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## RECOVERY OF COLEMANITE FROM TAILING USING A KNELSON CONCENTRATOR

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**Abstract:** Tailing from colemanite concentrators in Emet Boron Works contains significant amounts of boron and cause potential environmental problems. Therefore, the recovery of colemanite from these tailings is imperative to ensure no pollution of the environment. In addition, the tailings also have economic importance as a secondary resource due to their high content of  $B_2O_3$ . This study was undertaken to investigate the possibility of recovering colemanite from tailings using a Knelson concentrator. After samples in size of -1 mm and 0.5 mm were obtained from tailings (-3 mm) by comminution, these three different samples were placed into a Knelson concentrator. In addition to particle size, the effects of fluidization water velocity and bowl speed on the performance of the enrichment process were examined. A concentrate with a  $B_2O_3$  content of 34.2% was produced with a recovery of 78.3% from tailings with a  $B_2O_3$  content of 24.8%. Increasing the bowl speed improved the  $B_2O_3$  recovery. Increasing the fluidization velocity or reducing the particle size adversely affected the recovery percentage. The enrichment process also permitted the removal of any residual As and Fe.

**Keywords:** *Knelson concentrator, boron wastes, enrichment process, environment*

### Introduction

Turkey has a large reserve of boron minerals (Acarkan et al., 2005). Colemanite is one of the major boron minerals and is an important part of Turkey's boron mineral deposits (Koca et al., 2003). In colemanite ores, the major accompanying gangue minerals are clays, carbonate and, to a lesser extent, arsenic minerals. Beneficiation of coarser sized colemanite is accomplished by scrubbing for clay removal followed by classification (Koca and Savas, 2004). The finest fraction, which is typically less than 3 mm, is discharged into a tailings pond with the associated process water. This loss is not only the main cause of a significant loss of boron, but it also causes storage problems and environmental pollution (Ucar and Yargan, 2009).

Extraction of colemanite deposits in Turkey is operated by two sub-units of Eti Mine Works (Emet Boron Works and Bigadic Boron Works). In the two concentrators of Emet Boron Works (Espey and Hisarcik Concentrators), approximately 1.5 teragrams (Tg)/year of ore with 25-28%  $B_2O_3$  are processed to produce 0.7 Tg of concentrate, which contains up to 36-42%  $B_2O_3$ . However, 0.17 Tg/year of tailings are produced in these concentrators (0.07 Tg in Espey Concentrator and 0.10 Tg in Hisarcik concentrator). Approximately 4 Tg of tailings have already accumulated in the tailings ponds (1 Tg in Espey tailings pond and 3 Tg in Hisarcik tailings pond) (Emet Boron Works, 2014). The tailings have economic value due to their high  $B_2O_3$  grade (24.8%). In addition, stockpiling these tailings in the ponds causes potential problems, including the use of large areas of land and environmental pollution because of exposure to the atmosphere. Figure 1 shows Espey and Hisarcik tailings ponds. The recovery of boron from these tailings is important for resource extraction efficiency and to eliminate the problems associated with stockpiling.

The lifespan of Espey tailings pond will end in 2017, when it reaches its maximum capacity. It will be covered with top soil and revegetation will commence. As a result, huge amounts of colemanite present in the tailings will go unrecovered. Recovery activities of colemanite from this tailings pond by a Knelson concentrator will not only increase the lifespan of the pond, but it will also result in an increase in the amount of ore made available for sale.

In previous studies, different methods such as flotation (Gul and Kaytaz, 2006, Ucar and Yargan, 2009, Ozkan and Gungoren, 2012, Ucar et al., 2014, Klein et al., 2010), multi gravity separation (Ipek and Bozkurt, 2000), magnetic separation (Sonmez et al., 1996, Alp, 2008, Jordens et al., 2014) and hydrocyclones (Bentli et al., 2004) have been used to treat these process tailings.



Fig. 1. Colemanite tailings pond in Espey (left) and Hisarcik (right) areas

A Knelson concentrator is an enhanced gravity separator in which a centrifugal force is used as a separating force (Uslu et al., 2012). The feed material enters through a central feed tube as a slurry. The slurry is placed into the base plate at the bottom of the rotating conical bowl. Coarser/heavier particles are trapped within the grooves of

the bowl, forming a concentrate bed, whereas the finer/lighter particles are carried upward into the tailings stream when the water flow rises. The injection of water through fluidization ports located in the ribs of the bowl prevents compaction of the concentrate bed. This creates a fluidized bed, which acts as a concentrating chamber for coarser/heavier particles under an enhanced gravitational force (Coulter and Subasinghe, 2005).

In the enrichment of colemanite tailings using a Knelson concentrator, separation is not based on density differences. The density of the clay minerals and colemanite are almost the same. A detailed mineralogical examination has been undertaken by Colak et al. (2000). Smectite, illite, chlorite and kaolinite were reported in the clay minerals taken from the Espey colemanite ore. The density of these clays ranges from 2.5-3 g/cm<sup>3</sup> depending on their chemical structure. Therefore, gravity based separation of the colemanite clays cannot be considered. Colemanite processing by a Knelson concentrator is based on particle size/particle mass (such as the washing of finely sized clay minerals, which are finely dispersed in the slurry). The finely dispersed clay fraction is removed from the bowl by the overflow, whereas colemanite particles are captured in the bowl (Fig. 2).

A previous study demonstrated that a Knelson concentrator can be used to enrich a low grade colemanite concentrate (Uslu et al., 2015). In this study, the use of a Knelson centrifugal gravity separator for the recovery of colemanite from mine tailings was studied. The tailings studied here are characterized by clays with low colemanite contents. In the study, the effects of various factors such as particle size, bowl speed and fluidization water velocity, on the enrichment process, using a Knelson separator were investigated.

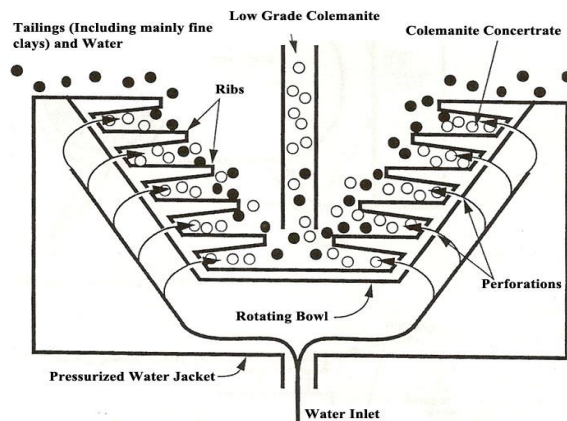


Fig. 2. Illustration of colemanite enrichment in Knelson Concentrator (Uslu et al., 2015)

## Material and method

### Material

A sample of colemanite tailings was obtained from the tailings pond of Espey colemanite concentrator from Emet Boron Works. The chemical and particle size analyses from the sample are provided in Tables 1 and 2, respectively. A graph of the sample tailings taken from Espey pond (cumulative undersize and B<sub>2</sub>O<sub>3</sub> grade) is shown in Fig. 3. Figure 3 also shows that P<sub>80</sub>, P<sub>75</sub> and P<sub>25</sub> are 0.4 mm, 0.13 mm and 0.04 mm, respectively. Chemical analyses were conducted in an accredited laboratory (Accredited by TURKAK TS EN ISO/IEC 17025) of the Emet Boron Works.

Table 1. Chemical analysis of tailings sample from Espey pond (%)

B <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	CaO	MgO	SrO	SO <sub>4</sub>	Fe	As (g·ton <sup>-1</sup> )
24.8	23.7	3.3	7.2	12.1	6.7	1.2	0.6	2.3	1065

The B<sub>2</sub>O<sub>3</sub> analysis was carried out using a titrimetric method according to ISO 21078-1/ASTM-C 169. Hot distilled water and concentrated HCl were added to the colemanite sample in a beaker. The mixture was heated for 30 min to achieve complete dissolution of the colemanite content fraction. The pH of the medium was adjusted to be 5.4-6.2 by addition of NaOH and HCl. After the pH adjustment, the solid residue was removed by filtration and the filtrate was collected. If the color of the filtrate was yellow, the color was changed to pink through the addition of HCl. The solution was allowed to cool to room temperature. The cooled solution was then titrated using NaOH until the color turned to that of an onion skin. Then, the B<sub>2</sub>O<sub>3</sub> percent content was calculated using a specific formula.

Arsenic (As) and iron (Fe) analyses were carried out using a polarized beam dispersive X-ray fluorescence spectrometer (XRF). Iron content (Fe, %) was calculated from the Fe<sub>2</sub>O<sub>3</sub>% data by multiplying the Fe<sub>2</sub>O<sub>3</sub>% by 0.6994.

Table 2. Particle size distribution and the B<sub>2</sub>O<sub>3</sub> grade of tailings sample from Espey pond

Size Fraction (mm)	Amount (%)	B <sub>2</sub> O <sub>3</sub> (%)	Cumulative undersize (%)
-3+1	4.7	19.8	100.0
-1+0.5	10.3	22.8	95.3
-0.5+0.3	8.0	22.3	85.0
-0.3+0.150	21.8	36.9	77.0
-0.150+0.106	8.9	29.1	55.2
-0.106+0.053	16.4	28.1	46.3
-0.053	29.9	11.1	29.9
Feed	100.0	24.8	

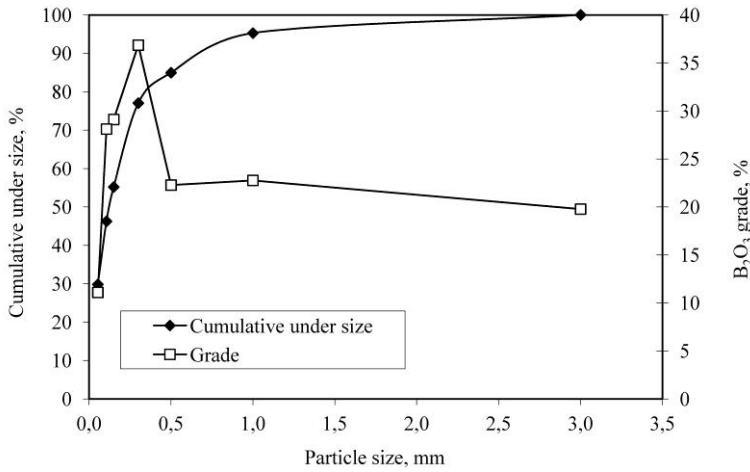


Fig. 3. Particle size and B<sub>2</sub>O<sub>3</sub> content of tailings sample from Espey pond

## Method

The sample was divided into three parts. The first part (originally -3 mm) was fed into the Knelson concentrator directly without any size reduction. The effect of particle size was also tested after grinding of as-received tailings to -1 mm and -0.5 mm using a rod mill. A laboratory batch type Knelson separator (KC-MD3) (Fig. 4) with a maximum bowl speed of 50 Hz (237 G-force) was used in the study. The bowl speed (8.3 Hz (11.2 G-force), 16.7 Hz (45 G-force), 25 Hz (100 G-force) and 33.3 Hz (179 G-force)) and fluidization water velocity (1, 3, 5 and 7 dm<sup>3</sup>/min) were investigated as the operational parameters. A range of bowl speeds and fluidization water velocities to be tested were generated from a preliminary study. Feed pulp of ~10% solids by weight was prepared in a volume of 500 cm<sup>3</sup>. Agitation of the beaker contents was performed for 15 min using an IKA RW-20 type overhead stirrer equipped with a 45° pitched blade turbine (four blades, each with a diameter of 50 mm). The dispersed slurry was fed into the Knelson concentrator at a rate of 25 cm<sup>3</sup>/min. Overflow (tailings) was collected in a bucket, whereas underflow (the colemanite concentrate) remained in the bowl. The bowl contents (i.e., the concentrate) were washed into a beaker. After dewatering using a vacuum filter, the products were dried, weighed and analyzed for boron oxide (B<sub>2</sub>O<sub>3</sub>), iron (Fe) and arsenic (As). Analyses were conducted in the Emet Boron Works laboratory. The B<sub>2</sub>O<sub>3</sub> recovery, Fe and As removal were calculated using the following equations:

$$\text{Recovery (\%)} = \frac{C.c}{C.c+T.t} \cdot 100 \quad (1)$$

$$\text{Removal (\%)} = 100 - \left( \frac{C.c}{C.c+T.t} \cdot 100 \right) \quad (2)$$

where,  $C$  is the amount of the concentrate (g),  $c$  is the grade of the concentrate (%),  $T$  is the amount of tailings (g) and  $t$  is the grade of the tailings (%).



Fig. 4. Lab-scale batch Knelson concentrator

## Results and discussion

Thirty-six tests were carried out, and the results are presented in Figs. 5-13. The  $B_2O_3$  recovery tended to increase with the bowl speed or by decreasing the fluidization water velocity (Figs. 5-7). The increase in the  $B_2O_3$  recovery results from increasing the centrifugal forces for high bowl speeds. A decrease in the velocity of the fluidization water resulted in lower  $B_2O_3$  grades for identical bowl speeds. Some of the clay particles entered into the area between the ribs (grooves) when the fluidization water velocity was insufficient. This resulted in a low  $B_2O_3$  grade in the concentrate. The negative effect of increasing the fluidization water on recovery was high for finer particle size (-0.5 mm) due to the increased wash-out of fine colemanite particles from concentrate grooves into tailings together with clays. Increasing the bowl speed and decreasing the water velocity were observed to produce an adverse effect on iron removal (Figs. 8-10), which can be explained in the same manner mentioned above. The centrifugal force at high bowl speeds appeared to also cause clay particles to remain between the ribs despite their fine sizes. In other words, the fine and light particles were overwhelmed by the centrifugal force. A higher fluidization flow assists in removing clay at the expense of increasing the colemanite losses. Because iron is associated with available clay minerals, iron removal is linked with the rejection of clay minerals in the tailings. Arsenic removal generally increased with decreasing bowl speeds and increasing water velocities (Figs. 11-13), which followed a similar trend as observed for clay/iron.

Although decreasing particle size adversely affected the  $B_2O_3$  recovery, it does not have a considerable impact on Fe and As removal (Figs. 5-13). As a result of the

size reduction, a considerable amount of fine colemanite and liberated clay particles were produced. In the enrichment process used in the plant, fine colemanite particles are lost in the overflow in the form of tailings along with the clays.

Table 3. Conditions and results for tests providing acceptable B<sub>2</sub>O<sub>3</sub> recovery

Particle Size, P <sub>100</sub> (mm)	Bowl speed (Hz)	Water velocity, (dm <sup>3</sup> ·min <sup>-1</sup> )	Concentrate amount (g)	Tailings amount (g)	B <sub>2</sub> O <sub>3</sub> grade of tailings (%)	B <sub>2</sub> O <sub>3</sub> grade of concentrate (%)	B <sub>2</sub> O <sub>3</sub> recovery (%)
-3	8.3	1	28.5	22.6	11.6	30.3	76.8
	16.7	1	35.8	15.7	9.1	30.2	88.3
	25.0	1	43.6	7.7	3.7	26.3	97.6
	33.3	1	44.8	6.8	2.7	25.8	98.4
	16.7	3	29.4	22.0	9.7	31.4	81.3
	25.0	3	33.6	15.8	5.6	29.2	91.7
	33.3	3	37.5	13.3	4.9	29.0	94.4
	25.0	5	30.4	22.6	8.9	32.2	82.9
	33.3	5	33.8	18.5	4.0	31.1	93.5
	25.0	7	22.5	25.4	8.4	34.2	78.3
33.3	7	30.5	21.0	6.9	32.7	87.4	
-1	8.3	1	30.8	24.1	12.9	26.0	72.0
	16.7	1	36.5	17.8	15.6	29.6	79.6
	25.0	1	46.8	7.6	6.6	28.1	96.3
	33.3	1	48.5	6.2	5.3	25.8	97.4
	16.7	3	28.9	26.0	14.6	32.8	71.4
	25.0	3	37.1	16.9	9.1	29.7	87.8
	33.3	3	42.0	13.2	6.4	30.0	93.7
	25.0	5	33.6	20.1	9.4	30.9	84.6
	33.3	5	36.2	17.0	7.2	30.8	90.1
	25.0	7	26.9	25.2	11.1	32.9	75.9
33.3	7	32.8	21.4	6.7	30.6	87.5	
-0.5	8.3	1	28.9	24.4	11.3	34.2	78.2
	16.7	1	38.5	15.1	6.1	31.0	92.9
	25.0	1	45.1	8.1	4.6	26.7	97.0
	33.3	1	47.3	6.6	7.5	26.5	96.2
	16.7	3	29.3	24.1	13.0	31.9	75.0
	25.0	3	36.8	15.4	7.5	30.3	90.6
	33.3	3	40.4	12.8	2.3	28.8	97.6
	25.0	5	32.1	19.7	9.0	31.4	85.1
	33.3		35.6	16.7	6.4	30.8	91.2
	25.0	7	28.3	22.7	9.4	27.9	78.8
33.3	7	33.6	18.6	7.3	31.6	88.6	

In terms of resource efficiency,  $B_2O_3$  recovery, exceeding 70% is considered acceptable for the plant. Test results and conditions providing acceptable  $B_2O_3$  recoveries ( $\geq 70\%$ ) and  $B_2O_3$  grades over the tailings grade ( $\geq 24.8\%$ ) are summarized in Table 3.

For a feed size of  $-3$  mm, a maximum  $B_2O_3$  content of 34.2% was achieved at a recovery of 78.3%. As expected, grinding the tailings resulted in a higher concentrate grade at the expense of a reduction in the recovery. A concentrate containing as high as 42.5%  $B_2O_3$  content was produced for a 3.7% recovery.

Although arsenic removals of up to 98.9% and iron removals of up to 98.7% could be obtained, arsenic removal of 4.5-45.0% and iron removal of 19.2-62.6% were achieved, providing acceptable levels of  $B_2O_3$  recovery. The minimum arsenic and iron grades in the concentrates were 765 g/Mg and 0.6%, respectively.

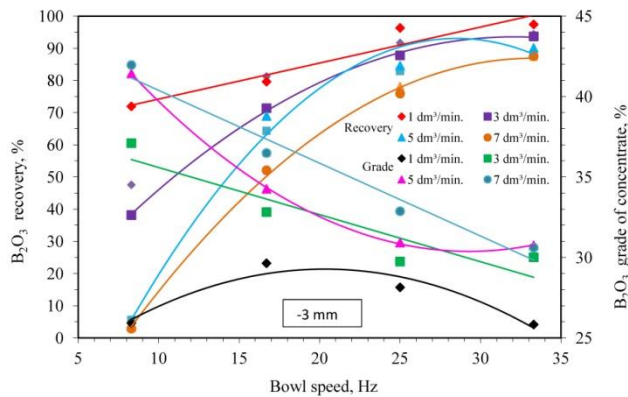


Fig. 5. Effect of bowl speed and fluidization water velocity on the  $B_2O_3$  recovery and grade (size  $-3$  mm)

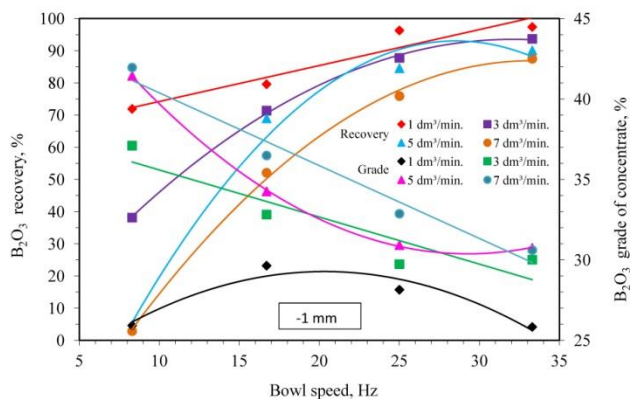


Fig. 6. Effect of bowl speed and fluidization water velocity on the  $B_2O_3$  recovery and grade (size  $-1$  mm)



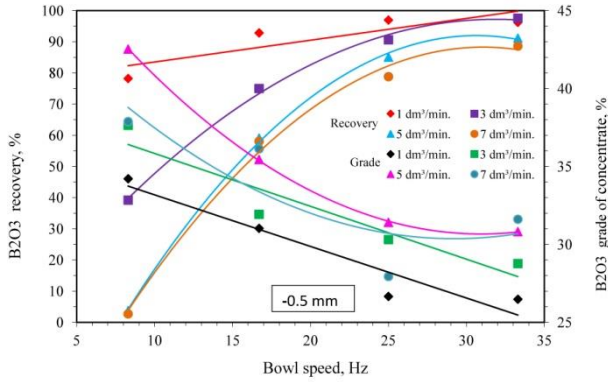


Fig. 7. Effect of bowl speed and fluidization water velocity on the B<sub>2</sub>O<sub>3</sub> recovery and grade (size -0.5 mm)

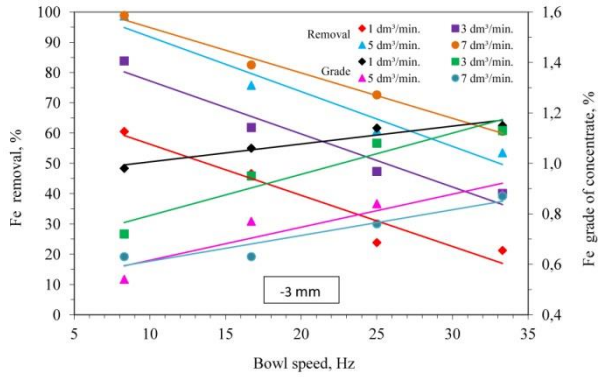


Fig. 8. Effect of bowl speed and fluidization water velocity on Fe removal and grade (size -3 mm)

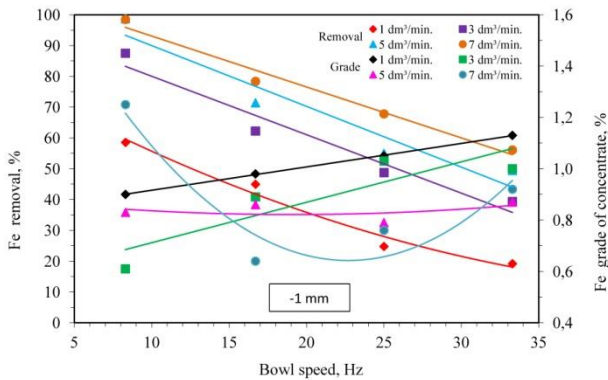


Fig. 9. Effect of bowl speed and fluidization water velocity on Fe removal and grade (size -1 mm)

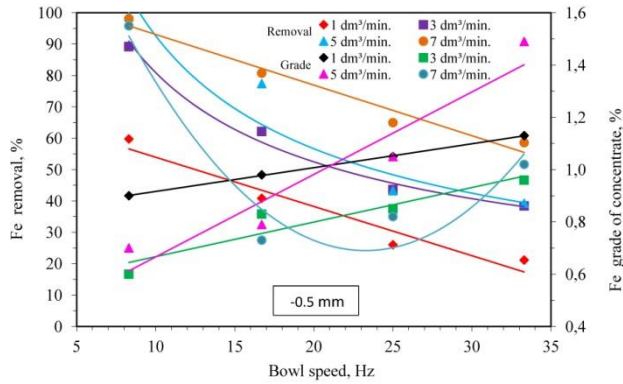


Fig. 10. Effect of bowl speed and fluidization water velocity on Fe removal and grade (size -0.5 mm)

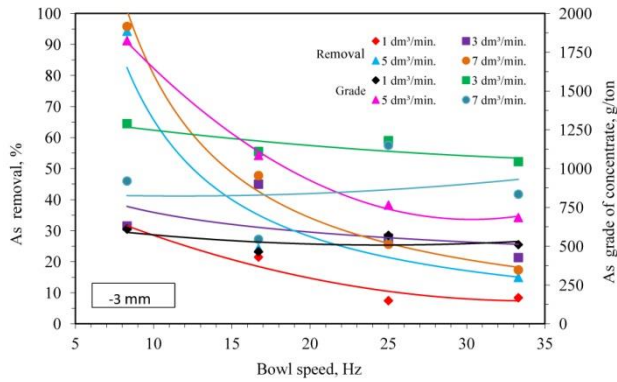


Fig. 11. Effect of bowl speed and fluidization water velocity on As removal and grade (size -3 mm)

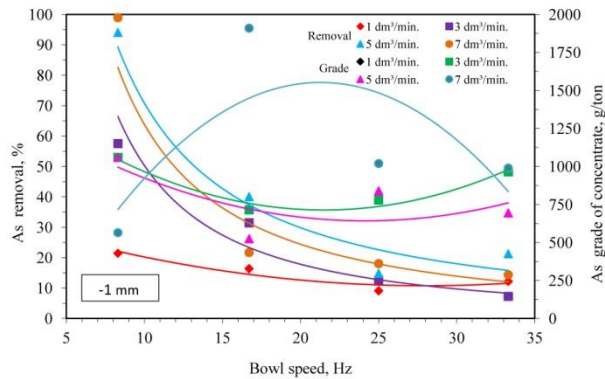


Fig. 12. Effect of bowl speed and fluidization water velocity on As removal and grade (size -1 mm)

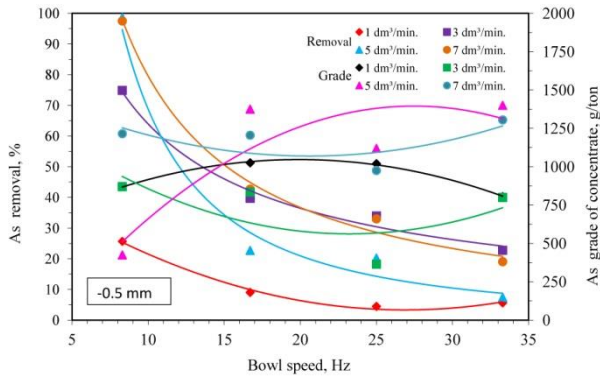


Fig. 13. Effect of bowl speed and fluidization water velocity on As removal and grade (size -0.5 mm)

High arsenic removal levels were found to be accompanied by a decrease in the  $B_2O_3$  recovery. This is attributed to the fine dissemination of arsenic in the colemanite and clays. A considerable amount of realgar and orpiment occurs in the voids/cracks of clays in crystalline form and are very fragile. As a result of the fragmentation of the colemanite during the concentration process, a high portion of fine sized realgar-orpiment is reported in tailings ponds. Therefore, in a Knelson concentrator, the level of arsenic was considerably reduced together with the clays by desliming and washing.

The test results showed that further size reductions in the colemanite tailings to produce a concentrate with a higher  $B_2O_3$  grade had no additional benefits, as it increases the  $B_2O_3$  loss in the tailings.

## Conclusions

A Knelson concentrator was used to increase resource extraction from colemanite tailings. The  $B_2O_3$  grade of the colemanite tailings increased from 24.8% to 42.5%, thus  $B_2O_3$  grade in the tailings increased by 71.4%.

Considering the acceptable  $B_2O_3$  recovery levels (>70%) for Emet Boron Works, a  $B_2O_3$  grade- $B_2O_3$  recovery combination of 34.2%-78.3% (for a -3 mm size) and 34.2%-78.2% (for a -0.5 mm size) yielded the best results in terms of the  $B_2O_3$  grade. For these combinations, As and Fe grades in the concentrates were 1150 g/megagram and 0.8% and 870 g/megagram and 0.9%, respectively.

A size reduction of colemanite tailings (-0.5 mm) did not enhance the enrichment process. The bowl speed and fluidization water velocity were determined to affect the separation performance, and the results showed a significant link between these parameters. The results also show that a Knelson concentrator can be used to scavenge colemanite from mine tailings.

However, a large scale Knelson concentrator, such as Knelson KC-CVD should be used in further studies because it would be more suitable for industrial mineral operations.

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