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# Effective circulating load ratio in mill circuit for milling capacity and further flotation process - lab scale study

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**Abstract:** The design of the grinding circuits and the control of the transferring load in the ore preparation plants are of great importance from a technical and economic point of view. The importance of the circulating load for grinding process is well known and stated in the literature. However, there are not many studies on the effect on the following processes. In this study, the effect of the circulating load on both the grinding capacity and the subsequent flotation process was investigated at laboratory scale. Copper ore was used in the experiments. The circulating load was adjusted by changing the residence time of the material in the mill. Then, flotation experiments were carried out with the materials obtained at different circuit loads. The results showed that the grinding capacity can be increased up to 180% by optimizing the circulating load and it will positively affect the flotation performance. It was observed that a concentrate with the highest recovery for the same Cu grade was obtained with CLR of 150 % when compared to flotation recoveries through various CLRs. It is suggested that the circulating load should not be evaluated only in terms of the grinding process, but also the subsequent processes should be considered. Future studies in this area may contribute to industrial applications.

***Keywords:*** circulating load, mill capacity, flotation performance

## 1. Introduction

Comminution is defined as a process covering the size reduction activities in mining, mineral processing and in a range of other industries as well for both crushing and grinding operations of materials for different purposes, mostly size liberation. In mineral processing, it is necessary to liberate valuable minerals from other invaluable constituents so that those can be concentrated effectively (King, 1994). The current mineral reserves of the world require finer liberation sizes to separate the valuable one from gangue, effectively (Gupta&Yan, 2016). So, comminution process to achieve producing fine sizes include grinding units which are both energy-intensive and expensive, with tremendous room for improvement (Tromans, 2008).

In comminution process ended up grinding operation, a classifier, mostly hydrocyclone, is used to make the grinding operation reasonably and economically efficient and prevent overgrinding. Overgrinding is of particular concern because not only does it waste energy in unnecessary size reduction, it can also produce slime much smaller than can be processed efficiently. When slimes are produced, they are largely lost to the tailings, which not only wastes materials, but also results in the loss of all of the energy used in producing the slime particles. So, the process, to separate the ores in target size from the grinding unit and direct the coarser ones to grinding unit by the classifier creates "circulating load". Due to their larger capacity and supplying smaller utilization areas hydrocyclones as "most common classifiers" are generally preferred in closed circuit grinding units. But just because of the low separation performance of them, recent attempts were done to replace the high capacity and separation performance screens with hydrocyclones (Dündar et al, 2014). That is, some researchers pointed out the effective use of high capacity screens is possible resulting in high classification efficiency, low circulating load and increase in mill capacity as well as decreased numbers of mills (Barrios, 2007; Barkhuysen, 2009; Albuquerque et al., 2013; Frausto et al., 2017; Dündar, 2020). In addition to the idea of using high capacity screens in closed grinding circuits, some attempts have been

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well documented in the literature, to change the operational parameters such as lowering the solid ratios of hydrocyclone feed (Bartholomew & Mcivor, 2013; Jankovic, et. al, 2013a) and locating the hydro cyclone in an uncommon way. In this manner, the studies of Hochscheid, 1987 and the recent publication of Jokovic et al. (2020) showed that by using semi-inverted hydrocyclones, it became possible to lower the shortcut of fines and decrease the amount of fines over ground materials. They also pointed out that it was possible to shift the cut size ($d_{50}$) up to larger size by semi inverted hydrocyclones. Considering these finding in the literature, it can be suggested that the reduction of the short cut of fines is crucial both for producing slime material and enlarge the mill capacity with lower circulation loads.

Circulating load is essential in the grinding process and its ratio is always optimized by the classification efficiency of either cyclones or screens (Hukki & Eklund, 1965; Jankovic et al., 2013b). In literature, effective range of circulating load ratio (CLR) is reported as 200-600%. When searched through the works and researches in the past, 250% CLR is critical since the production rates or capacity factors of grinding units can be increased to 200-250% with 250% CLR and higher increases on CLR from this point does not create more producibility; only 10-50% increase on producibility was reported (Davis, 1925; Dorr & Anable, 1934; Hukki, 1967; Jankovic, et al., 2013b).

Running out the flotation plant with over ground material results in inefficient separation. It has been well documented in literature that flotation efficiency is affected by the feed size and at coarser sizes than mainly 100 micron and lower sizes than 10 microns flotation recoveries decreases dramatically. Some important and detailed studies by different researchers shows the effective feed size of materials in different forms such as coal, sulphides are in the range of -100+10 micron (Trahar, 1981; Santana et al., 2008; Mankosa et al., 2016; Frausto et al., 2017; Sokolovic & Miskovic, 2018;)

Although the need of circulating load concept for efficient size reduction process is defined well in literature, how the CLR affects the further concentration or other processes is open to investigate. Therefore, the possibility of increasing the efficiency of the enrichment circuits by controlling the circulating load was the motive in this research. In this study, the effect of circulating load with eliminating the short cut of fines (by using lab screen) is subjected to investigate for further concentration operation. In this context, the flotation behaviour of the copper sample obtained from different circuit loads was evaluated in terms of efficiency, kinetics and entrainment.

## 2. Materials and methods

### 2.1. Material

A copper ore including 1.2 Cu %, 1.02 % Pb and 0.26 % Zn was subjected to experiments. Copper mineral in the ore is chalcopyrite and dominant gangue minerals are pyrite and quartz. Ore sample in size of approximately -14 mm was taken from the ball mill feed of the plant and was crushed down to 3.36 mm controlling and preventing the material to go into the fine sizes. The particle size distributions (PSD) of the original sample as received and crushed test sample is given in Fig. 1.

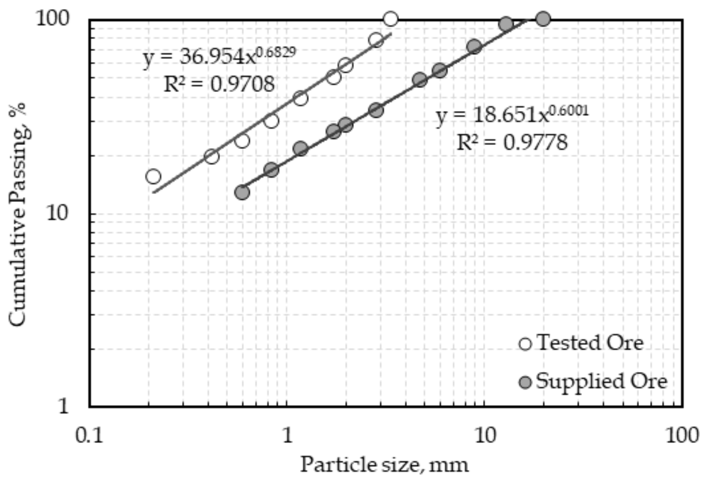


Fig. 1. PSDs of Tested and ROM ore

In plant, the ore after crushing down to 14 mm is fed to the ball mill (closed circuit) to produce -90 micron material (liberation size) for further concentration process. Ground material is initialy concentrated through bulk flotation at natural pH (7.2) using KAX (Potassium amyl xanthate) and Oreprep F549 (a mixture of polyglycols) as collector and frother, respectively. The bulk concentrate with approx. 3.5 % Cu and >90 % of recovery is reground using Vertimill (open circuit) to reduce the size down to -45 micron and the ground bulk concentrate is then introduced to final flotation concentration circuit including 3 cleaning flotation stages which produce a concentrate with 18-19 % of Cu.

### 2.2. Grinding experiments

Since bulk flotation is achieved with the feed size of 90 micron (d80) in the plant, the grinding tests is planned to produce material in similar size for flotation tests. For this purpose, locked cycle grinding tests (Fig. 2) were carried out to mimic the grinding conditions as in plant operation. As mentioned before, to eliminate the effect of short cut of fines, circulating load is created using lab scale screen allowing to almost no bypass.

In locked cycle grinding tests, 17.5x19.5 cm lab scale ball mill is used and operated with 60 % solid ratio. Ball charge and ball sizes are given in Table 1.

The locked cycle test started with 1000 gr of dry material and 667 gr water giving the standard solid ratio of 60 %. After grinding in time intervals of 2.5, 4, 6, 12 and 40 minutes (giving the circulating load ratios of 480, 270, 150, 70 and 0 %, respectively), ground materials are screened using lab scale screen with screen aperture of 106 microns. Following to screening, +106 micron material was taken to determine the amount of oversized material using graduated cyclinder and directed to grinding unit. In the folowing cycle, the fresh material was added to ball mill allowing to material amount of totaly 1000 gr again. The water is added to ball mill based on the solid-liquid mass balance. Cycles were continued till the amount of ground material is equal to amount of added freash material. After the final cycle, the locked cycle test were continued to collect sufficient material for further flotation tests.

### 2.3. Flotation experiments

Rougher flotation tests were carried out with the samples from completed locked cycle grinding tests have 0, 50, 150, 300 and 500 % circulating ratios. The experimental procedure of rougher flotation unit is shown in Fig. 3. In rougher flotation tests the effect of KAX (collector) dosage was investigated and varied from 25 to 75 g/t while the frother amount was kept constant at around 12.1 g/t . Concentrates were taken at specified time intervals to check for changes in flotation kinetics under different milling conditions. The flotation kinetics were evaluated with the rate constant of the first-order kinetic model. Water recoveries through rougher flotation test were also determined to realize the degree of entrainment.

Table 1. Grinding tests conditions

| | | |
|---|---|---|
| Diameter, cm | | 19.5 |
| Length, cm | | 17.5 |
| Mill volume, $cm^3$ | | 5224 |
| Medium volume, $cm^3$ | | 2052 |
| Medium weight, g | 50 mm (7) | 3074 |
| | 30-35 mm (11) | 2175 |
| | 25-30 mm (14) | 1584 |
| | 20-25 mm (29) | 2187 |
| | 10-20 mm (54) | 1240 |
| | Total (115) | 10260 |
| Critical speed, rpm | | 95.8 |
| Operational speed, rpm | | 72.8 |
| Fraction of critical speed, $\phi$ | | 0.76 |

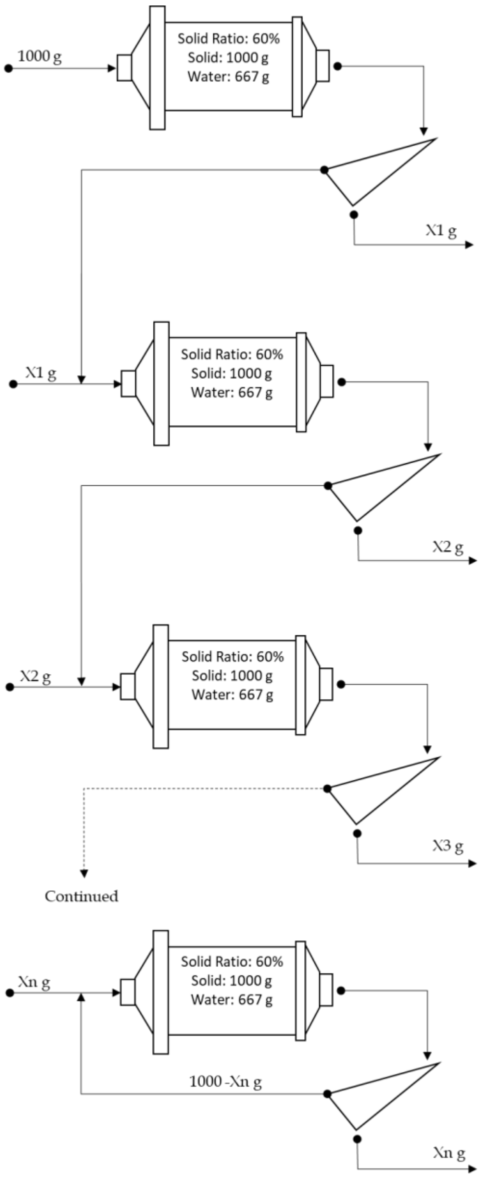


Fig. 2. Experimental procedure for milling

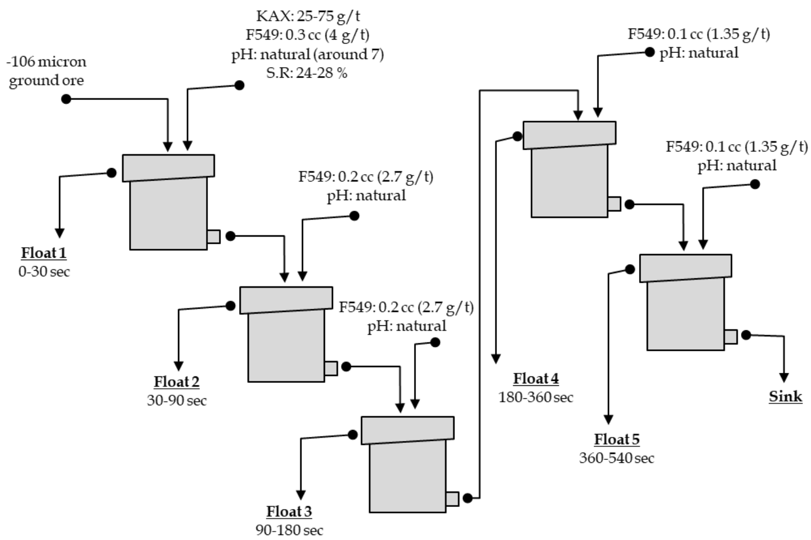


Fig. 3. Flotation experiments procedures

## 3. Results and discussion

### 3.1. Grinding experiments

Through the project, one of the important stages of the experimental study was to prove the validity of methodology for locked cycle test. The fast weigth analysis of the ground products show the success of the applied methodology for locked cycle grinding tests as shown in Fig. 4. The errors in weigths (difference between predicted and actual values) were in reasonable and acceptable levels.

The amount of products in size of -106 micron during different residence times in ball mill and accompanied circulating load ratios were given in Fig. 5. Based on the values shown in Fig. 5, the CLRs were determined as 0, 8, 70, 150, 270 and 480 % for the residence times of 40, 30, 12, 6, 4 and 2.5 mins, respectively.

The producibility of -106 microns material was varied and increased up to 167 % with CLR of 150 % and very small increase was observed with further increased on CLR up to 480 % (Fig. 6). This finding was also matched up well with reported values in the literature.

Following the locked cycle grinding tests with diffefent CLRs, PSDs of the products in size of -106 micron are given in Fig. 7. As reported well in literature, coarse and ultrafine size fractions within the PSDs of feed play an important role for further flotation effciciency, recovery and selectivity. Especialy the size fraction of -10 micron creates difficulty for particle-buble interactions of hyrophobic materials and slime coatings of hydrophilic ones. Therefore, because of the suitable top size of feed (-106 micron) only the amount of size fraction of -10 microns was detected. As shown in Fig. 7, there is no big change in amounts of -10 microns for PSDs of the material ground through varying CLRs except milling for 40 minutes residence time. Cumulative percent weights of -10 micron sizes are 35,0-30,4-27,2-28;4 and 25,1 for CLR of 0-70-150-270 and 480 respectively. The average of the amounts is 29.2 % and a significant deviation from this value is observed only when there is no circulating load. It was only observed that the amounts of the medium size fractions (-106+10 micron) differed; however, the variation in these fraction does not play an important role in flotation.

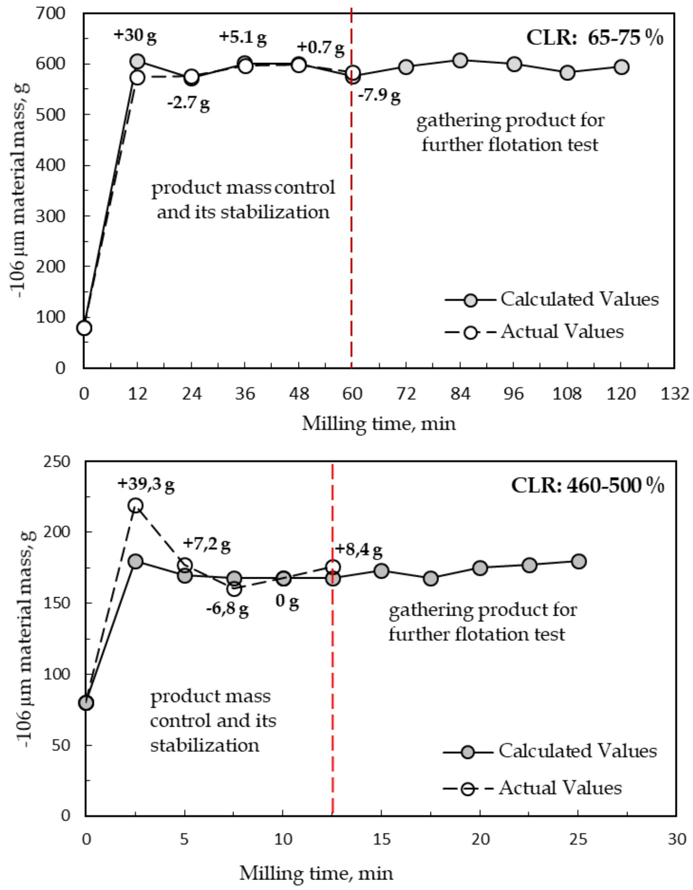


Fig. 4. Checking out the errors on mass balance for locked cycle grinding test

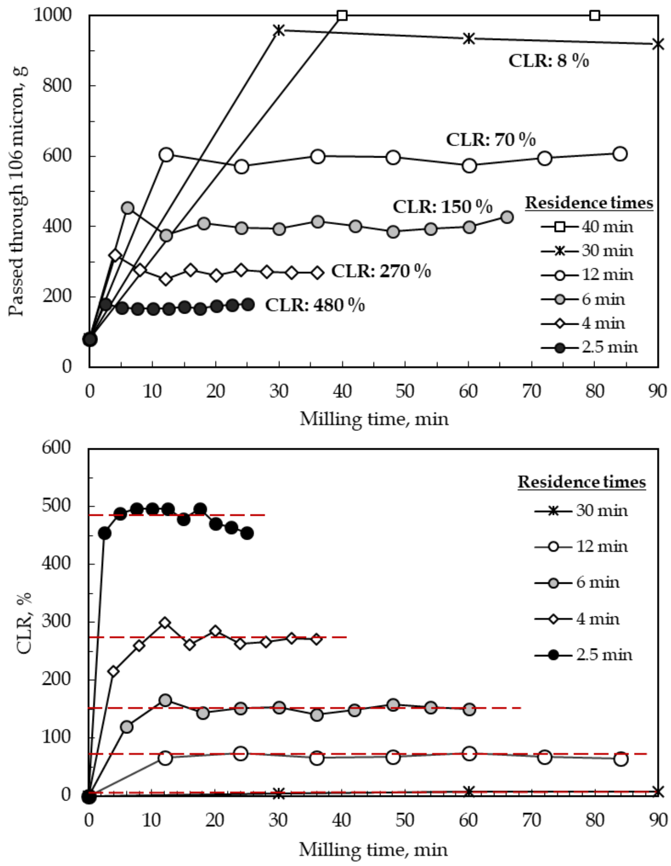


Fig. 5. CLRs depending on the residence time in Ball Mill

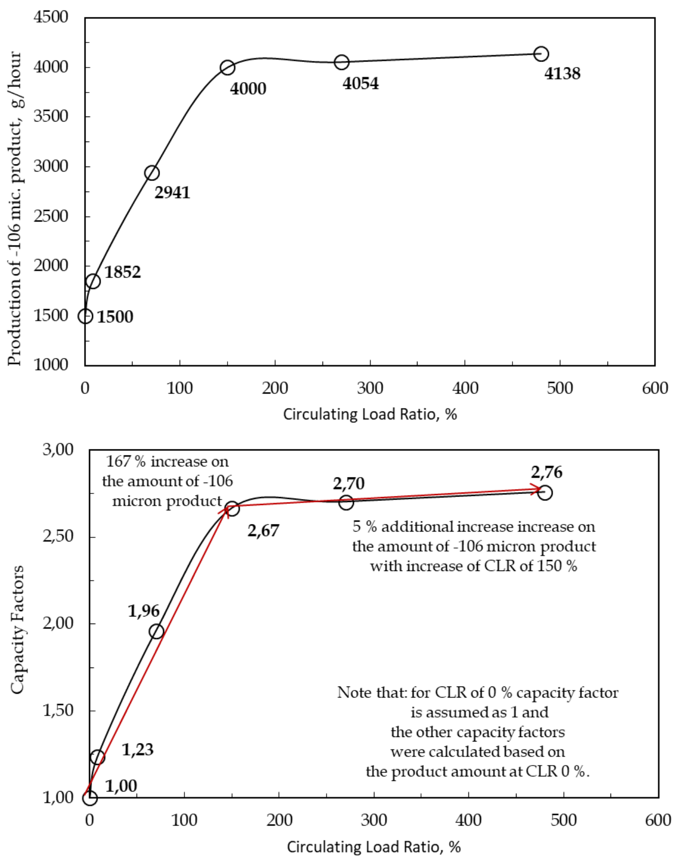


Fig. 6. Producibility of product in target size for varying CLRs

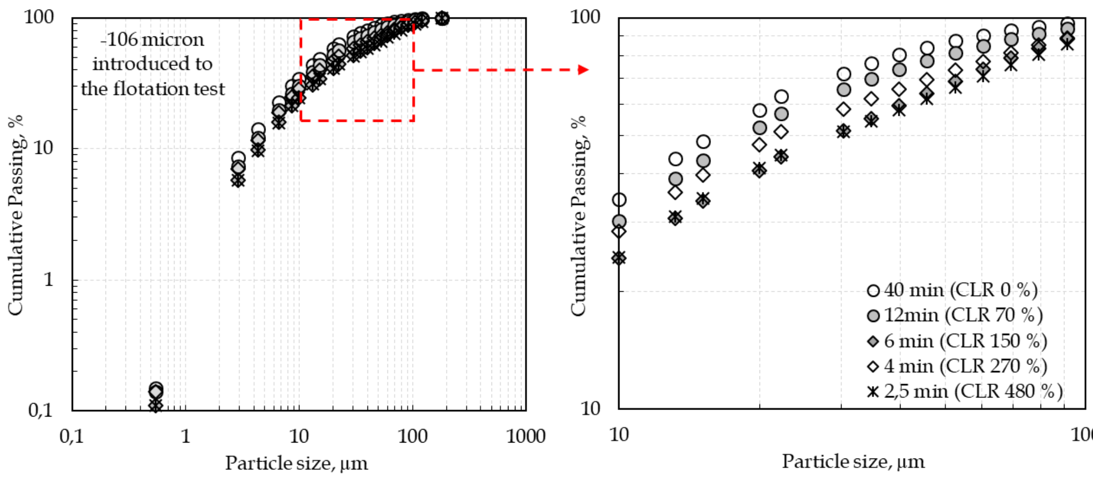


Fig. 7 . PSDs of products (-106 micron) for varying CLRs

### 3.2. Flotation experiments

The results of rougher flotation tests with samples of varied CLRs were shown in Fig. 8 realizing the relationship between cumulative recovery and cumulative grades. As seen from Fig. 8, the flotation feeds from grinding unit with CLR % of higher than 150 % (less than 6 min. residence time) give the

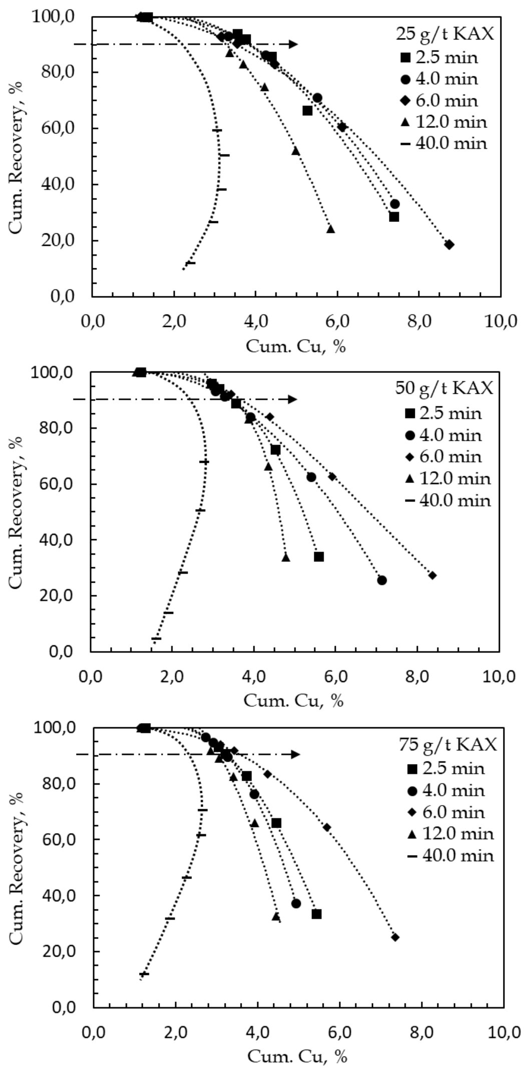


Fig. 8. Cumulative grades versus cumulative recovery

best flotation behaviour. That is, the high Cu grades of concentrates are available with relatively higher cumulative recoveries for the flotation feeds from grinding unit with higher CLR than 150 %. It was also realized that the flotation feed from open circuit grinding unit (CLR: 0 %) exhibited poor flotation behaviour just because of the overgrinding conditions.

Flotation kinetic tests allow to realize flotation rate constants. Cumulative recovery versus time plots and first-order kinetic equation fitted to the experimental data were used to determine the model parameters as shown below (Fig. 9 – For 75 g/t KAX and 0 % CLR).

When the flotation rates are compared as in Fig. 10, it was realized that the samples ground in 6 and lower residence times (CLR > 150 %) give the higher flotation rates and the further increase on CLR allows the products with almost same flotation rates

Cu grades for targeted recovery of 90 % was illustrated in Table 2. As seen in Table 2, 6 min or lower residence times in grinding produced flotation feeds giving concentrate with higher Cu grades for targeted flotation recovery of 90 %. It shows that it was possible to obtain rougher Cu concentrate of 3.5 % with flotation recovery of 90 %, if the CLR % was limited to 150-500.

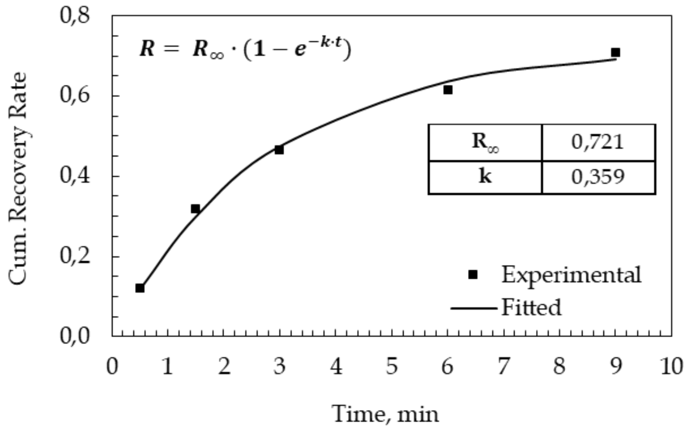


Fig. 9. An example for estimation of flotation kinetic parameters

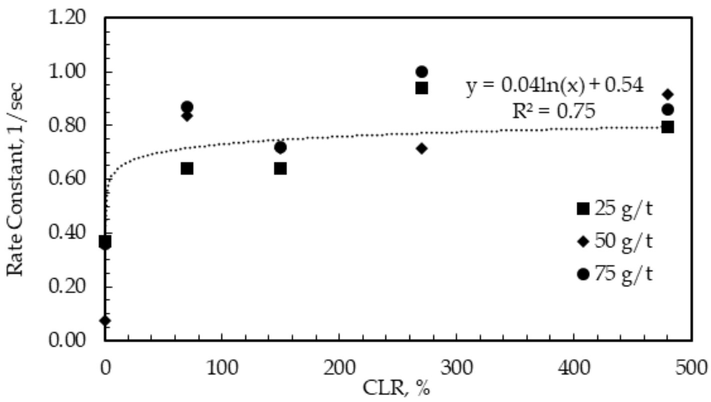


Fig. 10. Flotation rates of samples produced by varied CLR % on grinding unit

Table 2. Cu % of bulk concentrates for the target flotation recovery of 90%

| RT min | CLR % | Grades for Rec. of 90 % 25 g/t KAX | 50 g/t KAX | 75 g/t KAX |
|---|---|---|---|---|
| 2.5 | 500 | 3.50 | 3.50 | 3.25 |
| 4 | 300 | 3.50 | 3.50 | 3.25 |
| 6 | 150 | 3.50 | 3.50 | 3.25 |
| 12 | 50 | 2.75 | 3.50 | 2.65 |
| 40 | 0 | 2.25 | 2.50 | 2.40 |

Water recoveries in froths with concentrate were also determined and calculated to Fig. out the entrainment degree. Entrainment degree effects the grades of concentrates resulting in the selectivity. The calculated entrainment degrees for the flotation of material ground with varying CLRs are given in Fig. 11. Water recovery in froth or entrainment is mainly based on the frother type and concentration. However, for fixed frother concentration, the change on water recoveries varied surprisingly and this was attributed to the change on particle properties such as PSD and roughness. The CLRs lower than 50 % produce material in ultrafine sizes. Checking out the PSDs of the flotation feeds it was observed that the difference in amounts of -10 micron size fraction was in the range of 5-10 %. Surprisingly it was Fig. d out that the increase on amounts of ultrafine size fractions creates dramatical decrease on flotation recoveries.

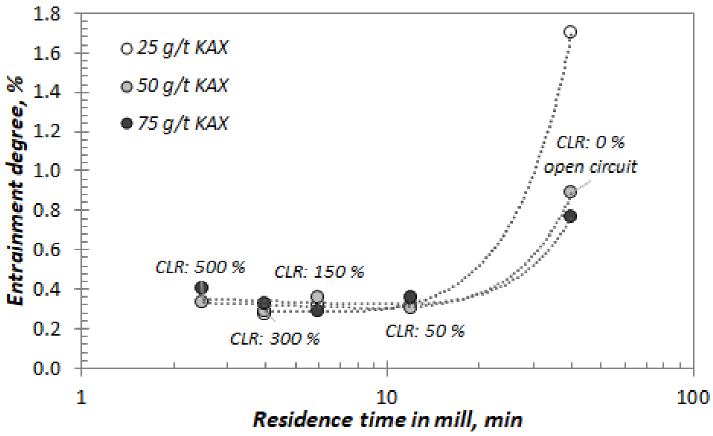


Fig. 11. Entrainment degree in rougher flotation of feeds from grinding units with varied CLR %

## 4. Conclusions

In this study, the circulating load concept is examined at laboratory scale in terms of both the milling capacity and the subsequent flotation process. It has been shown that grinding circuit capacity can be increased up to 176 % in comparison to open circuit operation by optimizing the circulating load. From the point of view of flotation, it has been revealed that the circulating load has an effect on both flotation recovery and kinetics. Higher recoveries to some extend were obtained for the same Cu grade when the circulating load ratio was higher than 150%. It has been determined that circulating load not only provides high recoveries, but also positively affects the flotation kinetics. Moreover, it was stated that entrainment would be much less in closed circuit grinding compared to open circuit.

In summary, the circulating load should be evaluated not only in terms of the grinding circuit, but also in terms of subsequent enrichment processes, especially flotation. Future studies on this subject will also provide great benefits on an industrial scale.

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