ISSN 2176-3135

IMPROVEMENTS ON INDUSTRIAL IRON ORE FLOTATION USING A NOVEL CO-DEPRESSANT[1]

Elton Carlos de Souza[2]
Yolacir Carlos de Souza Santos[2]
Antonio Carlos Papes Filho[3]
Lívia Mara Cândido[2]
Arthur Pinto Chaves[4]
Armando Corrêa de Araujo[5]
Daniel Silva Bueno[2]
Luiz Henrique Martins[3]
Igor Furlan Moya[3]

Abstract

Laboratorial and industrial trials were conducted at Companhia Siderurgica Nacional (CSN), Casa de Pedra mine, using a novel co-depressant developed by Georgia-Pacific (GPR-855), in association with corn starch, as depressant. Bench flotation experiments were performed partially replacing starch by GPR-855. The best results were achieved with 30% replacement ratio, obtaining an increase of 3.8% on mass recovery (2.5 percentage points, "p.p.") and 1.8% on iron recovery (1.5 p.p.), compared to the reference condition. Silica on concentrate was slightly higher than the reference condition. An industrial trial was conducted at CSN's beneficiation plant to validate these results, adding GPR-855 (240 g/t) directly into the process at the same point of gelatinized starch solution dosage (560 g/t). GPR-855 replaced partially starch, in the same ratio (30%) of the best condition indicated by the lab trials. The industrial results surpassed the values achieved at the laboratory scale, with significant improvement on mass recovery (5.1 p.p. or 8.6 %) and iron recovery (7.3 p.p. or 9.0%). The iron content on tailings was reduced in 30%, with lower silica assay on concentrate, compared to the base condition.
Key words: Iron ore; Froth flotation; Depressant; Recovery.

AVANÇOS NA FLOTAÇÃO INDUSTRIAL DE MINÉRIO DE FERRO UTILIZANDO NOVO REAGENTE CO-DEPRESSOR

Resumo

Testes laboratoriais e industriais foram conduzidos na Companhia Siderúrgica Nacional (CSN) na mina de Casa de Pedra, utilizando um novo reagente co-depressor desenvolvido pela Georgia-Pacific (GPR-855), em associação ao amido de milho como depressor. Ensaios de flotação em bancada foram realizados substituindo-se parcialmente o amido por GPR-855. Os melhores resultados foram obtidos com a substituição de 30%, obtendo-se um aumento de 3,8% na recuperação mássica (ou 2,5 pontos percentuais, "p.p.") e 1,8% na recuperação metálica (1,5 p.p.), comparado à condição de referência. A sílica no concentrado apresentou níveis ligeiramente maiores que a condição de referência. Um teste industrial foi conduzido na planta de beneficiamento da CSN para validar estes resultados, adicionando-se GPR-855 (240 g/t) diretamente no processo, no mesmo ponto de dosagem da solução de amido gelatinizado (560 g/t). O GPR-855 substituiu parcialmente o amido, à mesma razão (30%) da melhor condição indicada em laboratório. Os resultados obtidos industrialmente ultrapassaram aqueles obtidos em laboratório, com aumento significativo da recuperação mássica (5,1 p.p. ou 8,6%) e da recuperação metálica (7,3 p.p. ou 9,0 %). O ferro no rejeito foi reduzido em 30%, com menor teor de sílica no concentrado, comparando-se com a condição de referência.
Palavras-chave: Minério de ferro; Flotação; Depressor; Recuperação.

1 *Contribuição técnica ao 40º Seminário de Redução de Minério de Ferro e Matérias-primas e 11º Seminário Brasileiro de Minério de Ferro, 19 a 22 de setembro de 2010, Belo Horizonte, MG.*
2 *CSN - Companhia Siderúrgica Nacional, Casa de Pedra*
3 *Georgia-Pacific*
4 *Mining Eng., PhD, Escola Poliécnica da USP, Departamento de Engenharia de Minas e de Petróleo*
5 *Universidade Federal de Minas Gerais, UFMG-DEMIN*

ISSN 2176-3135

1 INTRODUCTION

Iron ore demand has been growing steadily due to increasing steel consumption in emerging economies, especially in China. Iron ore prices have also been pushed up,(1) fostering the development of new projects for expansions and optimization,(2) in order to maximize the production, including the use of poorer ores, which must be concentrated to reach the customers' quality standards.
In Brazil, it is evident the massive investment on concentration facilities at several mines at the Iron Quadrangle, in Minas Gerais state, consisting principally on flotation units. Companhia Siderurgica Nacional, CSN, is a leading company in this new wave, installing 26 flotation columns to increase pellet feed production from 4,000,000 t/yr to 9,000,000 t/yr.
Besides capital investment, production can be rapidly improved by plant optimization,(3) through better selectivity of flotation process, increasing metallic recovery and maintaining product quality. This is a fast way to reach higher production standards with operational expenses (OPEX), compared to long term capital investments (CAPEX). An effective way to improve flotation selectivity is through proper reagents selection, markedly depressants and collectors.(4)
Starches and starch-derived products are well-established in the industry as depressants for the cationic reverse flotation of iron ore.(5) Starches adsorb preferentially onto iron oxide particles protecting their surfaces from the adsorption of the collector species. The collectors are usually amines, markedly ether-diamine acetate, ether-monoamine acetate or a combination of both. The successful adsorption of a collector is a function of the concentration of surfactant species (ionic or, in many instances, a combination of ionic and non-ionic species) that transforms the particle surface character from hydrophilic to hydrophobic.(6) The collector used in the reverse cationic flotation of iron ores, in the absence of a depressant like starch, would impart a certain degree of hydrophobicity to all mineral surfaces in the flotation pulp. Taking into account that hematite surfaces are generally transformed in a lesser extension by collector than quartz surfaces are (amines adsorb more strongly and extensively onto quartz surfaces than they do onto hematite surfaces), the required selectivity level for the separation is often not achieved without the help of a depressant.(7)
New depressants have been continuously tested for iron ore flotation, in an effort to replace starch, but no success was achieved so far due to technical or economical reasons. Araujo et al.(8) reported excellent flotation performance by using synergetic combination of depressants: starch as depressant and new reagents developed by Georgia-Pacific as co-depressants. The co-depressant labeled as GPR-855 was selected as the best candidate. Laboratorial flotation testing conducted by Araujo et al.(8), using as feed an ore from the iron quadrangle and GPR-855, showed improved selectivity compared to the standard practice: higher selectivity index, with lower silica on concentrate, keeping recovery levels constant.
This paper reports the industrial trial performed at Companhia Siderurgica Nacional, with GPR-855 in combination with starch, implementing the findings of the previous work.(8) The same trends were observed industrially and, after process stabilization, silica on concentrate was kept on the set-point by increasing concentrate flow. The partial replacement of starch by GPR-855 resulted in higher mass recovery, higher iron recovery and improved selectivity, with product quality fitting all specifications.

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2 MATERIALS AND METHODS

2.1 Co-depressant GPR-855

The co-depressant GPR-855 was specially developed by Georgia-Pacific for iron ore flotation. It consists in a low molecular weight cationic polymer of the polyamine-polyamide family. Figure 1 shows a generic representation of this polymer.

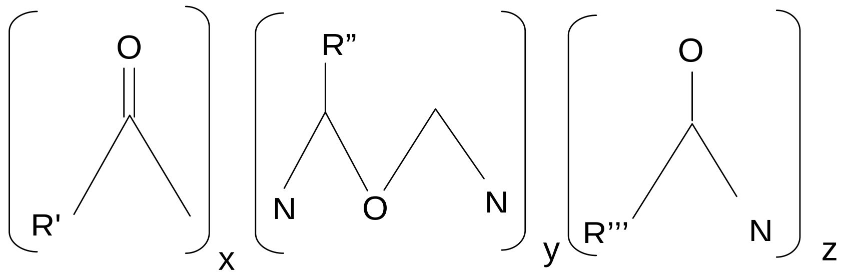

Figure 1. Chemical representation of GPR-855 polymer.

GPR-855 is supplied as a low viscosity yellow liquid, ready to use. Industrially, there is no need to dilute the reagent, which can be directly pumped into the conditioner, using a very simple system, as presented on Figure 3. It is a non-hazardous chemical, requiring neither special protective equipment nor particular engineering methods. No odor is perceived either at reagent storage or at the process.
The product was stored in tote-bins for the trial, but storage tanks could have been used as well.

2.2 Standard Reagents

Besides co-depressant GPR-855, CSN employed corn starch as a depressant and ether-monoamine acetate as a collector.
Corn meal (starch) was gelatinized with caustic soda, using 6:1 ratio (solid basis, condition used during the trial), in a solution with 10% starch. After gelatinization, the solution was diluted to 1.5% and dosed to the conditioner feed.
The amine collector was diluted to 1.9% prior to use in the conditioner tank.
Figure 3 shows the addition point of the reagents.

2.3 Laboratorial Conditions

Laboratorial flotation trials were conducted in a CDC cell at 1,200 rpm, with 700 g dry samples, slurry dilution of 60% solids by weight and pH of 10.7. Reagents: 55 g/t of ether-monoamine acetate (collector) diluted to 1.9% and 600 g/t of gelatinized corn meal diluted to 1%. GPR-855 was also diluted to 1% for easier dosage.
Starch and GPR-855 were conditioned together for 5 minutes and, in sequence, the collector was conditioned for 1 minute. In the sequence, air was fed to the cell and froth was collected until extinction. Froth and depressed material were dried in an oven and analyzed by X-Ray fluorescence for chemical analysis.

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2.4 Industrial Conditions

The flotation facility at CSN consisted in one train composed by 5 rougher, 3 cleaner and 2 scavenger columns. Flotation feed was previously deslimed and pumped to a distribution box (#1), where starch and GPR-855 were dosed (Figure 2). In the sequence, the slurry overflows to the conditioning tank, where the collector is dosed in its second stage. A second distribution box (#8) receives the conditioned slurry and directs it to the storage tank, which feeds 5 rougher columns in parallel. The mixed streams from the rougher bottoms feed 3 cleaner columns.
The bottoms of the cleaner columns go to the concentrate thickener. The heads of the cleaner columns feed 2 scavenger columns. The bottoms of the scavenger are returned to the conditioner (rougher feed). The froths of the rougher and the froths of the scavenger are the tailings. Figure 3 shows a simplified flowchart of the process.

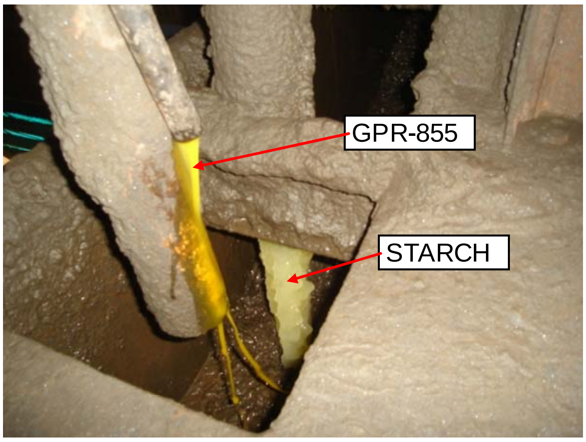

Figure 2. Addition point of starch solution and GPR-855.

During the trial, dry ore feed rate was 650 t/h, depressant dosage was 800 g/t and collector dosage was 50 g/t. According to previous lab trials results, GPR-855 replaced 30% of starch, dosing 240 g/t of GPR-855 and 560 g/t of starch. Other process conditions were maintained at the typical set-points during the trial, like pH (10.7), pulp solids (60%) and air flowrate at the columns.
Sampling procedures and chemical analysis were performed according to the routine practice at CSN. The recoveries were calculated based on the iron assays at feed, concentrate and reject, according to Equations 1 and 2. Gaudin's selectivity index (S.I.) was calculated according to Equation 3.

$$Mass\ Recovery = \frac{t_A - t_R}{t_C - t_R} \quad (1) \qquad Iron\ Recovery = \frac{t_C \times (t_A - t_R)}{t_A \times (t_C - t_R)} \quad (2) \qquad S.I. = \sqrt{\frac{t_C \times Si_R}{t_R \times Si_C}} \quad (3)$$

Where "t_A", "t_R" and "t_C" are the iron assays at feed, tailings and concentrate, respectively. Si_R and Si_C stand for the silica assay on tailings and concentrate, respectively.

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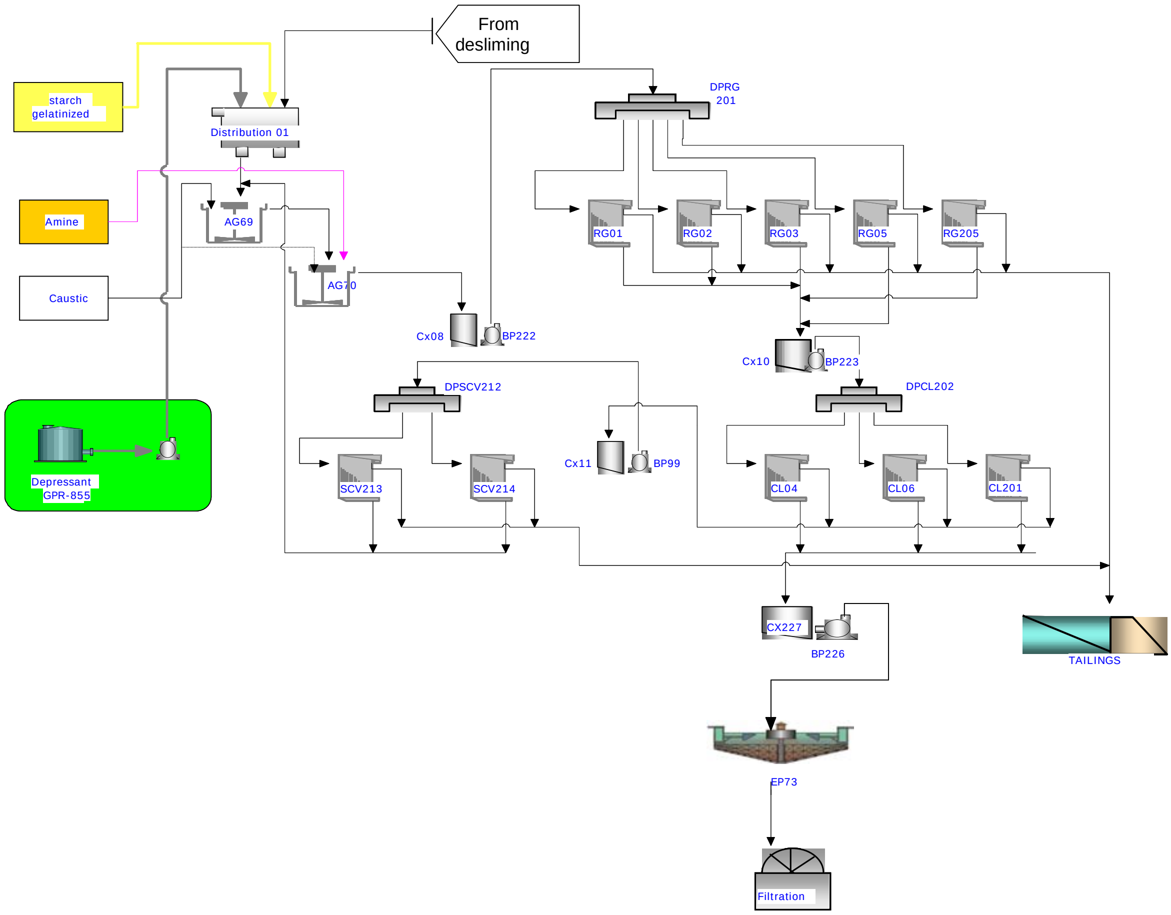

Figure 3. Flowchart of CSN flotation process.

3 EXPERIMENTAL RESULTS

3.1 Laboratorial Trials

Laboratorial trials were conducted at CSN in order to evaluate the performance of GPR-855 co-depressant, in a partial replacement of starch at different levels, from 0 to 50%. The relevant results are presented on Table 1.

Table 1. Lab Trial results, with partial replacement of starch by GPR-855

Starch	*GPR-855*	*SiO_2 conc.*	*Mass Recovery*	*Iron Recovery*
100%	0	1,2 %	65,5 %	82,7 %
90%	10%	1,2 %	65,1 %	81,8 %
80%	20%	2,4 %	65,9 %	82,5 %
70%	30%	1,6 %	68,0 %	84,2 %
60%	40%	1,6 %	68,0 %	83,8 %
50%	50%	1,7 %	67,5 %	83,7 %

3.2 Industrial Trial

The industrial trial was performed with GPR-855 replacing 30% of starch. 560 g/t of gelatinized starch (70% of normal dosage) were added to the distribution box before the conditioning tank. 240 g/t of GPR-855, in a liquid form, as received, was pumped to the same addition point of starch.

The total trial duration was 24 hours, divided into 2 days. Seven data points were collected for flotation concentrate in the 1st day, while using GPR-855. The first two

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hours after introducing GPR-855 were not considered for this analysis, due to the transition of the process (1 hour was enough to reach the stability on the new condition and an additional 1 hour was considered for sampling procedures). Seven successive data points for flotation concentrate taken in the period right before the trial were considered as a reference for the base condition.

Table 2: Results of 1st day of industrial trial, using GPR-855 (chemical analysis)

(a) FLOTATION FEED				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
49.80	27.07	0.61	0.18	0.032
48.70	28.70	0.59	0.17	0.030
48.88	28.44	0.59	0.18	0.030
50.86	25.36	0.62	0.18	0.031
48.39	29.20	0.55	0.16	0.028
49.33	***27.75***	***0.59***	***0.17***	***0.03***

(b) FLOTATION TAILINGS				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
13.41	79.89	0.41	0.06	0.011
15.18	77.21	0.48	0.08	0.012
18.55	72.46	0.42	0.08	0.012
17.75	73.17	0.73	0.10	0.015
15.70	76.38	0.57	0.06	0.011
16.12	***75.82***	***0.52***	***0.08***	***0.01***

(c) FLOTATION CONCENTRATE				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
67.72	1.27	0.54	0.22	0.042
67.52	1.59	0.55	0.21	0.043
67.38	1.83	0.54	0.20	0.042
67.23	1.93	0.58	0.22	0.043
67.40	1.61	0.63	0.22	0.044
67.68	1.34	0.57	0.22	0.043
67.65	1.39	0.56	0.21	0.044
67.51	***1.57***	***0.57***	***0.21***	***0.04***

Table 3: Reference data for 1st day of industrial trial, using only starch (chemical analysis)

(a) FLOTATION FEED				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
48.96	28.40	0.56	0.16	0.029
50.36	26.45	0.53	0.17	0.029
50.17	26.57	0.55	0.17	0.030
49.17	28.11	0.53	0.17	0.029
49.67	***27.38***	***0.54***	***0.17***	***0.03***

(b) FLOTATION TAILINGS				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
16.04	75.85	0.60	0.07	0.012
26.23	61.17	0.53	0.11	0.017
21.25	68.48	0.47	0.10	0.014
28.72	57.80	0.43	0.12	0.017
23.06	***65.83***	***0.51***	***0.10***	***0.02***

(c) FLOTATION CONCENTRATE				
Fe	*SiO_2*	*Al_2O_3*	*Mn*	*P*
67.75	1.27	0.54	0.20	0.046
67.25	2.01	0.56	0.20	0.045
67.36	1.80	0.60	0.21	0.045
67.11	2.16	0.56	0.21	0.043
66.78	2.68	0.55	0.22	0.043
67.25	1.82	0.63	0.23	0.045
66.95	2.47	0.53	0.20	0.043
67.21	***2.03***	***0.57***	***0.21***	***0.04***

Five successive data points were collected for flotation concentrate in the 2nd day, while using GPR-855. The first two hours were not considered as well. Six data points for flotation concentrate taken in the period right before the trial were considered as a reference for the base condition.
Tables 2, 3, 4 and 5 show the chemical analysis of the collected samples during the trial and for the reference condition just before introducing GPR-855. Chemical analysis comprises iron (Fe), silica (SiO_2), alumina (Al_2O_3), manganese (Mn) and

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phosphorous (P). The last row of each table (bold and shadow) shows the average for the period.
The sampling frequency for concentrate, feed and tails were not the same, according to regular practice of the plant. In this sense, recoveries were calculated using the assays averages for the test and reference periods, in order to minimize calculations errors.

Table 4: Results of 2nd day of industrial trial, using GPR-855 (chemical analysis)

(a) FLOTATION FEED					*(b) FLOTATION TAILINGS*				
Fe	***SiO_2***	***Al_2O_3***	***Mn***	***P***	***Fe***	***SiO_2***	***Al_2O_3***	***Mn***	***P***
49.13	28.10	0.48	0.14	0.029	20.05	70.53	0.26	0.07	0.012
49.13	28.27	0.46	0.14	0.029	22.30	66.52	0.64	0.13	0.019
48.68	28.87	0.49	0.14	0.028	24.65	63.28	0.63	0.13	0.019
48.98	***28.41***	***0.48***	***0.14***	***0.03***	***22.33***	***66.78***	***0.51***	***0.11***	***0.02***

(c) FLOTATION CONCENTRATE				
Fe	***SiO_2***	***Al_2O_3***	***Mn***	***P***
66.12	3.73	0.52	0.17	0.043
66.23	3.32	0.45	0.17	0.040
66.27	3.33	0.50	0.16	0.042
66.16	3.49	0.46	0.18	0.040
66.72	2.58	0.51	0.19	0.042
66.30	***3.29***	***0.49***	***0.17***	***0.04***

Table 5: Reference data for 2nd day of industrial trial, using only starch (chemical analysis)

(a) FLOTATION FEED					*(b) FLOTATION TAILINGS*				
Fe	***SiO_2***	***Al_2O_3***	***Mn***	***P***	***Fe***	***SiO_2***	***Al_2O_3***	***Mn***	***P***
49.62	27.46	0.48	0.16	0.028	24.63	63.56	0.46	0.11	0.015
50.43	26.47	0.44	0.15	0.028	19.56	71.10	0.36	0.07	0.011
49.70	27.48	0.48	0.14	0.029	29.48	56.86	0.35	0.10	0.016
49.92	***27.14***	***0.47***	***0.15***	***0.03***	***24.56***	***63.84***	***0.39***	***0.09***	***0.01***

(c) FLOTATION CONCENTRATE				
Fe	***SiO_2***	***Al_2O_3***	***Mn***	***P***
67.78	1.18	0.55	0.20	0.042
67.45	1.70	0.54	0.21	0.043
68.03	1.02	0.48	0.17	0.044
68.19	0.92	0.44	0.16	0.042
67.99	1.08	0.49	0.17	0.043
67.84	1.32	0.49	0.17	0.042
67.88	***1.20***	***0.50***	***0.18***	***0.04***

Table 6 shows a summary of the relevant results, including Gaudin's selectivity index (S.I.).

Table 6: Summary of trial results with GPR-855, compared to the normal condition

	TAIL	***CONCENTRATE***				***RECOVERIES***		
Period	***Fe***	***SiO_2***	***Al_2O_3***	***Mn***	***P***	***Mass***	***Iron***	***S.I.***
1st Day								
Starch	23.1 %	2.03%	0.57%	0.21%	0.04%	59.5 %	81.1 %	10
Starch + GPR-855	16.1 %	1.57%	0.57%	0.21%	0.04%	64.6 %	88.4 %	14
DIFFERENCE	***- 7.0***	***- 0.46***	***0.00***	***0.00***	***0.00***	***+ 5.1***	***+ 7.3***	
2nd Day								
Starch	24.6 %	1.20%	0.50%	0.18%	0.04%	58.5 %	79.6 %	12
Starch + GPR-855	22.3 %	3.29%	0.49%	0.17%	0.04%	60.6 %	82.0 %	8
DIFFERENCE	***-2.3***	***+ 2.09***	***-0.01***	***-0.01***	***0.00***	***+ 2.1***	***+ 2.4***	

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4 DISCUSSION

4.1 Lab Trials

Lab trials were conducted at CSN in order to demonstrate the efficacy of GPR-855 in partial replacement of starch. Results are presented on Table 1 and Figure 4. Best results were obtained with 30% replacement. Besides silica on concentrate was slightly higher than reference (+ 0.2 p.p., or "percentage points"), recoveries consistently surpassed the standard condition: +2.5 p.p. on mass recovery (or 3.8%) and +1.5 p.p. on iron recovery (or 1.8 %).

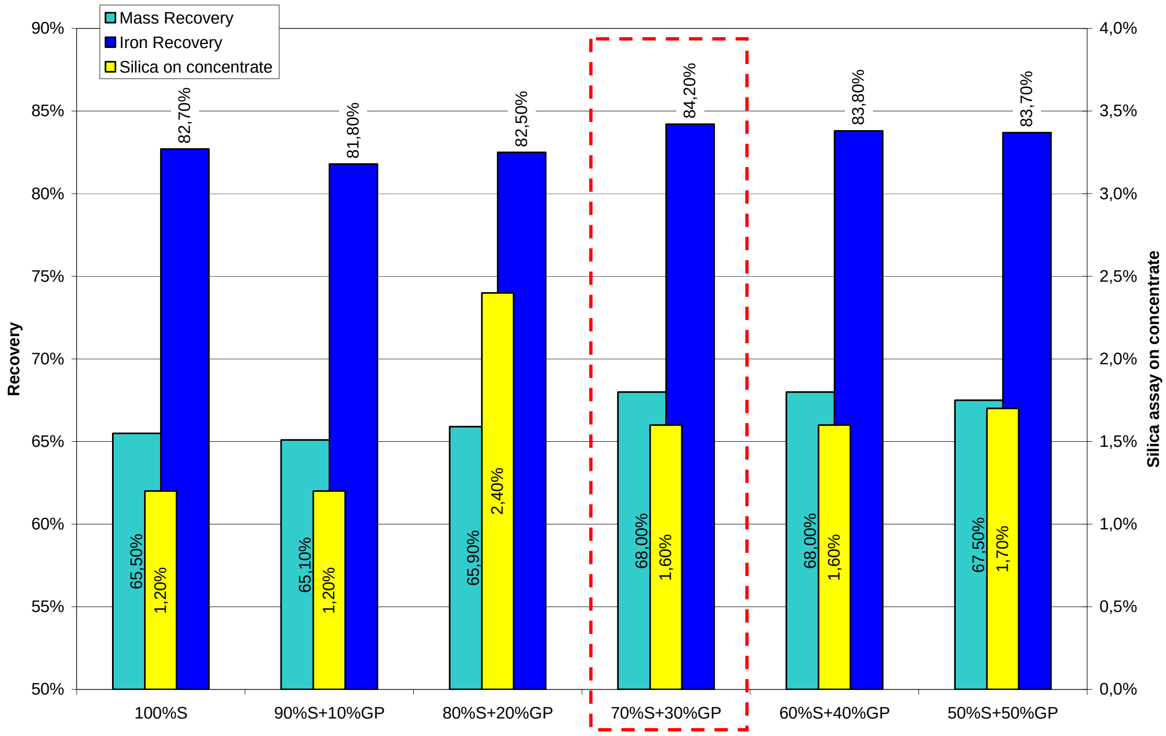

Figure 4. Lab trial results with different replacement ratios for GPR-855 (GP) over starch (S).

Experiments with 40% and 50% replacement presented improved results compared to standard condition, but similar to the ones achieved with 30% replacement. In this sense, this is the optimum condition, considering the economical aspect.

The replacement of 10% starch by GPR-855 showed no benefits as compared to the standard condition. Results with 20% replacement were considered not conclusive, as they are distant from the trend observed on the other points. As good results were achieved with 30% replacement, the first two experiments were not repeated.

These results justified an industrial trial to confirm the good levels of recovery and optimize the flotation process to guarantee the silica on concentrate fitting the product specification.

4.2 Industrial Trial

An industrial trial was conducted at the flotation unit of Casa de Pedra mine, replacing 30% of the normal starch dosage by the novel Georgia-Pacific's co-depressant GPR-855 , according to lab trials indication.

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Consistent flotation improvement was achieved using GPR-855, showing a reduction on iron at reject, with consequent increase on recovery, compared to the reference period just before the trial.

The trial took place in two different days. In the first day, the introduction of GPR-855 dropped the iron on tails in 7.0 p.p. or 30%. Consequently, a significant increase of mass and iron recoveries were observed: + 5.1 p.p. (or +8.5 % over the baseline) and +7.3 p.p. (or 9.0 %), respectively. A significant increase of 4 points at the selectivity index confirmed the good performance of GPR-855. The silica on concentrate was reduced in 0.46 p.p. (23%), while the other contaminants (alumina, manganese and phosphorous) remained at the same values seen before the trial.

In the second day of the trial, a mechanical problem on one of the rougher columns caused an increase on the silica assay on concentrate. The interface level meter of the column failed above the set-point during the trial and the bottom stream valve opened automatically, carrying more froth and silica to the cleaner stage, which was not able to absorb the disturb.

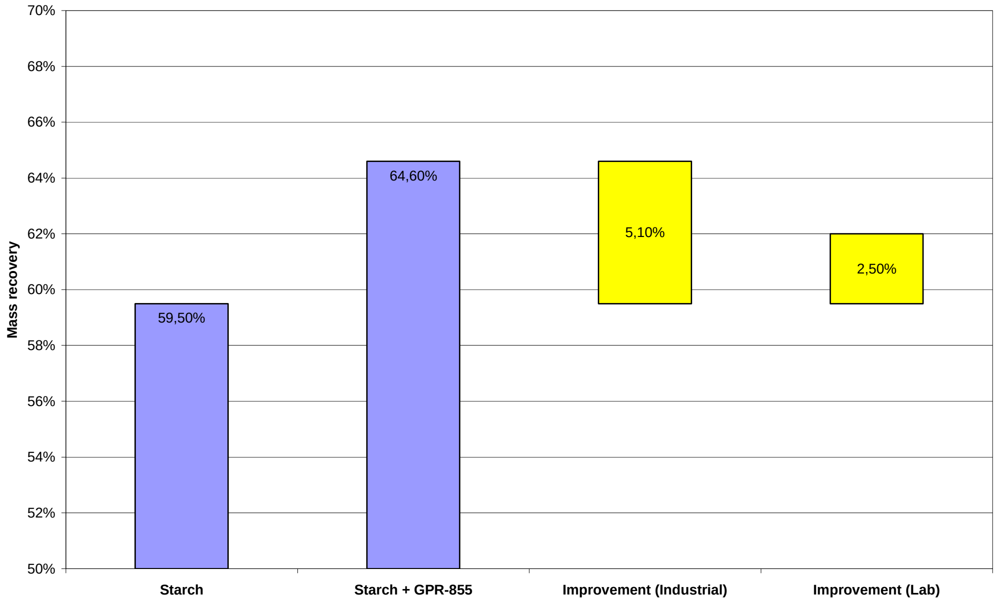

Figure 5. Mass Recovery results from the industrial trial.

In this sense, the analysis of the 2nd trial day was impaired by the deviation on concentrate assays. Nevertheless, a reduction of iron on reject was still observed (-2.3 p.p. or 9.4 % below the baseline), as well as the increase of mass recovery (+2.1 p.p. or 3.5 %) and iron recovery (+ 2.4 p.p. or 3.0 %). The analysis of Selectivity Index was also impaired by the deviated high silica content on concentrate.

The mass recoveries were calculated based on both iron and silica assays for confirmation, using Equation 1. The two results are very consistent, showing a deviation smaller than 1%. The values calculated on the iron assays were used for the analysis.

Figures 5 and 6 show the mass and iron recovery, respectively, obtained during the trial with GPR-855, compared to the values with normal practice (without GPR-855) right before the trial. Only results from the 1st trial day were considered due to the deviation of the silica on concentrate occurred in the 2nd trial day, which influenced the data collected in this period.

The significant recovery improvement achieved industrially was compared to the ones obtained from lab trials, in the yellow bars (in percentage points over the baseline). GPR-855 demonstrated a superior industrial performance as compared to the even good improvements obtained in the lab flotation.

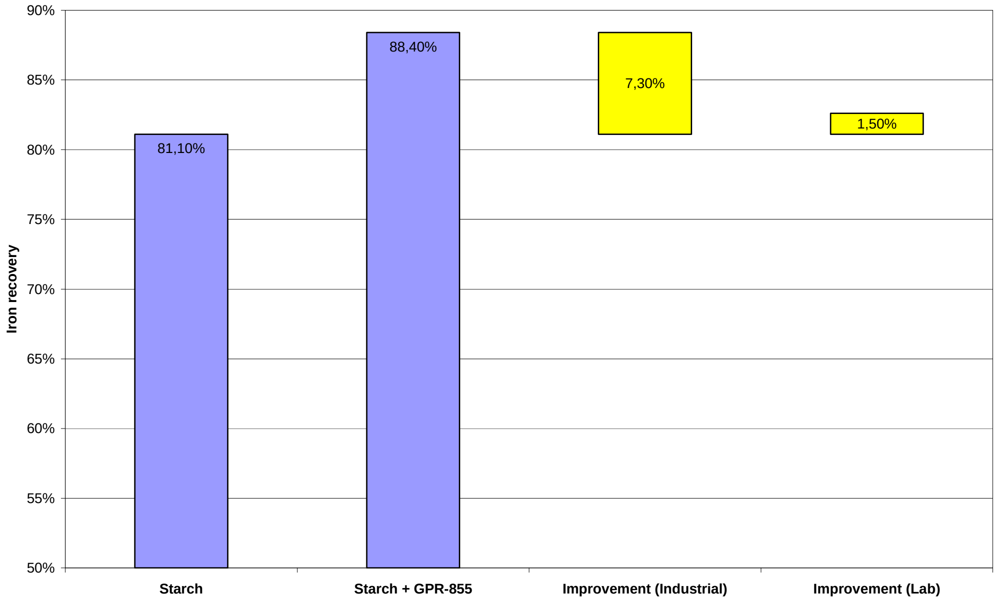

Figure 6. Iron Recovery results from the industrial trial.

5 CONCLUSION

The experimental work performed both on bench (laboratory) and continuous (industrial) scale at Companhia Siderúrgica Nacional (CSN), Casa de Pedra Mine, showed the advantage of using GPR-855 as a co-depressant in the reverse flotation of iron ores.

The laboratory stage showed the best substitution to be 30% of the added starch. It yielded an increase of 3.8% on mass recovery (2.5 percentage points, “p.p.”) and 1.8% on iron recovery (1.5 p.p.), compared to the reference condition, with 100% starch. Silica on concentrate was slightly higher than the reference condition.

The industrial trial was performed at CSN’s beneficiation plant, adding GPR-855 (240 g/t) directly into the process at the same point of gelatinized starch solution, with dosage of 560 g/t, in the same ratio indicated by the lab trials (30% replacement). The industrial results surpassed the values achieved at the lab, with significant improvement on mass recovery (5.1 p.p. or 8.6 %) and iron recovery (7.3 p.p. or 9.0%), compared to the period just before the trial, without GPR-855. Iron on reject was significantly reduced in 30%, in line with the increase in recovery. The concentrate produced showed lower silica assay (20%) as compared to the base condition. The reduction of iron on tail and also of silica on concentrate produced an important improvement of 4 points on Gaudin’s selectivity index.

Additionally to the excellent performance in recovery improvement, the use of GPR-855 requires minimal investment. No preparation is required for the co-depressant and a simple dosing system was used, consisting in a tote bin and a pneumatic pump. The reagent is not hazardous and it is user friendly.[9]

Acknowledgements

The authors acknowledge the engineers, operators and technicians of CSN who made the lab and industrial trials happen. The authors also acknowledge the researchers who performed the exploratory lab trials with GPR-855 reagent: Risia Magriotis Papini (UFMG), Paulo Magalhães Viana (UFMG), Georges Valadão (UFMG), Pablo Dopico (Georgia-Pacific, GP), John Hines (GP), Daniel Tao (University of Kentucky), José Carlos de Souza (GP) and Edimil Leonel Avila (GP).

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