Exploiting tailored carboxymethyl cellulose depressant for managing carbon recovery in refractory gold ore flotation

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1. Introduction

With the slow depletion of easily processable gold deposits, increasingly complex gold ores have gained interest but require novel solutions for overcoming extraction challenges. While gold can be directly extracted from simple free-milling ores with conventional leaching, more complex ores, such as refractory ores, often require additional pre-treatment or new leaching techniques. Increasingly common are the double refractory gold ores where gold is locked in host minerals, typically sulfides, and associated with material that interferes with leaching, e.g., carbon.

Carbonaceous material in the form of organic and graphitic carbon is often associated with a variety of gold, as well as base metal ores around the world [Miller et al., 2016]. Carbonaceous gold deposits are estimated to constitute more than 20% of known unexploited gold reserves [Li et al., 2021]. The presence of carbon is problematic, with negative impacts in both smelting and leaching processes. Carbonaceous matter has been shown to significantly reduce the recovery of gold during leaching due to the well-known preg-robbing phenomena. Several processing methods have been utilized to either remove or minimize the impact of carbonaceous matter on leaching, including flotation, roasting, blinding, or blanking as well as new leaching techniques and lixiviants.

For sulfidic double refractory ores, flotation is commonly used in combination with the oxidative destruction of sulfides, such as roasting or pressure oxidation (POX). Due to its inherent hydrophobicity, carbonaceous matter is typically recovered into the flotation concentrate by natural flotation. While roasting can also remove carbon from the leach feed, the high amount of energy consumption and pollution associated with it make it less attractive nowadays. This method is frequently replaced by alternative processes such as pressure oxidation, which requires addressing the issue of carbon separately.

Carbon removal can be incorporated into the flotation stage of the process by preventing it from reporting to the concentrate either through depression or by employing a separate pre-flotation stage. While pre-flotation can be effective, complete removal of carbon regularly results in significant losses of valuable mineral. Conversely, the alternative depression strategy requires a highly selective depressant that can provide the efficient removal of carbon without compromising the recovery of gold-bearing sulfides. While neither technique may not always offer sufficient selectivity on its own, a combination of the two may be optimal to achieve the highest rejection of carbon while maximizing valuables recovery. Several depressants and dispersants have been evaluated and utilized for carbon depression, including starch, nigrosine, and naphthalene sulfonates (NS) [Pyke et al., 1999].

Carboxymethyl cellulose (CMC) is a well-studied depressant chemistry for hydrophobic gangue minerals in general and is best recognized for the effective depression of talcaceous gangue. It is also acknowledged that the modifiable molecular characteristics of CMC play an important role in the selectivity and efficiency of depression of specific hydrophobic gangue minerals [Mierczynska-Vasilev, and Beattie, 2010]. In addition to its depression function, CMC is also known to function as a dispersant in sulfide flotation [Bremmel et al., 2005] and therefore presents the opportunity to behave as a dual-functioning reagent in flotation. Although the application of CMC as a carbon depressant has been reported [Solongo et al., 2021], little attention has been paid to selecting the most optimal type of CMC for this purpose.

This work aims to identify the optimal CMC type for the selective depression of organic carbon in double refractory gold ore flotation. For this purpose, a range of CMC depressants with different molecular characteristics were studied and compared to naphthalene sulfonate, one of the more commonly used chemistries in treating carbonaceous ores. This study includes both fundamental single mineral flotations and flotations with a complex double refractory ore where the relative depressant efficiency and selectivity are considered.

2. Material and methods

2.1. Depressants

Characteristics of the depressants used in the study are presented in Table 1. CMC depressant of varying degrees of substitution (DS) were included in the tests, as well as a naphthalene sulfonate depressant/dispersant.

Table 1. Depressant characteristics.

Depressant	Average Mw (kDa)	Purity (%)	Relative DS level
Celect® HPD CMC	150 – 170	>98	Low
Celect® SD CMC		>98	High
Finnfix® 300 CMC		>98	Medium
Naphthalene sulfonate	1 - 5	>87	N/A

2.2. Single mineral flotations

Single mineral anthracite flotation tests were conducted using a Denver D12 machine with a 750ml cell. Anthracite (15g) was slurried in synthetically prepared process water having a total dissolved solids content of 1000ppm. After slurrying, the pulp was conditioned for 1 minute with a depressant solution (between 0 g/t and 20g/t), followed by 1 additional minute with methyl isobutyl carbinol (MIBC) frother to produce a 50ppm concentration. A bulk concentrate was collected over 6 minutes and the mass of dry concentrate sample was used to determine the recovery level of anthracite in each test.

2.3. Double refractory ore flotation

Batch flotation tests with a real ore system were performed with an ore sample received from Agnico Eagle's Kittilä gold mine in Finland. Main gold bearing minerals of the ore are reported to be pyrite and arsenopyrite. The flotation test flowsheet (Fig. 1) consisted of carbon pre-flotation, in which majority of the floatable organic carbon was removed with a frother, and a three-stage rougher flotation. The depressant, collector, and frother were dosed in the rougher conditioning and additional collector and frother dosages were added prior to concentrate collections 2 and 3.

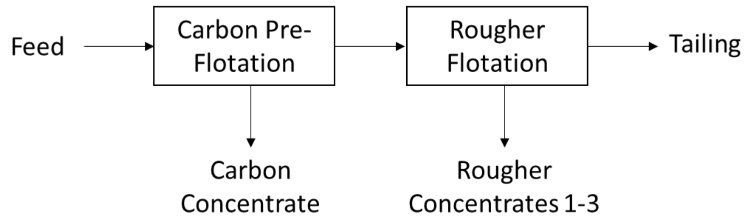

Figure 1. Flowsheet of the flotation tests with the double refractory gold ore.

Tests were performed with 1kg batches ground to the target flotation particle size in a stainless-steel rod mill and the flotation was performed with a Denver D12 flotation machine in a 2,5L cell at 35% solids content. A synthetic process water based on the mine process water analysis was used both in milling and flotation. The three concentrates were collected for 6, 9, and 13 minutes.

Gold was analyzed with fire assay + GFAAS. Carbon content as total carbon (TC), total inorganic carbon (TIC), and total organic carbon (TOC) was determined by combustion and acid treatment according to the standard SFS-EN 13137:2001.

3. Results and discussion

3.1. Single mineral flotation with carbon

The relative efficiency of carbon depression was compared between three different CMC types and a naphthalene sulfonate using single mineral flotation. For this purpose, anthracite was selected as a model carbon-rich mineral typically exhibiting a moderate to high natural hydrophobicity. In single mineral flotation depressant tests, the recovery response to the depressant dosage is typically near linear over a range which enables a relative efficiency to be obtained through interpolation. Two dosages of depressant were selected at which less than half the baseline recovery (in this case 66%) could be achieved while maintaining the frother concentration constant. For this system, the CMC dosages needed to be as low as 5g/t to 10g/t to present the appropriate near-linear response (Fig. 2).

While the system displayed moderately low sensitivity to the different CMC types, some clear trends were discerned. In terms of relative efficiency of anthracite depression, the order of decreasing efficiency was found to be: Celect® HPD CMC ≈ Finnfix® 300 CMC > Celect® SD CMC >> naphthalene sulfonate. This order of efficiency for the CMC depressants follows the charge density tendency where low-charge density CMCs are the most efficient at depressing the anthracite and high-charge density CMCs are the least efficient. This inclination is also consistent with depression studies on other naturally hydrophobic silicate minerals like talc [Mierczynska-Vasilev, and Beattie, 2010]. The low efficiency of the naphthalene sulfonate as a depressant in this study, appearing to be 5–10 times less efficient than the CMC depressants, illustrates the chemistry distinctions between CMC-based depressants/dispersants and naphthalene sulfonate dispersants. The higher relative efficiencies of the polysaccharides rivalling the naphthalene sulfonate may also reflect differences in the driving forces for adsorption, as well differences in the relative morphologies of the adsorbed layers.

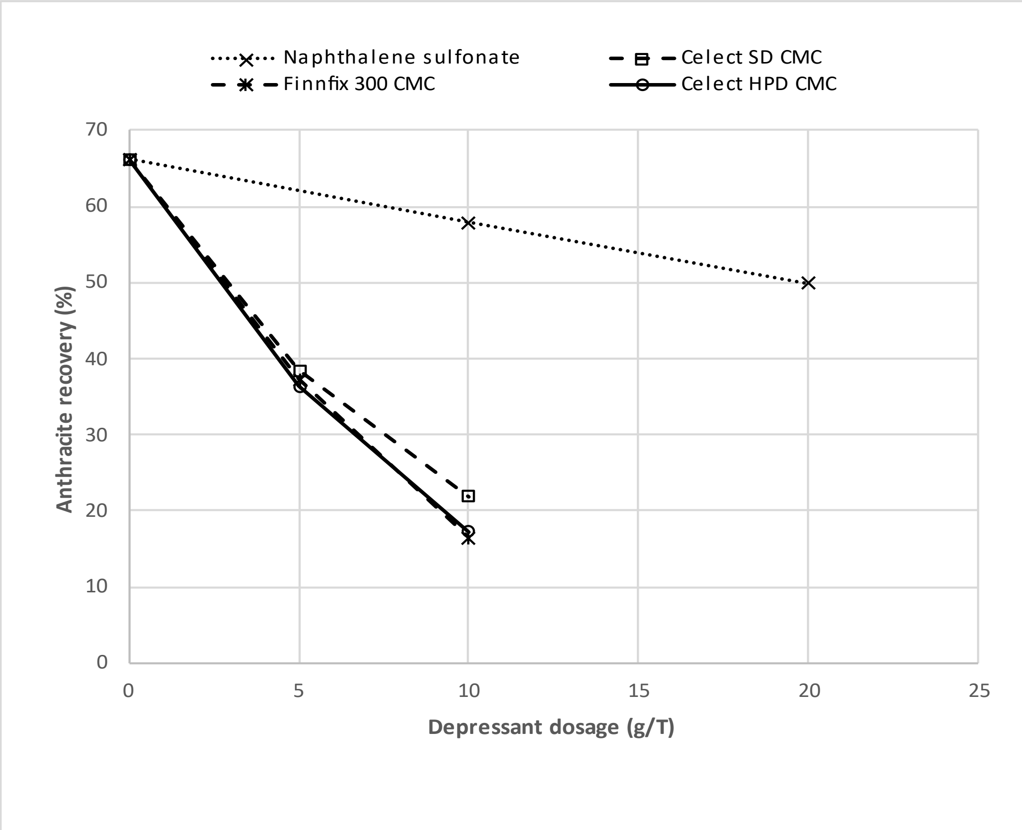

Figure 2. Single mineral flotation depressant dosage response curves for anthracite.

3.2. Flotations with double refractory ore

To evaluate the efficiency and selectivity of depression in a gold ore system, three CMC types were compared in batch flotation tests using a carbonaceous double refractory gold ore. The CMC dosage levels used were chosen to yield similar carbon recovery reduction levels, allowing for an objective comparison of the depression efficiency.

A baseline test with standard conditions (no depressant) was used to determine the reference conditions for selectivity comparison, affording gold recovery of 93,6 %, TOC recovery of 41,9 %, and TOC grade 5,4% in the rougher stage. All the tested CMCs reduced carbon recovery from the baseline test, with final TOC ranging from 32,5 % to 39,0 % in tests where CMC was used.

Relative recoveries of gold and carbon in the selectivity plots of Fig. 3 show that, as in the single mineral study, the efficiency of the organic carbon depression inversely followed the charge density of the CMC. Approximately 40% less low-charge density CMC was required to achieve TOC depression nearly identical to the medium-charge density product. Furthermore, the same high dosage levels of the high-charge density product afforded a somewhat elevated TOC recovery. These results support the reports that low-charge density products deliver better coverage of naturally hydrophobic mineral surfaces [Mierczynska-Vasilev, and Beattie, 2010]. In contrast to the single mineral studies, the significant differences between the CMC types observed in the real ore flotation suggest the complex system to be more sensitive to the molecular characteristics of CMC depressants.

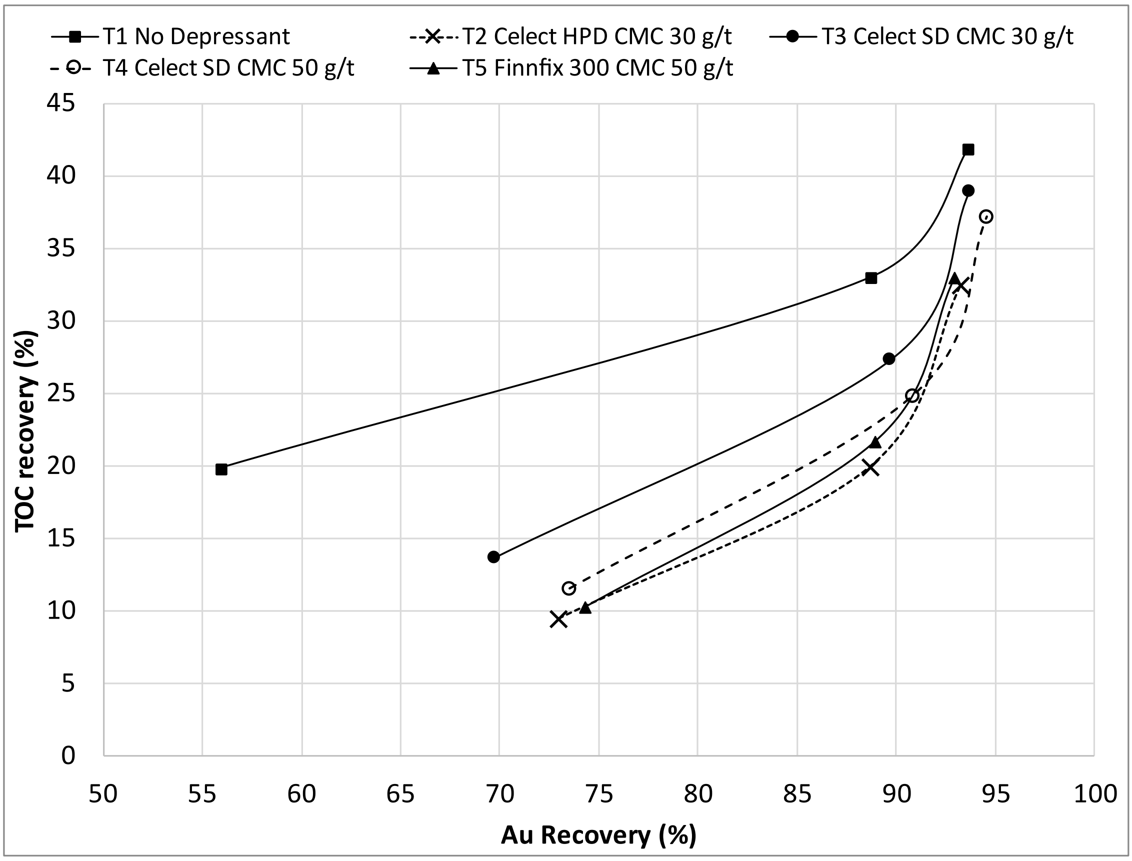

Figure 3. Rougher flotation with double refractory gold ore.

Overall, total recoveries of gold in CMC tests were at a similar level as the reference test, showing that the CMC depressants provided good selectivity with a high affinity of absorption on the gangue minerals. With all CMC depressant types, the recovery rate of gold bearing minerals was observed to be initially faster than in the reference test, yielding higher gold recovery in the first concentrate. It has been previously reported that CMC can improve flotation recovery of pentlandite through the dispersion of slimes from the sulfide mineral surface [Bremmell et al. 2005]. The uppermost level of gold recovery observed in this work was obtained with the highest charge density CMC when used at high dosage. This is consistent with the hypothesis that CMC can improve recovery through slimes dispersion but requires sufficient dosage to function as a dispersant.

The most efficient depressant type, Celect® HPD CMC, was further compared to the naphthalene sulfonate dispersant/depressant. The ore sample used for this comparison was observed to contain a lower level of TOC overall, allowing for an accurate comparison between the two tests only. Naphthalene sulfonate provided a significantly higher organic carbon recovery than the Celect® HPD CMC, as observed in the gold versus carbon selectivity recovery plots (Fig. 4). The low efficiency of the naphthalene sulfonates is also consistent with the observations of the single mineral flotation tests.

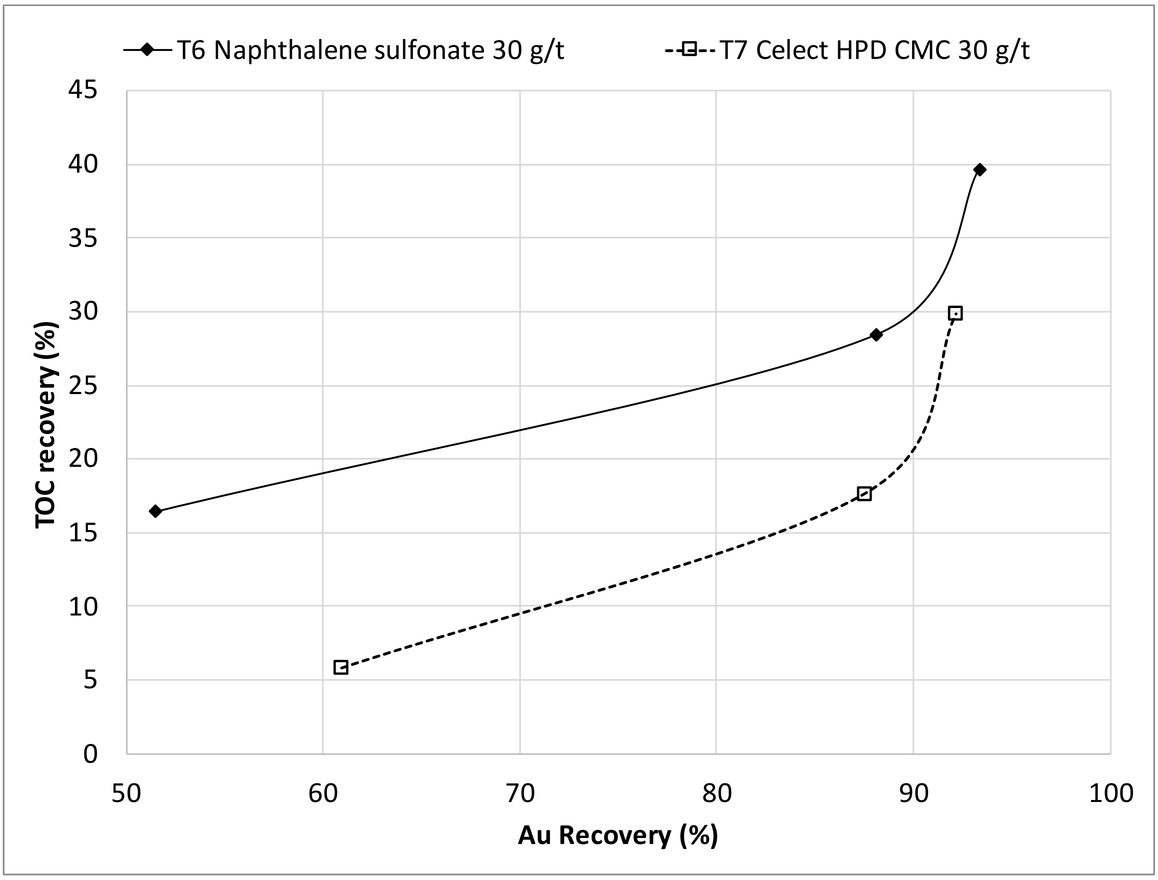

Figure 4. Rougher flotation comparison of naphthalene sulfonate with CMC.

4. Conclusions

Investigation into determining the optimal CMC type for carbon depression in flotation has revealed the important functionality of the CMC molecule charge density. While all CMC depressant reduced organic carbon recovery at a relatively low dosage, low-charge density CMC resulted in more efficient depression of carbon than high-charge density CMC, consistent in both the single mineral carbon depression and double refractory gold batch flotation tests. CMCs overall were observed to perform more efficiently as carbon depressants than a naphthalene sulfonate dispersing depressant.

In the single mineral system, differences in efficiency between CMC and naphthalene sulfonate were clearly visible, but the system did not exhibit the same level of sensitivity to each CMC type as the more complex real mineral system did. Furthermore, while the single mineral system demonstrated an estimation of depression efficiency, the actual selectivity of mineral separation could only be evaluated in a real system. The dual functionality of CMC as a depressant and a dispersant was manifested as a higher recovery rate of gold could only be observed in the complex mineral system.

5. References

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