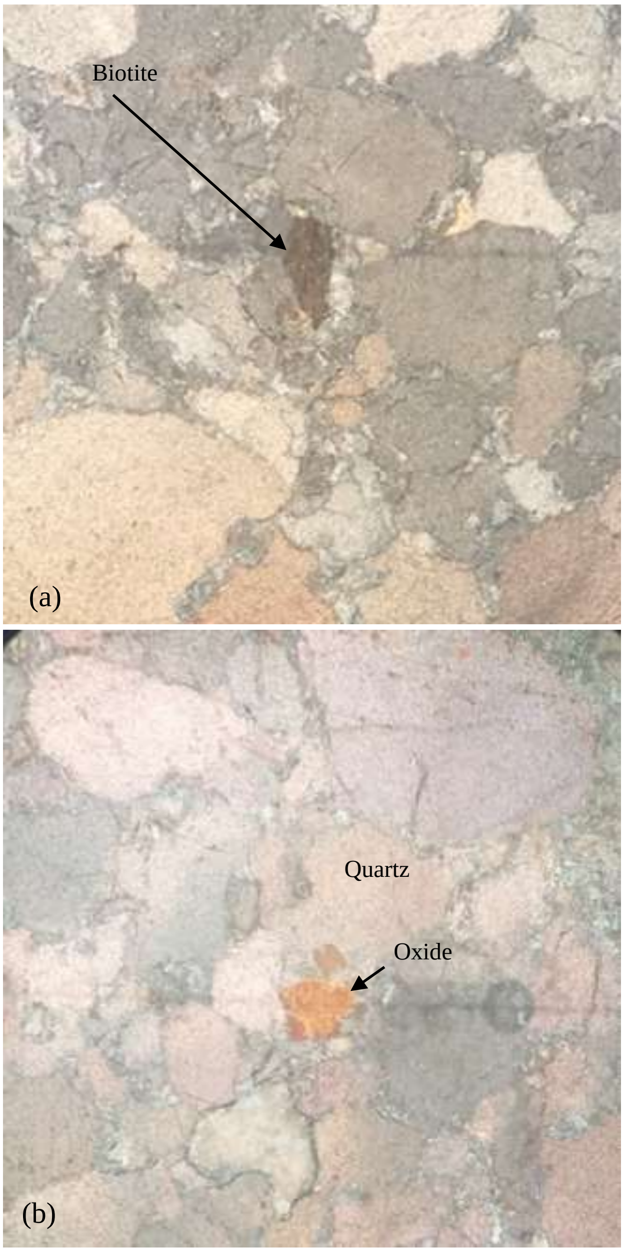

Figure 2. Microscopic observation (a) Sandstone with biotite, (b) sandstone with oxide (LPA)

The X-ray diffraction (XRD) pattern of the analyzed siliceous sandstone confirms the dominance of quartz as the primary mineral phase. Distinct and sharp diffraction peaks at characteristic 2θ positions, such as 20.9°, 26.6°, 36.5°, 39.4°, 42.5°, 50.1°, and 59.9°, are consistent with the crystallographic planes of quartz, indicating its high crystallinity. The intensity of these peaks, particularly the prominent peak at 26.6°, reflects the significant abundance of quartz in the sample as shown in Figure 3.

The absence of notable peaks corresponding to other crystalline phases suggests that the sandstone is largely composed of quartz, with minor contributions from accessory minerals such as muscovite and zircon, which may not be detectable in this XRD pattern due to their low concentrations. Furthermore, the baseline noise remains low, signifying minimal amorphous content or poorly crystalline phases in the sample.

The data corroborates microscopic observations, which highlighted quartz as the predominant mineral along with minor inclusions of iron oxides and trace metallic minerals. The high crystallinity of quartz observed in this analysis further underscores the sandstone's suitability for potential industrial applications, such as in the production of glass or as a raw material for silicon extraction, though the presence of impurities like iron and aluminum may require additional refinement steps.

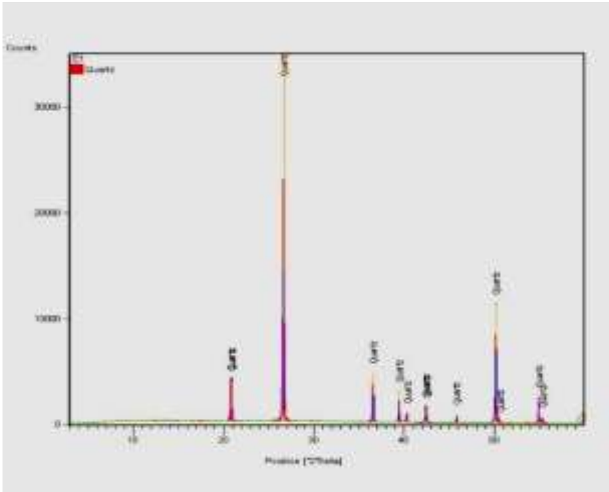

Figure 3. XRD Pattern of Siliceous Sandston

III.3. Granulometric Analysis and Chemical Composition (X-ray Fluorescence Analysis)

After crushing, grinding, and sieving, the granulometric analysis indicates that the quartz grains in the sandstone range from +800 µm to -100 µm in size (Figure 4). The granulometric analysis reveals the following characteristics:

- **Intact Quartz Grains**: These grains exhibit a distinct morphology, with clearly defined facets and sharp edges, giving them a vitreous appearance. A fine layer of silica powder is often observed to percolate on the surface of these quartz grains, indicating that the grains remain largely unaltered during processing.
- **Presence of Iron Oxides**: Iron oxide particles are observed adhering to the surface of quartz grains or dispersed throughout the sample. This suggests chemical interactions that have occurred within the

geological environment, potentially influencing the overall composition of the sandstone.

To further investigate the composition, X-ray fluorescence (XRF) analysis was performed on different particle sizes of the grinded sandstone to determine the silica content of the various fractions. The coarser fractions, particularly those above 800 µm, were observed via morphoscopy to be predominantly composed of intact quartz grains, which contain 85.97% SiO_2. This high silica content is characteristic of materials that are suitable for applications requiring larger particle sizes.

In contrast, the finer fractions, particularly those below 100 µm, were found to consist primarily of silica powder, containing 85.20% SiO_2. Among all the granulometric fractions, the range between 250 and 400 µm exhibited the highest silica content, reaching 89.15% (Table 1). This suggests that intermediate-sized particles offer the highest concentration of silica, which may have specific advantages in certain applications where fine silica content is crucial.

Additionally, the digital happiness aspect of this analysis is reflected in the precise and efficient determination of the material's characteristics through advanced analytical techniques. The integration of digital tools, such as XRF analysis and morphoscopy observation, has significantly enhanced the accuracy and speed of the granulometric and compositional evaluation, contributing to more informed decisions for industrial applications. The ability to obtain detailed information on the material’s composition and particle size distribution offers a level of convenience and certainty that contributes to the broader goals of optimizing material selection for various purposes, further emphasizing the digital transformation in material science.

Table 1. Granulométric size

Granulométric size (µm)	SiO_2 (%)
+800 µm	85.97
630-800µm	79.26
400-630 µm	84.81
250 -400 µm	89.15
160-250 µm	86.12
140 -160 µm	85.12
100 -140 µm	85.06
-100 µm	85.20

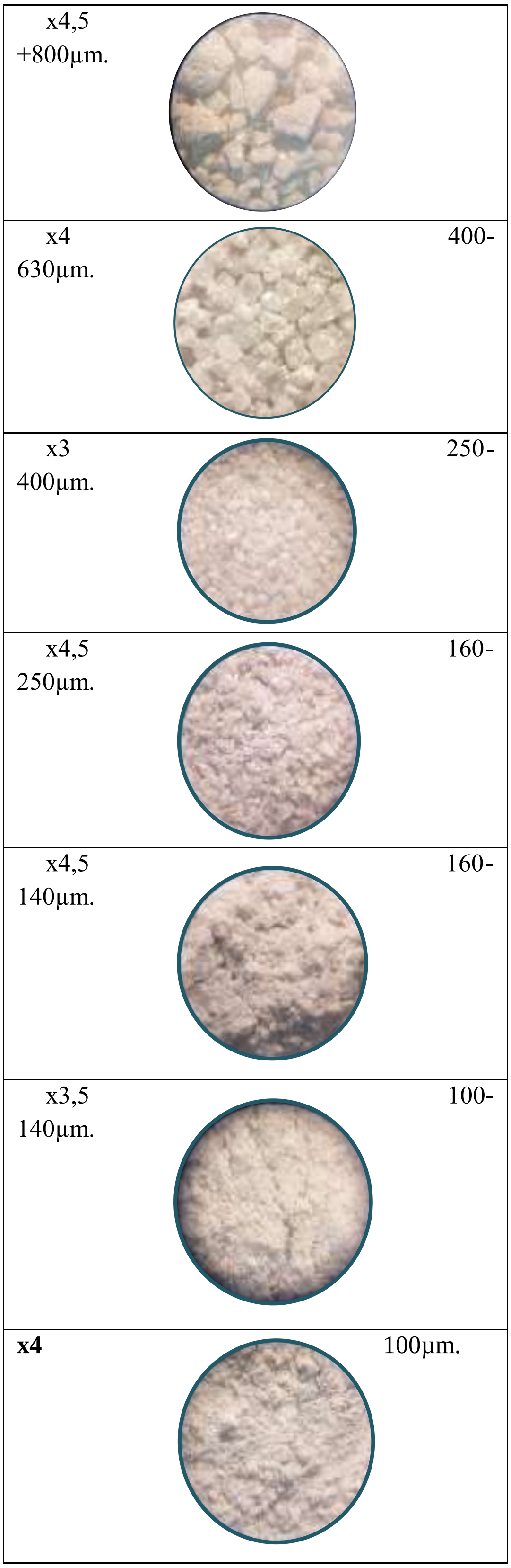

Figure 4. Microscopic observation of different granolumetric size of sandstone

The X-ray Fluorescence (XRF) results show that the silica content in studied samples was quite high, However, the presence of iron oxides (Fe_2O_3), alumina (Al_2O_3), and trace amounts of titanium oxide (TiO_2) and potassium oxide (K_2O).

Fe_2O_3, Al_2O_3 and K_2O are associated with oxide and clay minerals are present in small amounts but could be problematic for applications requiring high purity, such as in electronics or high-quality glass as shown in Table 2.

Type of application	Other elements (Maximum %)	Other elements (maximum ppm)
Clear glass grade sand	0.5	5.000
Semiconductor filter, LCD and optical glass	0.2	2.000
Low grade “high purity quartz”	0.05	500
Medium grade “high purityquartz”	0.1	100
High grade “high purityquartz”	0.003	30

Table 1.Typical silica sand and quartz specifications by market (source: Richard Flook) in
“High grade”, high purity quartz with <30 ppm is the standard high purity material produced by Unimin Corp. and TQC at Spruce Pine.

Note 1: Specific other elements may be limited by application, e.g. Fe_2O_3<100 ppm for float gases and <40 ppm for low iron gloat gases

Note 2: Generally “high purity” quartz has Fe_2O_3 <15 ppm, Al_2O_3<300 ppm and alkali earth oxides <150 ppm

Note 3: In some applicationsAl2O3can substitute forsome SiO_2e.g up to 1.5% Al_2O_3 in float glass.

Note 4: Limits can vary according to the composition of other row materials in the application.

III.4. 5. Comparison with Similar Studies

The results of this study were compared with previous work on silica sandstones from the El Aouana region. In a similar investigation, magnetic separation and lixiviation techniques were employed to reduce the iron oxide content [1] [3] [4] [8]. This is significantly lower than the levels observed in the current study, suggesting that further refinement of the enrichment process could reduce clay and iron contamination to acceptable levels for high-purity applications.

IV. Conclusion

The characterization of the studied sandstone reveals that it is predominantly composed of quartz with moderate silica content. X-ray fluorescence (XRF) analysis highlights that the granulometric fraction between 250 and 400 µm exhibits the highest silica content, reaching 89.15%, surpassing the silica content of both coarser and finer fractions. This finding indicates that this specific size range holds significant potential for industrial applications where relatively high silica purity is essential.

The presence of associated impurities, including iron oxides, aluminum oxides, and other fine particles, poses a limitation for high-end applications that demand ultra-pure silica. These impurities can interfere with the desired properties and performance of the sandstone in advanced industrial processes, such as glass manufacturing, ceramics, and silicon-based technologies.

Despite these challenges, the results suggest that enrichment techniques could be developed and applied to improve the purity of the sandstone. Methods such as chemical leaching, magnetic separation, or advanced flotation processes can be employed to effectively reduce the levels of associated impurities, enhancing the quality and applicability of the material. Such advancements in purification strategies would not only unlock the full potential of this sandstone deposit but also expand its usability in high-value applications.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

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