Recovery of Cerium Oxide Abrasive from an Abrasive–Glass Polishing Waste through Alkaline Roasting Followed by Water Leaching

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Abstract: Abrasive–glass polishing waste is generated from the polishing process of glass components by using cerium oxide abrasive, which contains the cerium oxide abrasive and the polished glass. This study attempted to recover the cerium oxide abrasive from the abrasive–glass polishing waste through removing the polished glass by alkaline roasting using sodium hydroxide (NaOH) followed by water leaching. The experimental results indicated that the polished glass in the abrasive–glass polishing waste could be fully removed under the optimal alkaline roasting and water leaching conditions of roasting temperature of 450 °C, mass ratio of polishing waste to NaOH of 1:1, roasting time of 30 min, leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 25 mL/g. The characteristics including elemental composition, particle size distribution, mineralogical phases, and morphology of the recovered cerium oxide abrasive obtained under the optimal conditions were similar to those of the original unused one, which was suitable to be reused for polishing again.

Keywords: cerium oxide abrasive; recovery; alkaline roasting; water leaching; rare earth element

1. Introduction

A cerium oxide abrasive is often used for polishing glass components [1,2]. The polishing process generates a polishing waste containing the cerium oxide abrasive and the polished glass. The cerium oxide abrasive is produced from rare earth minerals containing cerium such as monazite ((Ce,La,Nd,Th)PO₄), bastnasite ((REE)CO₃F), and loparite ((Ce,Na,Ca)(Ti,Nb)O₃) [3]. The estimated world reserves of cerium containing minerals are approximately 30 million tons and the recent production amount of cerium oxide (CeO₂) is around 54,400 tons (ca. 32% of rare earth oxides) [4]. Cerium is widely used in many industrial applications such as polishing, glass additives, catalysts, ceramics, phosphors, LEDs, etc. [5]. The glass industry consumes approximately 40,000 ton of rare earth oxides, among which around 16,000 tons are used for polishing [6]. Therefore, a great amount of abrasive–glass polishing waste is produced. Currently, a major portion of this polishing waste is discarded in landfills. However, the cerium oxide abrasive should ideally be recovered from this polishing waste, not only for acting as an alternative source of rare earth elements but also for reducing the production of solid waste.

Several methods have been developed for recovering rare earth elements from the abrasive–glass polishing waste. Recently, Borra et al. conducted a comprehensive review on this critical issue [7]. Most of the methods were based on either pyrometallurgy [8,9] or hydrometallurgy [10–16], which aimed at the recovery of rare earth elements such as cerium, lanthanum, neodymium, and praseodymium. Although both types of methods are technically feasible, they have some limitations such as high energy...
consumption and wastewater treatment requirement. On the other hand, the abrasive–glass polishing waste mainly comprises the cerium oxide abrasive and the polished glass. Effectively separating the two components in the polishing waste can be beneficial for the recovery of cerium oxide abrasive, which can reduce the foregoing limitations of pyrometallurgical and hydrometallurgical methods through reducing the treatment amount and the reagent usage, and thus can reduce the energy consumption and the wastewater production. In addition, the recovered cerium oxide abrasive can be reused for polishing again if its particle size distribution has no substantial change [7,14]. Therefore, part of the methods focused on the separation of the cerium oxide abrasive from the abrasive–glass polishing waste using physical separation methods such as flotation [14–16], sieving [16], gravity separation [16], and selective flocculation [16]. However, it is difficult to remove all of the polished glass because its particle size is very small (<5 µm) [7]. Recently, Wang et al. [17,18] applied the liquid–liquid–powder separation method, a technique effective for ultrafine particle separation, to separate the cerium oxide abrasive. Higher separation results of the cerium oxide abrasive (the grade and recovery were both higher than 90%) could be achieved; however, high purity cerium oxide abrasive could not be obtained because the polished glass still could not be fully removed. Therefore, a few studies focused on the removal of the polished glass to recover the cerium oxide abrasive through alkali leaching using a high concentration of sodium hydroxide (NaOH), potassium hydroxide (KOH), or sodium carbonate (Na₂CO₃) solution [19–22]. However, the main problems with alkali leaching are that it generates high volumes of alkaline wastewater and needs large scale facilities [7,16]. Besides, although the polished glass can also be dissolved in hydrofluoric acid (HF) solution and thus be removed, subsequent wastewater treatment is needed. In addition, the employment of HF solution has safety concerns and is not suitable for industrial application.

Alkaline roasting is a heat treatment technique used in extractive metallurgy which heats mineral with alkaline chemical such as NaOH, KOH, or Na₂CO₃. The certain metal component in the mineral reacts with the alkaline chemical and is transformed into a water soluble alkaline-metal compound, which is easy to be dissolved by water leaching; thus, is beneficial for the subsequent metallurgical process. Several studies applying the alkaline roasting followed by water leaching to recover valuable metals from minerals and secondary resources or to remove hazardous metals from industrial wastes have been reported [23–30]. Because the main constituent of the polished glass is silica (SiO₂), it is considered that by alkaline roasting using an alkaline chemical such as NaOH, the polished glass in the abrasive–glass polishing waste can be transferred to a water soluble compound of sodium silicate (Na₂SiO₃), which can be dissolved and removed by subsequent water leaching treatment; thus, the cerium oxide abrasive of high purity can be obtained.

This study attempted to recover the cerium oxide abrasive from the abrasive–glass polishing waste through removing the polished glass by alkaline roasting using NaOH followed by water leaching. The affecting factors of alkaline roasting, including roasting temperature, mass ratio of polishing waste to NaOH, and roasting time, as well as those of water leaching, including leaching pH, leaching temperature, leaching time, and liquid–solid ratio, on the removal efficiency of the polished glass, were investigated. The characterization of the recovered cerium oxide abrasive obtained under the optimal conditions was carried out and compared with the original one to confirm the possibility of its reuse for polishing.

2. Materials and Methods

2.1. Materials

Two kinds of experimental materials including abrasive–glass polishing waste and cerium oxide abrasive were obtained from Global Display Taiwan Co., Ltd, Taiwan. The abrasive–glass polishing waste was produced from polishing glass panels with the cerium oxide abrasive. Flocculants were not introduced for dewatering after polishing process and thus only the cerium oxide abrasive and the polished glass were in the polishing waste. The content of cerium oxide abrasive in the polishing waste
was 80.5 wt.%, and the remaining 19.5 wt.% was the polished glass. The cerium oxide abrasive contained 70 wt.% CeO$_2$, and the remainder was other rare earth oxides such as lanthanum oxide. The detail characteristics of the abrasive–glass polishing waste and the cerium oxide abrasive are demonstrated in Section 3.3 together with those of the recovered cerium oxide abrasive for comparison. Granular NaOH (Sigma-Aldrich Co., St Louis, MO, USA) was used in the alkaline roasting experiment. Concentrated hydrochloric acid (HCl) (37 wt.%) (Sigma-Aldrich) and 1 M NaOH solution (Sigma-Aldrich) were used to adjust the solution pH. All of the reagents were reagent grade.

2.2. Methods

A decided amount of the as-received abrasive–glass polishing waste sample and the granular NaOH reagent were put into a nickel crucible and homogeneously mixed. The crucible was then moved to an electric muffle furnace (HT-1000N, YE CHANCE Enterprise Co. Ltd., Taiwan), heated to decided roasting temperature, kept for decided roasting time, and then cooled down to room temperature. Water leaching was carried out to the roasting products by using distilled water under decided leaching conditions using a hot plate stirrer (PC-420D, Corning Inc., New York, NY, USA) and stirring at 400 rpm. After the water leaching experiment finished, solid–liquid separation was then performed by using a centrifuge (Tabletop Centrifuge Model 4000, KUBOTA Corporation, Osaka, Japan). The solid fraction (i.e., the water leaching residue) was further dissolved by using aqua regia at 70 °C for 3 h to remove the cerium oxide abrasive. The undissolved residue was dried at 105 °C and weighted to obtain the mass of polished glass without being removed. The glass removal efficiency was calculated based on the difference between that and the initial mass of polished glass in the as-received polishing waste sample. The characterization of the water leaching residue obtained under the optimal alkaline roasting and water leaching conditions (i.e., the recovered cerium oxide abrasive) was carried out. The elemental composition was determined by using X-ray fluorescence spectroscopy (XRF) (SEA6000VX, TechMax Technical Co., Ltd., New Taipei City, Taiwan). The particle size distribution (PSD) was measured using a laser particle size analyzer (Bettersizer S2, Bettersize Instruments Ltd., Hong Kong, China). The mineralogical crystal phases were analyzed using as X-ray diffraction (XRD) spectrometer (Bruker D2 Phaser, Blue Scientific, Cambridge, UK). The morphology was observed through scanning electron microscopy (SEM) (S-3000H, HITACHI, Tokyo, Japan). Each experiment in this study was performed at least twice. The mean value and standard deviation were calculated and plotted.

3. Results and Discussion

3.1. Alkaline Roasting

3.1.1. Effect of Roasting Temperature

The effect of roasting temperature on glass removal efficiency is presented in Figure 1. The mass ratio of polishing waste to NaOH was 1:1 and the roasting time was 2 h. The water leaching conditions were leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 200 mL/g. More than 85% of the polished glass was removed when the roasting temperature was 300 °C. The glass removal efficiency increased with the increase in the roasting temperature from 300 to 500 °C. The polished glass in the abrasive–glass polishing waste was fully removed when the roasting temperature was higher than 450 °C.

The photographs of the roasting products in the crucibles after roasted at various temperatures from 300 to 500 °C are shown in Figure 2. When roasted at 300 °C, white-gray powders of abrasive–glass polishing waste were observed in the crucible, which implied that the gray powders of polished glass were not fully reacted with NaOH. When roasted at 500 °C, white powders of cerium oxide abrasive and brown powders of sodium silicate were observed in the crucible, which suggested that the gray powders of polished glass were fully reacted with NaOH and transferred to brown sodium silicate powders.
The chemical reaction of SiO₂ and NaOH is shown in Equation (1).

\[
\text{SiO}_2 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SiO}_3 + \text{H}_2\text{O} \tag{1}
\]

The change in the Gibbs free energy (ΔG) of the above chemical reaction as function of temperature is presented in Figure 3. The Gibbs free energy changes were calculated by using the software HSC Chemistry version 6.0. The Gibbs free energy changes decreased with the increase in temperature and were all negative values throughout the temperature ranging from 100 to 1000 °C, which suggested the reaction between SiO₂ and NaOH was spontaneous. On the other hand, because the melting point of NaOH is between 400–500 °C, the roasting temperature of higher than 400 °C is needed to molten the NaOH to ensure its full reaction with the glass. According to the experimental results, the optimal roasting temperature for glass removal efficiency was higher than 450 °C, which was consistent with the theoretical one.

The XRD analysis results of the residues after alkaline roasting at various temperature followed by water leaching were illustrated in Figure 4. The residue roasted at 300 °C had the apparent characteristic peaks of CeO₂ (International center for Diffraction data (ICDD) card No. 43-1002). On the other hand, although not obviously, one possible characteristic peak of SiO₂ (ICDD card No. 40-1045, matching with the largest peak at 26.74288°) were detected. In general, glass is essentially an amorphous phase so that its characteristic peaks may not be simply detected in XRD analysis. With the increase in roasting temperature, this possible peak of SiO₂ disappeared. Only the characteristic peaks of CeO₂ could be apparently detected when the residue was roasted at higher than 400 °C. The results indirectly supported that the polished glass was removed.
could be apparently detected when the residue was roasted at higher than 400 °C. The results indirectly supported that the polished glass was removed.

![Figure 3](image-url)

**Figure 3.** The Gibbs free energy change of the chemical reaction of SiO$_2$ (silica) and NaOH as a function of temperature.

![Figure 4](image-url)

**Figure 4.** XRD (X-ray diffraction) analysis of the residues after alkaline roasting at various temperature followed by water leaching (experimental conditions: abrasive–glass polishing waste: approximately 1 g; mass ratio of polishing waste to NaOH: 1:1; roasting time: 2 h; water leaching pH: 3; leaching temperature: 25 °C, liquid–solid ratio: 200 mL/g).

3.1.2. Effect of Mass Ratio of Polishing Waste to NaOH

The effect of mass ratio of polishing waste to NaOH on glass removal efficiency is presented in Figure 5. The roasting temperature was 450 °C and the roasting time was 2 h. The water leaching conditions were leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 200 mL/g. When the mass ratio of polishing waste to NaOH was 1:0.5, the glass removal efficiency was 73.4%. The polished glass could not be fully removed from the abrasive–glass polishing waste. The glass removal efficiency increased with the increase in the mass ratio of polishing waste to NaOH. The polished glass in the abrasive–glass polishing waste was fully removed when the mass ratio of polishing waste to NaOH was higher than 1:1.

According to the chemical reaction of SiO$_2$ and NaOH as shown in Equation (1), the stoichiometric molar ratio of SiO$_2$ to NaOH is 1:2, i.e., 1 g SiO$_2$ (M.W. = 60) can react with 1.33 g NaOH (M.W. = 40) to form Na$_2$SiO$_3$. In this study, the amount of polished glass in the as-received abrasive–glass polishing waste sample was about 20 wt.%, i.e., the mass of polished glass in 1 g polishing waste was about 0.2 g. Therefore, 0.27 g NaOH was theoretically needed to fully react with the polished glass to form
Na$_2$SiO$_3$. However, the actual mass ratio of polishing waste to NaOH was 1:1. The results suggested that more NaOH is needed to achieve sufficient contact with the polished glass in the polishing waste during roasting.

![Figure 5](image-url) **Figure 5.** Effect of mass ratio of polishing waste to NaOH on glass removal efficiency (experimental conditions: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; roasting time: 2 h; water leaching pH: 3; leaching temperature: 25 °C, liquid–solid ratio: 200 mL/g).

3.1.3. Effect of Roasting Time

The effect of roasting time on glass removal efficiency is shown in Figure 6. The roasting temperature was 450 °C and the mass ratio of polishing waste to NaOH was 1:1. The water leaching conditions were leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 200 mL/g. The glass removal efficiency increased with the increase in the roasting time. When the roasting time was 1 min, the glass removal efficiency was 68.3%. The polished glass in the abrasive–glass polishing waste was fully removed when the roasting time was more than 30 min.

![Figure 6](image-url) **Figure 6.** Effect of roasting time on glass removal efficiency (experimental conditions: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; water leaching pH: 3; leaching temperature: 25 °C, liquid–solid ratio: 200 mL/g).

3.2. Water Leaching

3.2.1. Effect of Water Leaching pH

According to the above experimental results, the optimal alkaline roasting conditions were roasting temperature of 450 °C, mass ratio of polishing waste to NaOH of 1:1, and roasting time of 30 min.
The subsequent investigations on water leaching were applied to the roasting products under the above conditions. The effect of water leaching pH on glass removal efficiency is presented in Figure 7. The water leaching temperature was 25 °C and the liquid–solid ratio was 200 mL/g. The initial solution pH after the roasting product was put into the distilled water for water leaching was about pH 12. Even if the polished glass had been fully transformed to Na₂SiO₃ after alkaline roasting, however, the glass removal efficiency was extremely low at the initial pH of 12. The reason is speculated as follows. Although Na₂SiO₃ is a water-soluble compound, it is stably existed in a strong base solution. In reality, it was clearly observed during the experiment that the gelatinous Na₂SiO₃ appeared in the strong base leachate after the roasting product was put into the distilled water. Because the gelatinous Na₂SiO₃ could not dissolve into water, the Si component could not be removed but coexisted with the cerium oxide abrasive after water leaching experiment, which led to lower the glass removal efficiency. After adjusting the solution pH to neutral and acid pH range, the gelatinous Na₂SiO₃ started to be decomposed and dissolved; hence, the glass removal efficiency increased. The glass removal efficiency reached 100%, i.e., the Si component was fully removed from the cerium oxide abrasive when the water leaching pH was below pH 4.

![Figure 7](image-url)

**Figure 7.** Effect of water leaching pH on glass removal efficiency (experimental conditions: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; leaching temperature: 25 °C, liquid–solid ratio: 200 mL/g).

### 3.2.2. Effect of Leaching Temperature

The effect of water leaching temperature on glass removal efficiency at different solution pH is shown in Figure 8. The liquid–solid ratio was 200 mL/g. At pH 3, the polished glass was fully removed when the water leaching was carried out at 25–60 °C. When the leaching temperature was higher than 60 °C, the glass removal efficiency started to decrease. The glass removal efficiency decreased to 74.5% when the leaching temperature was 80 °C. It was observed during the experiment that the gelatinous Na₂SiO₃ appeared at the leaching temperature of 80 °C. It is speculated that when the leaching temperature is higher than 60 °C, the water starts to evaporate, which leads to the precipitation of gelatinous Na₂SiO₃ and thus the glass removal efficiency decreases. At pH 7, the glass removal efficiency was around 47% when the water leaching was carried out at 25–60 °C. When the leaching temperature was higher than 60 °C, the glass removal efficiency started to decrease. The tendency was the similar to that at pH 3. At pH 12, the glass removal efficiency was extremely low and had no substantial change with the increase in water leaching temperature. In addition to the reason of water evaporation at high temperature, it can also be attributed to the stability of Na₂SiO₃ in a strong base solution as mentioned in Section 3.2.1. Similarly, the gelatinous Na₂SiO₃ was observed during all of the experiments conducted at pH 7 and pH 12.
3.2.3. Effect of Liquid–Solid Ratio

The effect of liquid–solid ratio on glass removal efficiency is shown in Figure 9. The water leaching pH was pH 3 and the water leaching temperature was 25 °C. The glass removal efficiency was ca. 40% when the liquid–solid ratio was 10 mL/g. With the increase in liquid–solid ratio, the glass removal efficiency also increased. When the liquid–solid ratio was higher than 25 mL/g, the glass removal efficiency reached 100%, i.e., the polished glass was fully removed. Higher liquid–solid ratio helps to exceed the solubility of sodium silicate and thus is beneficial for its dissolution.

Figure 9. Effect of liquid–solid ratio on glass removal efficiency (experimental conditions: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; liquid–solid ratio: 200 mL/g).

3.3. Characterization of Recovered Cerium Oxide Abrasive

According to the above experimental results, the optimal water leaching conditions were leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 25 mL/g. The subsequent investigations on the characterization of the recovered cerium oxide abrasive, including elemental composition, mineralogical crystal phase, particle size distribution, and morphology, were applied to the water leaching residue after alkaline roasting followed by water leaching under the above optimal conditions. In addition, the characteristics of the original cerium oxide abrasive and the abrasive–glass polishing waste are also demonstrated for comparison.
The elemental composition of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste are shown in Table 1. The main content of Ce and La in the recovered cerium oxide abrasive was 67.3 wt.% and 20.4 wt.%, respectively. In addition, Si was not contained. On the other hand, the content of Ce and La in the original cerium oxide abrasive was 66.4 wt.% and 21.2 wt.%, respectively. Si was also not contained. By contrast, the content of Ce and La in the abrasive–glass polishing waste was 56.2 wt.% and 16.1 wt.%, respectively. In addition, the abrasive–glass polishing waste also contained Si of 18.5 wt.%. The main elemental composition of the recovered cerium oxide abrasive obtained under the optimal alkaline roasting and water leaching conditions was similar to that of the original one. Moreover, Si was fully removed compared to the abrasive–glass polishing waste.

Table 1. Elemental composition of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste (experimental conditions of the recovered cerium oxide abrasive: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

| Element | Recovered Cerium Oxide Abrasive | Original Cerium Oxide Abrasive | Abrasive–Glass Polishing Waste |
|---------|---------------------------------|--------------------------------|-------------------------------|
| Ce      | 67.3                            | 66.4                           | 56.3                          |
| La      | 20.4                            | 21.2                           | 16.1                          |
| Zn      | 4.08                            | 4.34                           | 4.66                          |
| Ni      | 3.98                            | 4.43                           | 1.64                          |
| Ag      | 2.74                            | 1.86                           | 1.39                          |
| Zr      | 1.50                            | 1.77                           | 1.41                          |
| Si      | N.D.                            | N.D.                           | 18.5                          |

[unit: wt.%].

The XRD analysis results of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste are shown in Figure 10. Only the characteristic peaks of CeO$_2$ (ICDD card No. 43-1002) were obviously detected in the recovered cerium oxide abrasive, the same as those observed in the original cerium oxide abrasive. In contrast, the abrasive–glass polishing waste also had the characteristic peaks of CeO$_2$ (ICDD card No. 43-1002). In addition, one possible characteristic peak of SiO$_2$ (ICDD card No. 40-1045, matching with the largest peak at 26.74288°) was detected. As also mentioned in Section 3.1.1, glass is essentially an amorphous phase so that its characteristic peaks may not be simply detected in XRD analysis. Compared with the result of the recovered cerium oxide abrasive, this possible peak of SiO$_2$ disappeared, which indirectly supported that the polished glass was removed after alkaline roasting followed by water leaching.

The particle size distribution of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste are shown in Figure 11. The recovered cerium oxide abrasive obtained after alkaline roasting followed by water leaching had a particle size distribution of 0.119 ($D_{10}$)–1.195 ($D_{90}$) μm, with a mean particle size ($D_{50}$) of 0.309 μm. On the other hand, the original cerium oxide abrasive had that of 0.112 ($D_{10}$)–0.852 ($D_{90}$) μm, with a mean particle size ($D_{50}$) of 0.274 μm. By contrast, the abrasive–glass polishing waste had that of 0.101 ($D_{10}$)–1.877 ($D_{90}$) μm, with a mean particle size ($D_{50}$) of 0.457 μm. The particle size distribution of the recovered cerium oxide abrasive was similar to that of the original one, which was suitable to be reused for polishing again.
Figure 10. XRD analysis of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste (experimental conditions of the recovered cerium oxide abrasive: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

Figure 11. Particle size distribution of (a) the recovered cerium oxide abrasive, (b) the original cerium oxide abrasive, and (c) the abrasive–glass polishing waste (experimental conditions of the recovered cerium oxide abrasive: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

The SEM images of the recovered cerium oxide abrasive, the original cerium oxide abrasive, and the abrasive–glass polishing waste are shown in Figure 12. The recovered cerium oxide abrasive had sharp edges similar to the original one, which could be reused for polishing. By contrast, the polishing waste did not have apparent sharp edges because its surface was covered by the polished glass. On the other hand, it is worth mentioning that if the particle shape of the recovered cerium oxide abrasive has substantial change (i.e., the sharp edges become round corners due to long-term usage), which affects
its polishing performance and thus no longer suitable for polishing, it still can be used as an alternative secondary resource of rare earth elements.

![Figure 11](image1.png)

![Figure 12](image2.png)

**Figure 11.** Particle size distribution of (a) the recovered cerium oxide abrasive, (b) the original cerium oxide abrasive, and (c) the abrasive–glass polishing waste (experimental conditions of the recovered cerium oxide abrasive: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

**Figure 12.** SEM (scanning electron microscopy) images of (a) the recovered cerium oxide abrasive, (b) the original cerium oxide abrasive, and (c) the abrasive–glass polishing waste (experimental conditions of the recovered cerium oxide abrasive: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

### 3.4. Economic Assessment

In this section, a brief economic assessment on the proposed recovery method is conducted based on the optimal alkaline roasting and water leaching conditions obtained from the foregoing experiments. The total cost of the proposed recovery method including electricity, water, and chemical reagents for the treatment of 1 kg abrasive–glass polishing waste is calculated using the local price data in Taiwan. The price unit is presented as New Taiwan Dollar (NT$). The results are summarized in Table 2.

According to the electricity prices set by the Taiwan Power Company [31], the price of low voltage electricity for industrial use in a medium and small factory is 3 NT$/kWh at peak hours and 2.06 NT$/kWh at off-peak hours. The average price of 2.5 NT$/kWh is adopted for cost calculation. The electricity consumption is contributed by both alkaline roasting and water leaching. In this study, the alkaline roasting experiment is performed using an electric muffle furnace (HT-1000N, YE CHANCE), including increasing the temperature from room temperature to 450 °C, maintaining that at 450 °C for 30 min, and decreasing that from 450 °C to room temperature. The consumed electricity measured by using a dynamometer (AR78-3, Arepu Co. Ltd., Taichung City, Taiwan) is 0.065 kWh. Therefore, the electricity price of alkaline roasting is NT$0.163. On the other hand, the water leaching experiment is performed using a hot plate stirrer (PC-420D, Corning Inc., Corning, NY, USA), including...
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adapting the solution pH from pH 12 to pH 3 for Na$_2$SiO$_3$ dissolution and from pH 3 to pH 7 for effluent discharge. The consumed electricity measured by using the dynamometer (AR78-3, Arepu) is 0.006 kWh. Therefore, the electricity price of water leaching is NT$0.015. Hence, the total electricity price for the treatment of 1 g polishing waste is NT$0.178. Consequently, the electricity cost is 178 NT$/kg. It needs to be mentioned that the above electricity cost may decrease if larger amount of polishing waste can be simultaneously treated in the electric muffle furnace and the hot plate stirrer.

Table 2. Cost of the proposed recovery method for the treatment of 1 kg abrasive–glass polishing waste (calculated based on the optimal experimental conditions: abrasive–glass polishing waste: approximately 1 g; roasting temperature: 450 °C; mass ratio of polishing waste to NaOH: 1:1; roasting time: 30 min; water leaching pH: 3, leaching temperature: 25 °C, liquid–solid ratio of 25 mL/g).

| Item                        | Consumed Amount (a) | Unit Price (b) | Price (a × b) | Total Cost  |
|-----------------------------|---------------------|----------------|---------------|-------------|
| Electricity                 |                     |                |               |             |
| Alkaline roasting (1)       | 0.065 kWh           | 2.5 NT$/kWh    | NT$0.163      |             |
| Water leaching (2)          | 0.006 kWh           | 2.5 NT$/kWh    | 0.178 NT$/g   |             |
| Total price (1) + (2)       | 0.171 kWh           |                | 0.178 NT$/g   | 178 NT$/kg  |
| Water                       | 25 mL               |                | 36 NT$/kg     |             |
| Chemical reagents           |                     |                |               |             |
| Granular NaOH (3)           | 1 g                  | 700 NT$/kg     | NT$0.7       |
| Concentrated HCl (4)        | 3 mL                | 1100 NT$/2.5 L | NT$1.32      |
| 1 M NaOH solution (5)       | 2.5 mL              | 800 NT$/L      | NT$2.0       |
| Total price (3) + (4) + (5) | 4.02 NT$/g          |                | 4020 NT$/kg  |
| Total cost                  |                     |                | 4234 NT$/kg  |             |

(NT$: New Taiwan Dollar).

The water consumption in the proposed recovery method is only contributed by water leaching. In this study, the liquid–solid ratio in the water leaching experiment is 25 mL/g; thus, the water quantity for the treatment of 1 kg polishing waste is 2.5 L. The water cost is calculated through the water fee trial query system of Taiwan Water Corporation [32]. The following conditions are input for trial calculation: Type of water: General user water (general, industry, business, and government agencies); Period: 1.0 (one month); Tube diameter: 20 mm; Water consumption: 0.0025 m$^3$; Not including the general waste disposal fee, the catchment conservation and compensation fees, and the sewage sewerage fee. As a result, the water cost is 36 NT$/kg.

The chemical reagents include the granular NaOH, concentrated HCl, and 1 M NaOH solution. According to a local chemical distributor (UNI-ONWARD Corporation, New Taipei City, Taiwan), the selling price of granular NaOH (purity: 98%) is 700 NT$/kg, that of concentrated HCl (37 wt.%) is 1100 NT$/2.5 L, and that of 1 M NaOH solution is 800 NT$/L. In the alkaline roasting experiment, the mass ratio of polishing waste to NaOH is 1:1; thus, the quantity of consumed granular NaOH is 1 g. Therefore, the price of granular NaOH is NT$0.7. In the water leaching experiment, the amount of concentrated HCl used to adjust the pH of water leachate from pH 12 to pH 3 for Na$_2$SiO$_3$ dissolution is 3 mL. Therefore, the price of concentrated HCl is NT$1.32. In addition, the amount of 1 M NaOH solution used to adjust the pH of water leachate from pH 3 to pH 7 for effluent discharge is 2.5 mL. Therefore, the price of 1 M NaOH solution is NT$2.0. Hence, the total chemical reagent price for the treatment of 1 g polishing waste is NT$4.02. Consequently, the chemical reagent cost is 4020 NT$/kg.

According to the above calculated costs of electricity, water, and chemical reagents, the total cost is 4234 NT$/kg. In contrast, the treatment cost of general industrial waste in Taiwan ranges from 2020–4600 NT$/kg. Therefore, the treatment cost of the proposed recovery method is within that of the general industrial waste. In addition, the selling price of cerium oxide abrasive is 600–1800 NT$/kg. Consequently, the economic assessment result suggests that the proposed recovery method by using
alkaline roasting and water leaching to recover cerium oxide abrasive from abrasive–glass polishing waste possesses economic benefits.

Nevertheless, it needs to be emphasized that the above assessment does not include the infrastructure cost due to the limitation in obtaining the actual price data. In addition, the treatment cost is variable because the prices of electricity, water, and chemical reagents will be changed depending on several factors such as treatment amount, facility scale, different countries/regions, etc. Furthermore, the selling price of cerium oxide abrasive is also variable, which directly affects the profit.

4. Conclusions

This study attempted to recover the cerium oxide abrasive from the abrasive–glass polishing waste through removing the polished glass by alkaline roasting using NaOH followed by water leaching. The affecting factors of alkaline roasting, including roasting temperature, mass ratio of polishing waste to NaOH, and roasting time, as well as those of water leaching, including leaching pH, leaching temperature, leaching time, and liquid–solid ratio, on the removal efficiency of the polished glass, were investigated. The characterization of the recovered cerium oxide abrasive obtained under the optimal conditions was carried out to confirm the possibility of its reuse for polishing. The following results were obtained:

1. The polished glass in the abrasive–glass polishing waste can be fully removed under the optimal alkaline roasting and water leaching conditions of the roasting temperature of 450 °C, mass ratio of polishing waste to NaOH of 1:1, roasting time of 30 min, leaching pH of 3, leaching temperature of 25 °C, and liquid–solid ratio of 25 mL/g.

2. The characteristics including elemental composition, particle size distribution, mineralogical phases, and morphology of the recovered cerium oxide abrasive obtained under the optimal conditions were similar to those of the original one, which was suitable to be reused for polishing again.

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