

The optimization of the strontium compounds production, using a celestine ore sample

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Abstract

The direct conversion of celestine (SrSO_4) to strontium carbonate as well as its enrichment by hydrometallurgy were investigated. A study was also conducted to investigate whether acid concentration affected the quality of strontium sulfate in celestine concentrates. Based on the results of a laboratory assay, it was determined that 98.04% SrSO_4 was leached optimally under agitation. The ground sample of celestine concentrate was then leached by agitation for three hours after the dimensional analysis had determined the appropriate grinding time. To determine the optimal approach for the agitated leaching of strontium carbonate, different approaches were tested. Various factors, including temperature, return water, solid percentage, and sodium carbonate to strontium sulfate ratio, were studied. At 90°C, celestine completely converts into strontium carbonate with a solid percentage of 20% and a sodium carbonate to strontium sulfate ratio of 4:5. As part of the investigation into the possibility of producing strontium oxide, samples of celestine concentrate and strontium carbonate produced under optimal conditions were heated at 500 and 1000°C to determine which phase would form the oxidized phase. An X-ray analysis indicates that the oxidation phase forms at a temperature of more than 750°C.

Keywords:

celestine processing; strontium compounds; strontium carbonate; strontium oxide

1. Introduction

Celestine (SrSO_4) and strontianite (SrCO_3) are two of the most common mineral forms of strontium. It should be noted that only celestine is commercially mined. Additionally, celestine is used primarily in the production of strontium carbonate (Zhang et al., 2019). Carbonate of strontium (SrCO_3) is a strontium compound that has been used in a variety of industrial and technological applications (Bingöl, Aydoğan and Bozbaş, 2012; Koopmann and Pichler, 2022). The majority of celestite produced worldwide is used in making strontium chemicals, such as strontium carbonate, strontium nitrate, and strontium hydroxide. Although celestite can be used in its natural form for many different applications, it is primarily used to produce strontium chemicals. As a result of these chemicals, cathode ray tubes are produced that are crucial for the production of color monitors. Magnetic materials such as optical glass, electromagnets, photocatalysts such as strontium titanate and zirconate for the aqueous degradation of organic pollutants, and ceramic ferrites are also produced (Massonne, 1982). Additionally, it is used in medicine, chemical reagents,

pigments, coatings, electrolytic zinc, sugar refining, as well as explosives and flares that contain brilliant red colors. As a result of rapid technological advances, the demand for strontium carbonate will continue to increase (Martínez and Uribe, 1995; Bingöl, Aydoğan and Gultekin, 2010; Liu et al., 2012, 2014).

Among the strontium minerals, celestite (SrSO_4) occurs naturally in China, Mexico, Iran, and Spain. Usually found in sedimentary deposits associated with rock salt and gypsum, it has a specific gravity of 3.96 g/cm³ and a hardness of 3–3.5 on the Mohs scale. The majority of these deposits contain celestite, which ranges between 70 and over 90% SrSO_4 (Bulatovic, 2015). Celestite ore can be beneficiated using a variety of methods, including physical concentration and flotation. The physical concentration of high-grade ore containing calcite and silicate is accomplished by gravity and heavy liquid separation. A flotation process is currently the most commonly used method of beneficiating celestite ores in the mining industry. Beneficiation of the ore might include ore selection followed by crushing, sizing, washing, and flotation to remove gangue minerals (mainly clay and silica), obtaining a concentrate grade >90% SrSO_4 , the grade required for the manufacturing of strontium chemicals (Bulatovic, 2015; Koopmann and Pichler, 2022). In industrial applications, celestite is first converted into

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Table 1: Chemical properties of celestine

Major compound	BaO (%)	Al ₂ O ₃ (%)	SiO ₂ (%)	Fe ₂ O ₃ (%)	Na ₂ O (%)	CaO (%)	SO ₃ (%)	SrO (%)
content	0.37	0.34	0.82	0.19	>	3.66	39.98	51.48

Table 2: Characteristics of sodium carbonate

Specifications	Range
alkaline (NaCO ₃)	up to 99.2
NaCl	lower than 0.4
iron content	lower 0.004
insolubility in water	lower than 0.1

SrCO₃ through pyrometallurgy, hydrometallurgy, or mechanochemical processes. Celestite is then converted into SrCl₂, SrCrO₄, Sr(NO₃)₂, and SrO (Erdemoğlu and Canbazoglu, 1998; Owusu and Litz, 2000; Kobe and Deiglmeier, 2002).

The two most commonly used commercial processes for manufacturing SrCO₃ from celestite are the black ash process and the double decomposition process (direct conversion). A water-soluble SrS is produced by reducing SrSO₄ with coke (or coal) at temperatures over 1000°C in the black ash process. The precipitation of strontium carbonate occurs by using soda ash, ammonium bicarbonate, or CO₂ after the sulfide is leached in hot water (Moore and Swart, 2022). Additionally, sodium sulfate is produced as a by-product of a double decomposition reaction taking place in a hot sodium carbonate solution (more than 90°C) on finely powdered celestite. In the second process, finely powdered celestite is used to react with a hot sodium carbonate solution (over 90°C) to produce SrCO₃ and sodium sulfate as by-products. Although the black ash method produces a higher purity product, it is more energy-intensive (Erdemoğlu and Canbazoglu, 1998; Owusu and Litz, 2000; Sonawane et al., 2000; Zhang et al., 2019) compared to the double decomposition method (Martínez and Uribe, 1995; Castillejos E., De La Cruz Del B. and Uribe S., 1996; Bingol, Aydogan and Gultekin, 2010). Besides the two above commercial methods, celestite can also be converted to SrCO₃ by reaction with sodium or potassium carbonate at high temperatures and pressures, or by direct leaching with Na₂S. Such methods are complex, expensive, and usually require specialized equipment. Therefore, the two commercial methods mentioned above are the most widely used (Setoudeh, Welham and Azami, 2010; Zhu et al., 2022). Ming et al. have developed a new method of preparing strontium chloride by using aeration to dissolve disodium celestite in hot water, which results in a strontium sulfide solution. In the strontium sulfide solution, sulfated hydrogen gas is added to generate strontium hydrosulphide, which reacts with magnesium to produce strontium chloride. In order to obtain strontium chloride and magnesium hydrate, hydrogen sulfide from the reaction is used in order to

produce strontium hydrosulphide, which is obtained by circulating the desired material at a favourable recovery rate (Inamura et al., no date).

A major advantage of the studied method is the lack of need for chemical raw materials, its simplicity and low cost in obtaining raw materials, as well as the high quality of the finished product. In addition to the production of magnesium hydrate, the process will also prevent hydrogen sulfide pollution, so it is beneficial from an economic and social point of view, and it is especially appropriate for areas with high magnesium chloride reserves. The main point of the concentration process of celestite is to increase celestite grade to use in other processes which need pure compounds of celestine. The present study examined hydrometallurgical methods to produce strontium carbonate as the base material for other strontium compounds of celestine as well as determining the temperature of strontium oxide formation in order to produce a variety of these compounds. Also, the formation phase of strontium oxide in the heating of strontium carbonate was investigated.

2. Materials and methods

2.1. Materials

2.1.1 Celestine concentrate

Celestite concentrate was obtained from a mine located in the Semnan Province of Iran. The chemical composition of celestite concentrate is shown in Table 1.

The grade of strontium sulfate in the celestine concentrate sample is about 91.87% by using Equation 1.

$$\begin{aligned} \text{the } \frac{\text{molar mass of sulphur trioxide}}{\text{molar mass of strontium sulphide}} &= \\ &= \frac{\text{grade of sulphur trioxide}}{\text{grade of strontium sulphate}} \quad (\text{Eq.1}) \end{aligned}$$

The process of washing calcite with different acids has been investigated as a means of enriching strontium carbonate, which is a major objective in mineralogy. Based on the findings of this study, strontium carbonate production lines are intended for industrialization, whereas organic acids are not suitable for industrial use due to technical and economic constraints. Furthermore, hydrofluoric acid destroys silicate bonds, nitric acid dissolves sulfide minerals and produces nitrogen oxides, sulfuric acid produces silica gel, and nitric acid dissolves calcium carbonate. As a result, 37% hydrogen chloride, manufactured by Neutron Company, was used in this study to enrich strontium carbonate. For the conversion

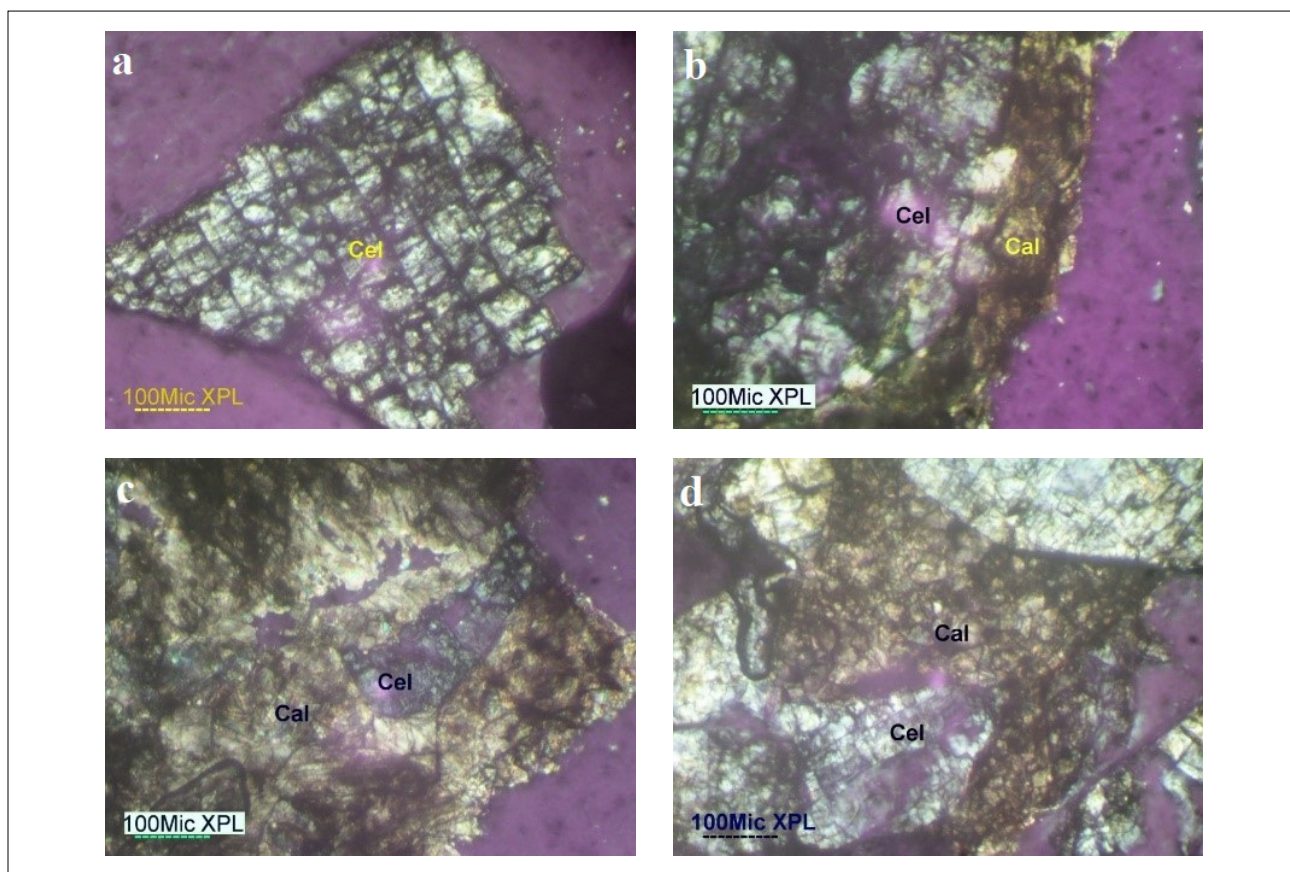


Figure 1: a) Part of the celestine crystal, b) calcite with celestine, c) celestine crystal surrounded by calcite crystals, d) calcite placement among celestine crystals (Cel: celestine, Cal: calcite).

of strontium sulfate into strontium carbonate and also for the enrichment of strontium carbonate, sodium carbonate manufactured by Kaveh Sodium Carbonate Company was used. The specifications of this product are presented in **Table 2**.

2.1.2 Mineralogical studies

The microscopic studies are shown in **Figure 1**. The mineralogy of celestine concentrate was examined using a microscopic section prepared from a thin, polished blade. A study of the sample revealed that celestine was present in over 90% of the samples. As shown in **Figure 1a**, celestine crystals are blade shaped. **Figure 1b** demonstrates that more than 90% of celestine fragments are free of calcite, and only a few are mixed with it. There is a significant amount of calcite in the sample, approximately 7%. There are two types of calcites: automorphic crystals with a mosaic texture (sparites) and microcrystalline crystals (micrites). It appears that some parts of the celestine crystals are covered with calcite in **Figures 1c** and **d**. Calcite has also entered the spaces between the crystals and cavities.

2.2. Chemical analysis

Test samples were analyzed using X-ray fluorescence chemical analysis (XRF) under various conditions to de-

termine their chemical composition. X-ray diffraction (XRD) was used to identify the phase composition of heated strontium carbonate samples. TGA measurements were performed under controlled conditions on celestine and strontium carbonate samples using a TGA device (TG 209F3 NETZSCH, Germany).

2.3. Experimental procedure

2.3.1 Milling

To determine the appropriate grinding time based on the dimensional analysis, stirring leaching experiments were performed on celestine concentrates for three hours with sodium carbonate.

Celestine concentrate was ground using a rod mill to obtain 37-micron size fractions, with the aim of passing about 95% of the sample through this screen at each grinding time (15, 20, and 25 minutes) due to mineralogical studies results. The results are shown in **Figure 2**. Based on the particle size distributions, it was determined that the grinding time of 25 minutes was the most appropriate grinding time.

2.3.2 Strontium carbonate enrichment

The major problem in producing strontium carbonate from celestine is the removal of impurities such as cal-

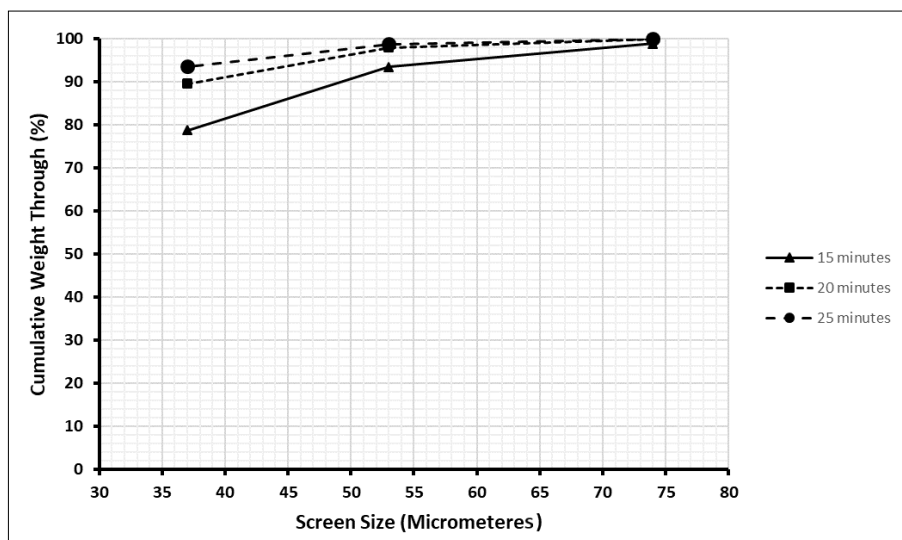


Figure 2: The consistency of celestine samples after grinding based on the time elapsed.

cite and dolomite, iron (Fe_2O_3), and barium oxide (BaO) as well as enrichment to produce an industrial product. To determine the best conditions for acid washing with hydrochloric acid on the most appropriate sample from the leaching experiments, three sets of tests were conducted.

- 1) To perform the first test set, 25 grams of strontium carbonate were poured into a 500 ml Erlenmeyer flask, and 100 ml of water was added in 10 ml increments until the solution was no longer boiling.
- 2) Similar to the previous test set, 100 ml of water, 25 g of strontium carbonate, and 50 ml of HCL acid were poured into an Erlenmeyer flask and filtered after 30 minutes (end of boiling), the exception being that 20 g of sodium carbonate were added four times throughout the boiling process.
- 3) 100 ml of water, 25 g of strontium carbonate, and 25 ml of HCL acid were added to an Erlenmeyer flask and filtered after 20 minutes (end of boiling). Each stage added 5 grams of carbonate to a total of 20 grams of carbonate.

2.3.3 Formation of strontium oxide in the heating of strontium carbonate

The strontium carbonate produced from celestine concentrate was heated for two hours at 500, 750, and 1000°C in order to determine whether strontium oxide could be produced from celestine concentrate. For the purpose of determining which phase is capable of forming an oxidized phase, thermal distribution analysis and X-ray diffraction were performed on the samples. The X-ray diffraction analysis was conducted using the Rietveld method.

3. Results and discussion

There was a study conducted to examine the effect of different parameters on stirring leaching experiments for

the conversion of strontium sulfate to strontium carbonate, including temperature, return water effect, solid percentage, and sodium carbonate to strontium sulfate ratio.

3.1. Effect of temperature

In the first step, the temperature of the mixing leaching process was determined. The optimal temperature was determined by conducting two experiments at 50 and 90°C while keeping the other conditions constant. During a 3-hour period, celestine samples were leached with 259.2 g of sodium carbonate and 1632 ml of water. It is important to note that all tests had a solid percentage of 15%. According to **Table 3**, there is a difference in grade between these two temperatures. Consequently, strontium carbonate was more readily produced at higher temperatures, and strontium oxide grade was higher when carbonate ions penetrated and formed strontium carbonate. There are two possible explanations for this increase:

- (1) As the temperature increases, LeChatelier's principle states that the percentage of carbonate increases as a result of an endothermic reaction (**Equation 2**).
- (2) It is also predicted by Arenos' equation (**Equation 3**) that diffusion coefficients increase with an increase in temperature.



$$D = D_0 \times e^{\left(\frac{-Q}{RT}\right)} \quad (\text{Eq.3})$$

Table 3: Effect of process temperature on strontium carbonate grade.

Process temperature (°C)	SrO (%)	SrCO ₃ (%)
50	62.95	89.68
90	63.86	90.98

3.2. Effect of backwater

In order to examine the effect of returning water, 300 g of celestine sample was mixed with 259.2 g of sodium carbonate and 1632 ml of water at 90°C for three hours. In a second test, the remaining sample was washed again with the output water of the filter device for ten minutes under the same test conditions. A comparison of these two cases is presented in **Table 4**. Compared to mixing leaching without return water, mixing leaching with return water increased the grade of strontium carbonate produced by mixing leaching by 2.81%. Therefore, all subsequent mixing leaching experiments used returned water to wash the product.

Table 4: The effect of return water in the process on the grade of strontium carbonate

Explanation	SrO (%)	SrCO ₃ (%)
strontium carbonate without using return water	60.63	87.37
strontium carbonate after using return water	62.44	90.38

3.3. Effect of solid percentage

In this section, the solid percentage of strontium sulfate was discussed as an important parameter affecting the grade of strontium carbonate. To determine the optimal value, four experiments were conducted with solid percentages of 10, 20, 30, and 40. **Table 5** presents the results of these tests. Based on the results of the experiments, the quality and recovery of strontium carbonate increased up to a solid percentage of 20%, but after that, both parameters decreased. Since the solid portion of sodium carbonate has increased in solid percentage, it no longer combines with strontium sulfate and forms an insoluble part of the final product.

3.4. Effect of ratio of sodium carbonate to strontium sulfate

Using an optimal solid percentage of 20%, four experiments were conducted evaluating the effects of varying sodium carbonate to strontium sulfate ratios. **Table 6** shows that a ratio of 4 to 5 sodium carbonate to strontium sulfate (number 2) was optimal.

Table 5: Effect of process solid percentage on strontium carbonate grade

Solid percentage (%)	Celestine (g)	Carbonate (g)	Produced strontium carbonate (g)	SrO (%)	SrCO ₃ (%)
10	55.5	47.9	46	62.23	88.80
20	125	108	106.5	63.19	90.02
30	214.2	185.06	182.5	62.74	89.38
40	333	287.7	331	60.98	86.87

Table 6: Effect of sodium carbonate to strontium sulfate ratio on strontium carbonate grade.

	Solid percentage (%)	Celestine (g)	Carbonate (g)	SrO (%)	SrCO ₃ (%)
1	20	125	113.4	63.52	90.49
2	20	125	102.6	63.93	91.08
3	20	125	97.2	63.39	90.31
4	20	125	91.8	63.29	90.16

Table 7: The results of XRF analysis of the input feed of the acid washing process with hydrochloric acid

Major compounds	SrO (%)	SrCO ₃ (%)	CaO (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	BaO (%)
content	63.20	90.04	3.99	1.71	0.97	1.10	0.84

Table 8: Acid-washed residue chemical analysis of the filter.

Major compound	SrO (%)	SrCO ₃ (%)	CaO (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	BaO (%)
content	57.43	81.82	5.21	3.11	0.11	0.08	0.23

Table 9: Analysis of the materials remaining on the filter after adding 5 g of sodium carbonate.

Major compound	SrO (%)	SrCO ₃ (%)	CaO (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	BaO (%)
content	56.94	81.12	3.94	8.26	0.05	>	0.17

Table 10: Analysis of acid washing product of the second test set.

Major compound	SrO (%)	SrCO ₃ (%)	CaO (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	BaO (%)
2	63.04	89.81	4.26	5.26	0.15	0.06	0.24
3	63.81	90.91	4.26	4.51	>	>	0.21
4	63.39	90.31	3.75	5.67	>	>	0.18

Table 11: Chemical analysis of the products of test process number 3 acid washing.

Major compound	SrO (%)	SrCO ₃ (%)	CaO (%)	Na ₂ O (%)	Fe ₂ O ₃ (%)	SiO ₂ (%)	BaO (%)
1	65	92.60	4.51	2.77	>	>	>
2	64.05	91.25	4.51	4.12	>	>	>

Table 12: Effect of hydrochloric acid concentration on celestine grade.

Acid Concentration (%)	Hydrochloric acid (g)	Weight of water (g)	Final celestine's weight (g)	Casualty (%)	SrO (%)	SrSO ₄ (%)
5	25	1145	472.5	5.5	53.41	95.08
10	50	1120	453.6	9.28	54.43	97.54
15	75	1095	452.1	9.58	55.05	98.04

3.5. Enrichment of strontium carbonate

For the purpose of removing impurities resulting from stirring leaching, three test sets were designed and evaluated under optimal conditions at 90°C, a solid percentage of 20%, and a sodium carbonate to strontium sulfate ratio of 4 to 5. **Table 7** provides the specifications of the strontium carbonate used in this series of experiments.

3.5.1 Acid washing test number 1

In the first test set, 25 g of strontium carbonate was washed in 100 ml of water with 50 ml of hydrochloric acid, and any remaining substance was discarded on filter paper. The solution was precipitated by adding 20 g of sodium carbonate at the end. The results of this test are presented in **Table 8**.

To ensure complete precipitation of strontium carbonate, sodium carbonate was added to the remaining solution, followed by two-stage filtering, and the resulting sample was analyzed. **Table 9** presents the results of this test.

3.5.2 Acid washing test number 2

The second test set was designed to reflect the effect of reducing strontium oxide levels during the previous test mode. A mixture of 100 ml of water, 25 g of strontium carbonate, and 50 ml of hydrochloric acid was poured into an Erlenmeyer flask and filtered after 30 minutes (the end of boiling). An experiment was conducted in which 20 grams of sodium carbonate were added to a solution in four stages, a total of 5 grams per stage, and the solution was filtered after each stage. The first sample was considered an impurity and the three

subsequent samples were sent to a laboratory for testing. As shown in **Table 10**, the results are summarized.

There is a direct correlation between the grade and the level of sodium carbonate, as can be seen in these three tables. Nevertheless, if it exceeds a certain level, it will have the opposite effect.

3.5.3 Acid washing test number 3

Additional tests were conducted to determine the effect of acid amount on the production of strontium oxide. During the third test, 100 ml of water, 25 g of strontium carbonate, and 25 ml of hydrochloric acid were added to an Erlenmeyer flask in half the amount compared to previous tests. The mixture was filtered after 20 minutes. It was necessary to add 20 g of carbonate to the solution in four stages, 5 g at a time, and to filter the solution after each stage. First and second-stage filtered samples were sent to the laboratory, whereas third and fourth-stage filtered samples were considered impure. **Table 11** presents the results of this test.

Analyses of the results indicate that after adding 5 g of sodium carbonate to the solution, the highest grade was obtained among all tests, and impurities such as sodium oxide, iron oxide (hematite), silica oxide (quartz), and barium oxide were minimized. Therefore, this method is the most suitable for strontium carbonate enrichment in terms of titration and minimization of chloric acid and sodium carbonate consumption.

3.6. Effect of acid concentration on strontium sulphate

As a first step, stirring leaching on celestine concentrate samples was conducted to determine the effect of



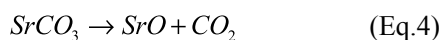
Figure 3: Acid washing process with hydrochloric acid and celestine sample after acid washing process.

acid concentration on strontium oxide recovery. At three concentrations of hydrochloric acid: 5, 10, and 15% (see **Table 12**), celestine was recovered after 30 minutes of acid washing. There was a solid percentage of 30% in these experiments and a dilution ratio of 7:3.

Based on the chemical analysis, it was found that the grade of strontium sulfate increases as the amount of acid increases. The sample in **Figure 3** represents the high quality sample following the process.

3.7. Oxidation of strontium carbonate

Strontium oxide is a critical raw material for the production of other strontium salts. According to **Equation 4**, strontium carbonate becomes strontium oxide at high temperatures.



A high-quality celestine mineral sample was heated in a furnace under optimal conditions at 500, 750, and 1000 degrees Celsius to determine whether strontium oxide could be produced. The weight of each sample was 50 g. Based on a thermal distribution analysis, the following results were obtained regarding the formation of the oxidized phase.

Thermal distribution analysis begins with the loss of water and moisture between the structures, which occurs at approximately 100°C. This is when the material starts to lose weight (the decrease in the graph indicates a weight loss between structure and moisture in the system, which was approximately 2%). The weight loss has been linked to the transformation of strontium oxide at temperatures between 750°C and 1000°C, as shown in **Figure 4**. As a result, SrCO_3 groups were converted. The transformation of SrCO_3 into SrO and CO_2 took place during this process. Around 7% of the weight is lost at 750°C, while almost 7.8% of the weight is lost at 1000°C.

The weight loss of strontium carbonate samples at different temperatures is also included in **Table 13**.

As shown in **Figure 5**, celestine samples showed lower weight loss. It has been observed that the humidity of

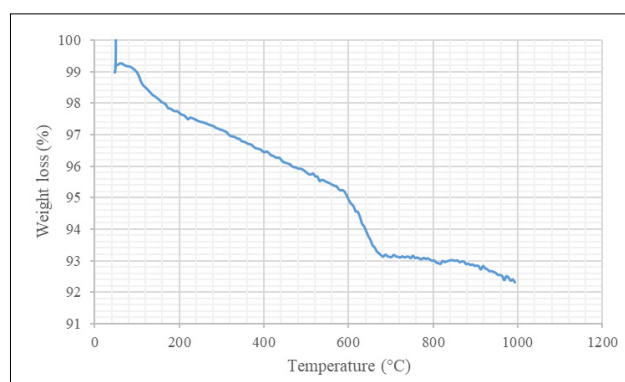


Figure 4: Weight loss graph of strontium carbonate sample with increasing temperature.

Table 13: The amount of weight loss of strontium carbonate sample in thermal distribution analysis.

	Temperature (°C)	Amount of celestine prototype (g)	Sample amount after heating (g)
1	500	50	48.98
2	750	50	47.44
3	1000	50	42.1

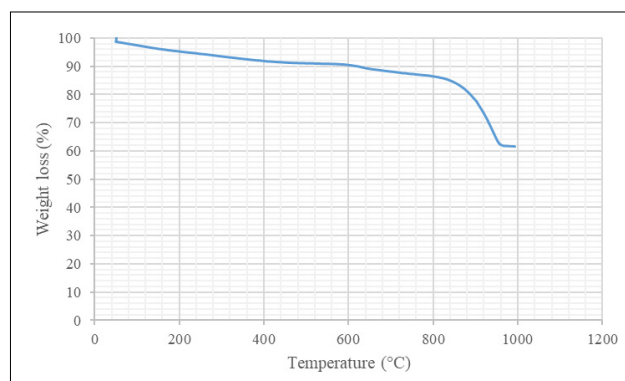


Figure 5: Weight loss graph of celestine sample (in percent) with an increase in temperature

Table 14: The amount of weight loss of celestine sample in thermal distribution analysis.

	Temperature (°C)	Amount of celestine prototype (g)	Sample amount after heating (g)
1	500	50	49.80
2	750	50	48.79
3	1000	50	48.74

the system has reduced at a temperature of 100°C, which has resulted in a weight loss of approximately 5%. The weight loss began at 800°C, when the transformation to strontium oxide began, which continued until 1000°C. As a result, SrCO₃ groups have been transformed into SrO and CO₂. There is a greater loss of weight in this case, approximately 31%.

Table 14 includes the weight loss of high-quality celestine mineral samples in different temperature conditions.

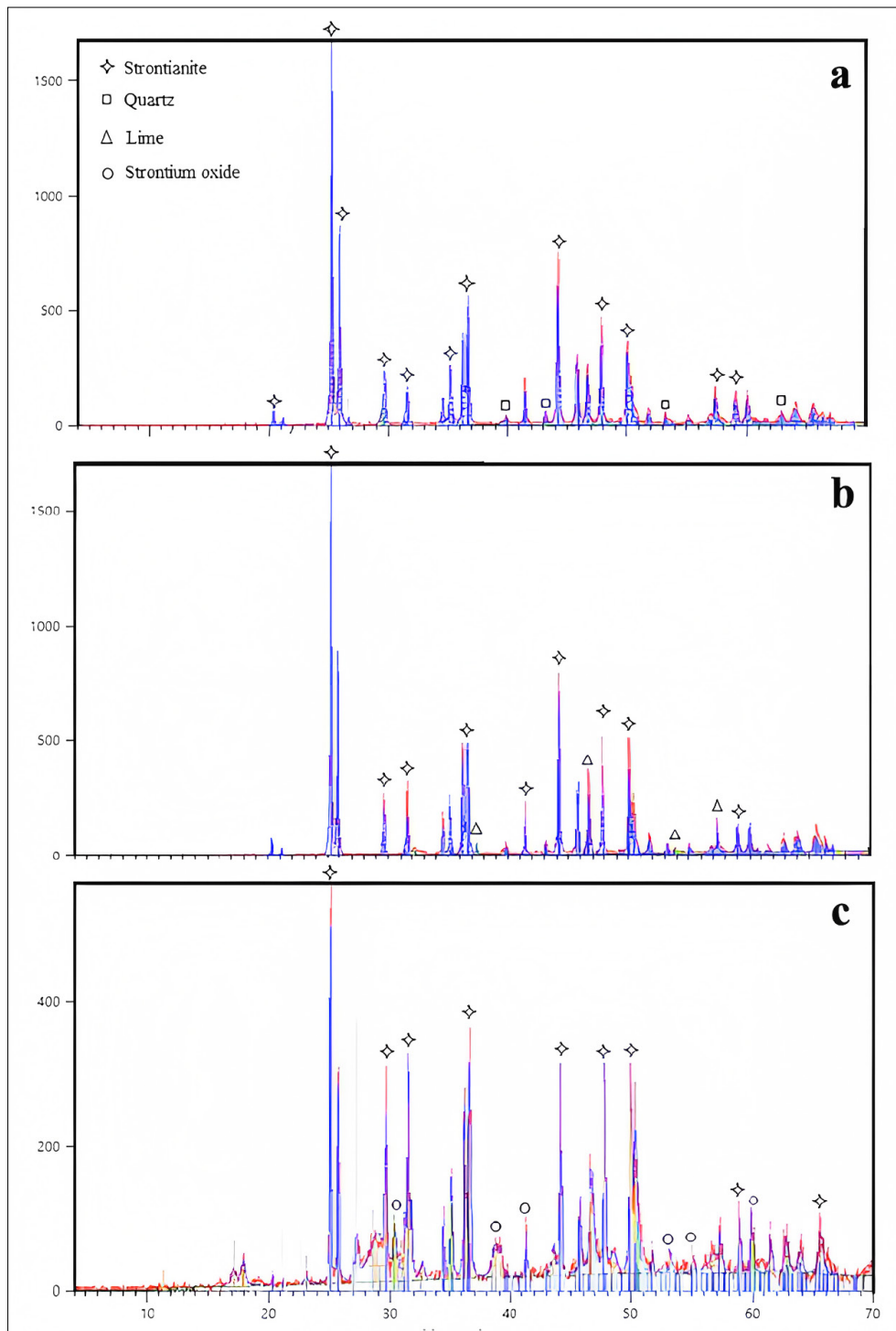


Figure 6: X-ray diffraction analysis spectrum of strontium carbonate at 500, 750, and 1000°C.

3.8. X-ray diffraction analysis

The next step was to conduct X-ray diffraction analysis on strontium carbonate samples after being heated in the furnace and ground to equalize their dimensions, in order to better understand the weight and thermal distribution analysis peaks. The Rietveld analysis method was conducted using Malvern Panalytical XRD Data Analysis Software.

As a first step, the card number corresponding to each material was determined using a sample of strontium carbonate, a mineral containing calcite and quartz as its main impurities. As a next step, strontium carbonate samples were heated at 500, 750, and 1000°C and measured using an X-ray diffractometer at angles between 4 and 70 degrees. Chemical analysis was used to identify the compounds found in the samples.

Strontium carbonate was observed in the highest concentration at 25.2383 degrees when compared to the reference peaks. It was also not observed that strontium oxide phase formed in this analysis. As a result of the thermal distribution analysis results up to 500°C, it is concluded that strontium carbonate has not yet been converted to strontium oxide. **Figure 6a** illustrates the spectrum of strontium carbonate heated in a furnace at 500°C during X-ray diffraction tests.

It was determined that the highest level of strontium carbonate was detected at 25.2005 degrees based on the alignment of sample peaks with reference peaks. This analysis did not reveal the formation of strontium oxide phase. Therefore, based on the results of the thermal distribution analysis up to 750°C, it can be concluded that strontium carbonate has not been converted to strontium oxide. However, in light of the results of this analysis, it can be concluded that the sudden drop in temperature of 638°C in the graph associated with the thermal distribution analysis is caused by the conversion of CaCO_3 to CaO . **Figure 6b** shows the X-ray diffraction spectrum of strontium carbonate heated to 750°C. It has been determined from the comparison of the sample peaks with the reference peaks that the most strontium oxide occurred at an angle of 36.591, while the most strontium carbonate occurred at a 25.166 degree angle. Additionally, a strontium oxide phase was observed in this analysis. As a result, strontium carbonate is converted into strontium oxide at a temperature of 750 to 1000°C. **Figure 6c** illustrates the X-ray diffraction analysis of strontium carbonate heated at 1000°C.

4. Conclusions

A study was conducted on the effects of hydrochloric acid concentrations on reagent grade SrSO_4 and celestine concentrate. An experimental stirring leaching study was conducted in order to investigate the effect of different parameters on the transformation of strontium sulfate into strontium carbonate. Temperature, return water effect,

solid percentage, and sodium carbonate to strontium sulfate ratio were studied in this study. Strontium sulfate is converted into strontium carbonate at a temperature of 90°C, a solid percentage of 20%, and a sodium carbonate to strontium sulfate ratio of 4:5. The mechanism of celestine conversion under leaching conditions was proposed based on experimental observations. The production of strontium oxide was also tested using samples of strontium carbonate placed in a furnace at various temperatures. As the temperature increases, the formation of the oxidized phase begins and strontium carbonate is converted to strontium oxide at an increasing rate.

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SAŽETAK

Optimizacija proizvodnje stroncijevih spojeva pomoću uzorka celestinske rude

U radu se istražuje izravna pretvorba celestina (SrSO₄) u stroncijev karbonat i njegovo obogaćivanje hidrometalurjskim postupcima. Također, provedeno je istraživanje o utjecaju koncentracije kiseline na kvalitetu stroncijeva sulfata u koncentratima celestina. Na temelju rezultata laboratorijskih ispitivanja utvrđeno je da se 98,04 % SrSO₄ optimalno izlužuje uz miješanje. Nakon što je dimenzijskom analizom određeno odgovarajuće vrijeme mljevenja, samljeveni uzorak koncentrata celestina izlužen je protresanjem tijekom tri sata. Testirani su različiti pristupi kako bi se odredio optimalan postupak za izluživanje uz protresanje stroncijeva karbonata. Proučavani su različiti čimbenici, uključujući temperaturu, povratnu vodu, postotak čvrste tvari i omjer natrijeva karbonata i stroncijeva sulfata. Na 90 °C celestin se potpuno pretvara u stroncijev karbonat s 20 % udjela čvrste tvari i omjerom natrijeva karbonata i stroncijeva sulfata od 4 : 5. Kako bi se utvrdilo koja će faza tvoriti oksidiranu fazu u sklopu istraživanja mogućnosti proizvodnje stroncijeva oksida, uzorci koncentrata celestina i stroncijeva karbonata načinjeni su u optimalnim uvjetima zagrijavanjem na 500 i 1000 °C. Rendgenska analiza pokazuje da se oksidacijska faza formira na temperaturi višoj od 750 °C.

Ključne riječi:

oplemenjivanje celestina, stroncijevi spojevi, stroncijev karbonat, stroncijev oksid

Authors' contribution

Ardalan Alishahi (1) (MSc Student of Mineral Processing) performed tests, analyses, provided reports and wrote the article. **Mohammad Noaparast** (2) (Full Professor of Mineral Processing) proposed the idea, provided technical suggestions, guided the research, and wrote the article. **Ali Rezaei Ashani** (3) (MSc of Mining Engineering) performed tests and provided the samples. **Marzieh Hosseini Nasab** (4) (Assistant Professor of Minerals Processing) proposed the idea and guided the research.