Evaluating the Chemical Composition and Quality of Magnesite Ore in the Sró Area, Gia Lai Province, Vietnam

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Received: 23 January 2024
Accepted: 13 May 2024
Published: 30 June 2024

Abstract
Magnesite plays a crucial role in various industrial sectors, particularly in the manufacturing of refractory and insulation materials. The objective of this study is to analyze the characteristics of the composition and quality of magnesite ore in the Sró area of Gia Lai Province, Vietnam. To evaluate the composition and quality of magnesite ore in the Sró area, the study collected and analysed: 1,642 samples for basic chemical analysis of rock are taken from drill cores of magnesite ore bodies, 3 technological experimental samples in the laboratory, some thin-section petrographic analysis, X-ray diffraction, and differential thermal analysis samples. The results showed that these ores have a metamorphic sedimentary origin. The main component of the ore is magnesite (average 70-85%); followed by dolomite, calcite, chlorite, and talc. Overall, the magnesite ore in the Kong Queng area belongs to the category of ores with average to good quality with an average MgO content of 37-38%.

Keywords: Raw material base; Refractory materials; Thermal treatment; Mineralogical composition; Ceramics and composites.

1. Introduction
Magnesite is a mineral resource essential for various industrial sectors (Wu et al., 2021). The primary fields utilizing magnesite ore include the production of refractory materials, abrasive materials, insulation and soundproofing construction materials, as well as the manufacturing of magnesium metal, magnesium sulfate, medicinal products containing magnesium (Bilge et al., 2017; Shand, 2006; Zhaoyou et al., 2005). Furthermore, it is employed in the production of paper, rubber, high-speed highway concrete, viscose fiber, fertilizers, and ceramics (Alhaddad and Ahmed, 2022; Najim, 2021; Shand, 2006; Wu et al., 2021). Approximately 90% of magnesite serves the refractory material industry. It is apparent that the demand for magnesium refractory materials in Vietnam is significant, particularly within the steel industry, non-ferrous metallurgy, and cement, despite the fact that this resource is predominantly imported.

In recent years, Vietnam has discovered the Kong Queng magnesite deposit in the Central Highlands, which possesses a fairly large reserve and relatively good quality (Minh et al., 2004; Thiet et al., 2010). Exploration results from the Geological and Mineral Resources Corporation have determined the magnesite ore body in the form of layers and pseudostrata lying within the Phong Hanh Formation, metamorphosed carbonates aged Cambrian-Silurian (€- Sph1), irregularly covered by strata belonging to the Mang Yang Formation, with an intermediate Triassic age (T2 my) (Minh et al., 2004;
Thiet et al., 2010). According to the National Technical Standards of Vietnam (General Department of Geology and Minerals, 2012), the reserve of magnesite ore in ore body 1 is 23,575,535 tons of grades 121 + 122. Of this, grade 121 amounts to 5,772,176 tons, grade 122 amounts to 17,803,359 tons, and the resource at grade 333 is 8,393,479 tons. The associated dolomite reserve (interlayer in ore body 1) amounts to 3,650,566 tons, of which grade 121 is 1,438,711 tons and grade 122 is 2,211,855 tons. The dolomite reserve in ore body 3 is 136,419 tons at grade 122 and 137,794 tons as resource grade 333. The depth of the reserve estimation reaches a maximum elevation of +290m (Thiet et al., 2010).

To efficiently exploit and utilize magnesite ore for various industrial sectors, apart from evaluating the reserve of the deposit, it is also essential to conduct an in-depth analysis of the mineral composition, properties, and quality of the ore. The objective of this study is to initially assess the mineralogical characteristics, chemical composition, as well as the quality of magnesite ore in the Sró area, Kong Queng, Gia Lai Province, Vietnam. Furthermore, this research aims to identify harmful minerals and other minerals that decrease the refractory temperature of magnesia clinker. This serves as a crucial foundation for investigating the use of magnesite ore for refractory material production following extraction.

2. Materials and Methods

2.1. Study Area

The research area, where the Kong Queng magnesite deposit was explored, spans an area of 52.75 hectares in Sró commune, Kong Chro district, Gia Lai Province, approximately 25 kilometers east of Kong Chro Town. The Kong Queng magnesite deposit area is situated on the western edge of the Kon Tum uplift (Tran and Nguyen, 1981). The geological structure of the deposit area is a small part of the regional geological structure, comprising metamorphosed Cambrian - Silurian limestone-carbonate strata belonging to the Phong Hanh Formation and intermediate Triassic-age volcanic strata belonging to the Mang Yang Formation. The magnesite ore body, interlayered with dolomite, is located in the lower part of the Phong Hanh Formation (Shand, 2006).

The topography of the Kong Queng mine area is on the northern slope of the Kong Queng mountain range, ranging in elevation from +390m to +600m. The undulating mountain slopes resemble the shape of an inverted fan, with numerous streams and ravines. The general terrain has slopes ranging from 150 to 300. A relatively thick layer of soil covers the surface, typically ranging from 2-3m to 7-8m in depth, extensively developed along both sides of the Dak Toman stream.

River and stream network: The northern and eastern boundaries of the deposit are bordered by the Dak Toman stream, which flows in an east-west direction, with a fairly wide streambed of 20 - 30m and flowing water throughout the year. Most of the streams and ravines in the exploration area flow south to north or southwest to northeast, originating from the Kong Queng mountain range and emptying into the Dak Toman stream.

The Sró, Kong Queng area falls within a tropical monsoon highland climate zone, characterized by two distinct seasons throughout the year. The rainy season typically starts from May to October, while the dry season occurs from November to April of the following year. The highest rainfall is recorded during June, July, and August, while the dry season experiences minimal or no rainfall, particularly in the months of February and March. The average annual rainfall ranges from 1,200 mm to 1,750 mm. The average temperature throughout the year ranges from 22 to 25°C, with the lowest temperatures in December and January at approximately 18 to 20°C and the highest temperatures in April and May reaching 30 to 32°C.
Fig. 1. [Left] The location of study area in Viet Nam; [Right] Geological map and distribution of ore bodies (above) and the geological cross-section diagram along line AB (below) in the Sró area, and Gia Lai Province, Vietnam (Source: Thiet et al., 2010)

2.2. Sampling Method

To evaluate the composition and quality of magnesite ore in the Sró area, we collected and analyzed 1,642 samples of basic core drilling from the magnesite ore body, 3 samples of technological experiments in the laboratory, and some samples for thin section petrography, X-ray diffraction, and thermal expansion analysis.

The mass of the laboratory testing samples: 3 samples with sample codes CND2-1, CND2-2, and CND2-3, each weighing 100 kg (obtained from the core drilling samples of the boreholes, ensuring the representativeness of the distributed magnesite ore in the Kong Queng area), with corresponding MgO contents of 22.5%, 36.7%, and 41.7%. Specifically: X-ray diffraction samples: samples taken from ore-bearing boreholes, obtained in block form with dimensions of 5x5x5 cm. The analysis of these samples aimed to identify the magnesite mineral components and to distinguish magnesite from other minerals.

Thermal analysis samples: samples collected from the ore-bearing boreholes, obtained in block form with dimensions of 5x5x5 cm. Conventional thermal methods (DTA, DTG, and TG) were used to determine the mineral components in magnesite ore.

Petrographic thin section samples: taken from boreholes, pits, and outcrops. Sample dimensions: 4x4x4 cm. The analysis of these samples aimed to identify the mineral components and structural architecture of magnesite, dolomite, and surrounding rock, as well as to determine the rock name.
Basic chemical samples: samples taken from the boreholes cutting across the ore body from the wall to the core, with minimum basic chemical sample lengths ranging from 0.4m to 2m in the ore and up to a maximum of 4.30m in the interlayer.

2.3. Sample Analysis Method

X-ray and differential thermal analysis included:

Analysis of raw ore: determining the useful and harmful mineral components and the existing forms of the sample to evaluate the quality of the raw ore and select the beneficiation process.

Analysis of magnesite clinker: identifying the newly formed mineral components in the products (after heating) to assess the quality and potential uses of the magnesite clinker in alkaline refractory production.

Analysis of raw ore using a electron microscopy: determining the useful and harmful oxide components of the magnesite mineral in the raw ore sample to evaluate the ore quality.

X-ray diffraction and differential thermal analysis samples were sent for analysis at the Geological Analysis and Experimentation Laboratory of the Institute of Geological Sciences and Minerals, Hanoi, Vietnam. Petrographic and basic chemical samples were sent for analysis at the Geological Map Analysis and Experimentation Laboratory of the Southern Geological Association, Ho Chi Minh City, Vietnam.

3. Results

3.1. Mineral Composition of Magnesite Ore in the Kong Queng Area

The synthesis of thin section, X-ray, and thermal expansion analysis results from the research samples (Tables 1 and 2) reveals that magnesite ore in Sro consists primarily of magnesite, followed by dolomite, calcite, chlorite, talc, and minor amounts of quartz and ore minerals (pyrite, goethite). The ore exhibits a foliated metamorphic grain structure and an inconsistent speckled texture. The specks are small to very small in size, primarily composed of dolomite, talc, and chlorite.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Mineral composition (%) based on X-ray analysis</th>
<th>Mineral composition (%) based on thermal analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnesite</td>
<td>Dolomite</td>
</tr>
<tr>
<td>CND2-1</td>
<td>18-20</td>
<td>68-70</td>
</tr>
<tr>
<td>CND2-2</td>
<td>74-76</td>
<td>10-12</td>
</tr>
<tr>
<td>CND2-3</td>
<td>80-82</td>
<td>6-8</td>
</tr>
</tbody>
</table>

*Note: Other minerals include quartz, chlorite, talc, mica, and amphibole.*

Table 1 shows that samples CND2-2 and CND2-3 are magnesite ores, while sample CND2-1 is a dolomite ore. Magnesite is whitish-gray, with a vitreous luster and a density of 2.9-3.1 g/cm³. It has tabular crystal forms ranging in size from 0.1 to 0.2mm to 6 mm, with the most common size being 1 to 3mm. Magnesite often forms densely packed aggregates. Under polarized light microscopy, magnesite appears colorless or occasionally pink, with distinct pseudo-absorption, high-degree white interference, and perfect cleavage (Shand, 2006). Among the magnesite particles, as well as in the cleavage planes
and fissures, there are accumulations of fine particles and flakes of dolomite, calcite, talc, chlorite, and ore minerals (pyrite altered to limonite, and goethite).

The ore composition consists of magnesite, accounting for 60 - 100%, with an average of 70 - 85%. The magnesite ore also contains some other minerals, accounting for <20%, including dolomite at approximately 6% - 12%, calcite at approximately 3 - 5%, and quartz at approximately <2%. All these minerals have small grain structures ranging in size from <0.01 mm to 0.05 mm. Talc and chlorite minerals, accounting for approximately 1 - 5%, have flaky structures. On the X-ray diffraction pattern, magnesite is easily recognizable by its diffraction lines (Å): 2.10 - 2.11; 2.32; 2.51; 2.74. On the Differential Thermal Analysis (DTA) chart, magnesite is characterized by an endothermic effect reaching a peak at 650°C, indicating the thermal decomposition reaction:

\[
\text{MgCO}_3 \xrightarrow{650^\circ C} \text{MgO} + \text{CO}_2 \uparrow
\]

Electron microscope analysis results (Table 2) indicate that the magnesite minerals in the magnesite ore samples contain a significant amount of harmful impurities concerning the production of alkaline refractory products.

**Table 2. Microscopic analysis results of magnesite ore**

<table>
<thead>
<tr>
<th>Point No.</th>
<th>MgO (%)</th>
<th>CaO (%)</th>
<th>FeO (%)</th>
<th>SiO$_2$ (%)</th>
<th>MnO (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.63</td>
<td>0.36</td>
<td>3.29</td>
<td>0.05</td>
<td>0.11</td>
<td>42.44</td>
</tr>
<tr>
<td>2</td>
<td>38.53</td>
<td>0.14</td>
<td>3.17</td>
<td>0.05</td>
<td>0.04</td>
<td>41.93</td>
</tr>
<tr>
<td>3</td>
<td>38.39</td>
<td>0.14</td>
<td>3.29</td>
<td>0.1</td>
<td>0.1</td>
<td>42.02</td>
</tr>
<tr>
<td>4</td>
<td>34.04</td>
<td>0.06</td>
<td>9.53</td>
<td>0.13</td>
<td>0.49</td>
<td>44.25</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>37.40</strong></td>
<td><strong>0.18</strong></td>
<td><strong>4.82</strong></td>
<td><strong>0.08</strong></td>
<td><strong>0.19</strong></td>
<td><strong>42.66</strong></td>
</tr>
</tbody>
</table>

Dolomite is gray or dark bluish-gray, with a density of 2.8 - 2.9 g/cm³. Dolomite exhibits optical properties similar to magnesite, but the main distinguishing feature is that dolomite usually occurs in small grains or aggregates, with sizes typically less than 0.05 mm, rarely reaching 0.5 - 1 mm. On the X-ray diffraction pattern, dolomite is easily discernible from magnesite and other carbonate minerals due to its diffraction lines (Å): 1.81; 2.02; 2.19; 2.41; 2.67; 2.89. On the thermal expansion chart, dolomite displays two endothermic effects reaching peaks at 660°C and 780°C, characteristic of the two decomposition stages of dolomite according to the reaction:

\[
\text{CaMg(CO}_3\text{)}_2 \xrightarrow{660^\circ C} \text{CaCO}_3 + \text{MgO} + \text{CO}_2 \uparrow \xrightarrow{780^\circ C} \text{CaO} + \text{MgO} + \text{CO}_2 \uparrow
\]

The microscopy analysis results identified the chemical composition of pure dolomite as follows: MgO 19.19%, CaO 27.14%, FeO 1.46%, and MnO 0.09%.

Thin section analysis revealed that dolomite often occurs alongside calcite, interspersed among magnesite particles. In many cases, dolomite is found with calcite, talc, and chlorite, forming small clusters or streaks within the fissures and cleavage planes of magnesite minerals.

Calcite is white or gray-white, occurring in small grains or aggregates with sizes ranging from <0.01 mm to 1 - 2 mm, and a density of 2.7 - 2.9 g/cm³. On the X-ray diffraction pattern, calcite is identified by its diffraction lines (Å): 3.03; and 4.19. Calcite often accompanies dolomite, interspersed between magnesite particles. In several instances, it is observed alongside dolomite, talc, and chlorite, forming small clusters or streaks within the fissures and cleavage planes of the magnesite mineral.

Talc appears as flaky particles with sizes less than 0.01 mm and a density of 2.6 - 2.8 g/cm³. Talc is consistently present in the ore, with a content of 1 - 3%, and occasionally reaching 5 - 6%. Talc is often found with dolomite, calcite, and chlorite, forming small clusters or streaks within the fissures and
cleavage planes of the magnesite mineral. On the X-ray diffraction pattern, talc is identified by a set of diffraction lines (Å): 3.13; and 9.36.

Chlorite appears in flaky form, with sizes less than 0.01mm and a density of 2.6 - 3.3 g/cm³. Chlorite is consistently present in the ore, with a content ranging from <1% to 5%. Chlorite often occurs with dolomite, calcite, and talc, forming small clusters or streaks within the fissures and cleavage planes of the magnesite. On the X-ray diffraction pattern, chlorite is characterized by diffraction lines (Å): 4.73; 4.75 - 4.76; 3.54 - 3.56; 7.12; and 7.15 - 7.17.

Quartz occurs as small, granular particles, with sizes ranging from 0.01 to 0.02 mm, and a density of 2.6 - 2.7 g/cm³. Quartz is present in the ore with a content of <2%, often accompanying chlorite and pyrite, forming small veins penetrating the fissures of the magnesite ore. On the X-ray diffraction pattern, quartz is identified by diffraction lines: 3.34 Å to 3.35 Å.

Ore minerals constitute a very small proportion (<0.5%), mainly comprising pyrite altered to hydrogoethite and goethite. Goethite and hydrogoethite appear as granular forms within the fissures of the ore or form thin layers on the surface and cleavage planes of carbonate minerals.

3.2. Chemical Composition of Magnesite in the Sró Area

The chemical composition of the processed raw magnesite ore samples is summarized in Table 3.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Sample Code</th>
<th>Chemical composition (%) by Chemical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MgO</td>
<td>CaO</td>
</tr>
<tr>
<td>1</td>
<td>22.50</td>
<td>22.30</td>
</tr>
<tr>
<td>2</td>
<td>24.84</td>
<td>21.45</td>
</tr>
<tr>
<td>3</td>
<td>36.70</td>
<td>4.60</td>
</tr>
<tr>
<td>4</td>
<td>41.70</td>
<td>0.70</td>
</tr>
<tr>
<td>5</td>
<td>41.45</td>
<td>3.06</td>
</tr>
<tr>
<td>6</td>
<td>40.19</td>
<td>4.16</td>
</tr>
</tbody>
</table>

(Source: Thiet et al., 2010)

Thus, samples CND2-2 and CND2-3 are magnesite ore samples, while sample CND2-1 is a dolomite ore sample.

The analysis of 1,642 simple chemical samples showed that the MgO content varied from 0.47% to a maximum of 45.06%. The MgO content fell into three categories: MgO <14% accounted for 99 samples, or 6%; dolomite with MgO content ranging from 14% to <24% accounted for 320 samples, or 19.5%; and magnesite with MgO content from 24% to 45.06% accounted for 1,223 samples, or 74.5%.

3.3. Forms of Major Oxides in Magnesite Ore

The synthesis of the chemical analysis, X-ray diffraction, thermal analysis, electron microscopy, and thin section analysis results can identify the forms of major oxides in magnesite ore in Table 4.

<table>
<thead>
<tr>
<th>Oxides in magnesite ore</th>
<th>Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>Primarily exists in the crystal lattice structure of magnesite and dolomite minerals, and to a lesser extent in talc and chlorite minerals.</td>
</tr>
<tr>
<td>CaO</td>
<td>Mainly exists in the crystal lattice structure of dolomite and calcite minerals. It is also present in magnesite with a small content.</td>
</tr>
</tbody>
</table>
SiO$_2$ Exists in the structure of quartz, talc, and chlorite minerals. It is also found in magnesite with a small content.

Al$_2$O$_3$ Exists in the crystal lattice structure of chlorite minerals.

Fe$_2$O$_3$ Exists in the crystal lattice structure of goethite and chlorite minerals. Ranges from 1.10% to 3.45%, with an average of 2.62%. FeO exists in the crystal lattice structure of chlorite and magnesite minerals. It is also found in pyrite and dolomite with a small content.

FeO Ranges from 1.10% to 3.45%, with an average of 2.62%. FeO exists in the crystal lattice structure of chlorite and magnesite minerals. It is also found in pyrite and dolomite with a small content.

MnO Occurs in very small quantities (<0.2%) and exists in magnesite and dolomite minerals.

3.4. Quality of Magnesite in the Sró Area

The results of material composition analysis indicate that the raw magnesite ore samples belong to the category of relatively high to medium-low quality ores. Specifically:

Samples CND2-2 and CND2-3 have relatively high magnesite content, ranging from 74% to 82%, with an average of 78%. However, the magnesite minerals have not very high MgO content (34.04% to 38.63%, averaging 37.40%), and they often contain harmful impurities such as CaO, FeO, SiO$_2$, and MnO with relatively high total content (3.40% to 10.21%, averaging 5.26%). Among these, CaO accounts for 0.06% to 0.36%, averaging 0.18%; FeO ranges from 3.17% to 9.53%, averaging 4.52%; SiO$_2$ ranges from 0.05% to 0.13%, averaging 0.08%; and MnO ranges from 0.04% to 0.49%, averaging 0.19% (Table 2).

If the recovery of ore produces a concentrate with a magnesite mineral content of about 95%, the resulting magnesite clinker will have the following chemical composition as in Table 5:

Table 5. Chemical composition of magnesite clinker

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Percentage range (%)</th>
<th>Average (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>71.22 - 86.50</td>
<td>82.15</td>
</tr>
<tr>
<td>CaO</td>
<td>0.13 - 0.80</td>
<td>0.38</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>7.98 - 22.36</td>
<td>11.88</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0.11 - 0.27</td>
<td>0.18</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09 - 1.03</td>
<td>0.41</td>
</tr>
</tbody>
</table>

This product has higher quality than type 3 magnesite clinker, but lower than type 2, meeting the requirements for refractory materials (Thiet et al., 2010; Thai et al., 2008, 2009). If the recovery of ore yields a concentrate with a magnesite content of 98% to 100%, the resulting magnesite clinker will have the following chemical composition as in Table 6:

Table 6. Chemical composition of magnesite clinker

<table>
<thead>
<tr>
<th>Oxides</th>
<th>Percentage range (%)</th>
<th>Average (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>74.96 - 91.05</td>
<td>86.63</td>
</tr>
<tr>
<td>CaO</td>
<td>0.13 - 0.84</td>
<td>0.41</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>8.40 - 23.54</td>
<td>12.5</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>0.12 - 0.29</td>
<td>0.19</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09 - 1.08</td>
<td>0.42</td>
</tr>
</tbody>
</table>

This product has higher quality than type 2 magnesite clinker, but lower than type 1, meeting the requirements for type 2 refractory materials (Thiet et al., 2010; Thai et al., 2008, 2009). Harmful minerals including dolomite, calcite, talc, chlorite, quartz, goethite, and pyrite frequently appear in magnesite ore (samples CND2-2 and CND2-3) with relatively high content ranging from 18% to 20% to 24% to 26%, averaging 21% to 23% (Table 1). It is noteworthy that both harmful and useful minerals share similar physicochemical characteristics. Therefore, recovering ore with a magnesite mineral
content of ≥95% is challenging (Thiet et al., 2010). Sample CND2-1 is dolomite ore. Compared to magnesite ore, sample CND2-1 has very low magnesite content (18% to 20%), a relatively high dolomite mineral content (68% to 70%), and a total content of harmful minerals (calcite, t alc, chlorite, quartz, goethite, and pyrite) at about 12% to 13%. Hence, using ores with a composition equivalent to sample CND2-1 for producing magnesia refractory materials is inefficient.

4. Conclusions

The chemical composition and quality of magnesite ore in the Sró area, Gia Lai Province, Vietnam were evaluated. Overall, the magnesite ores in the Kong Queng area belong to the category of ores with relatively high to medium quality (average MgO content from 37% to 38%), with the main components being magnesite, followed by dolomite, calcite, chlorite, and t alc. The majority of the samples have a magnesite mineral content above 75% to 94%, corresponding to dolomite <10% with MgO content >40% to 45%, and magnesite content >45% to 69%, corresponding to dolomite >45% to 30% with MgO content >30% to 40%. Additionally, the ores also contain some other minerals such as t alc ranging from 0% to 10%, chlorite from 0% to 12%, and small amounts of mica, siderite, and feldspar. The research results have identified the mineral components, chemical composition, structure, and composition of the surrounding rocks and ores in the Sró magnesite area. The study’s results on the quality and material composition of magnesite ore are an essential basis for the ore extraction work as well as for the development of the beneficiation process and the production of magnesia clinker, providing possibilities for the application of magnesia clinker products in alkaline refractory material production fields.

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