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Influences of Materials Segregation on Feeding Conditions and Performance of HPGR Mill

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Abstract
HPGR (high-pressure grinding rolls) is widely used as a pre-grinding option in iron ore beneficiation plants. During operation, the wear at the center areas of the rolls is more intense than the edge areas. In this research, the wear pattern on roll surfaces of HPGR in a case study plant was investigated which operates in a close circuit with a wet double-deck vibrating screen. After plant audits, collecting reliable data, and efficient evaluation, it was found that the wear pattern is asymmetric, and the gap between rolls would not be properly adjustable. The reason for the asymmetrical wear was the segregation occurrence in the HPGR feeding chute originating from the non-uniform distribution of HPGR's feed on the belt conveyor. The results showed that segregation in the feeding bin happens when the bin level is lower than 70%, and it was completely obvious for levels lower than 40%. Also, the non-uniform distribution of HPGR's feed on the belt conveyor can be decreased by implementing modifications on the connection chute of screen recycle and belt conveyor of HPGR feed.

Keywords Iron ore · Segregation · HPGR · Wear rate

1 Introduction

HPGR (high-pressure grinding rolls) technology was invented in the 1970s and developed in the 1984s [1–4]. Over the past decades, HPGR application in the mining industry and comminution stages has been on the rise [5–7] as a grinding equipment with lower energy consumption [8]. HPGR application in the mining industry is very notable because of its high capacity, low specific energy consumption, fast start-up phase, and low time and cost maintenance [9–12]. Nowadays, utilizing HPGR at a grinding stage before the ball mill is common, which causes a reduction of the specific energy consumption by about 20% [13].

Crushing and grinding in the HPGR happen when a bed of particles is placed between two movable pressurized rolls [14–17], and many parameters have a remarkable influence on the performance of the rolls. The wear phenomenon on the rolls surface is an important parameter in HPGR operation, and it approximately depends on three main factors: (1) properties of rolls and studs, (2) ore properties, and (3) the adjustment of operational parameters related to the equipment [18]. It confirmed that, apart from the maximum size and particle size distribution, some parameters such as finer particles, hardness, bulk density, and abrasiveness of HPGR's feed have a considerable influence on the HPGR milling process [19]. On the other hand, breakage behavior does not correlate with the Bond work index, and the reason is a difference in breakage mechanism in HPGR and the procedure of this index [20]. The sufficient moisture content contributes to the formation of a protective layer on the roll's surface and decreases the roll's wear rate [21]. Extra feed moisture content causes materials to slip from the roll surface, which leads to material layers washing off from the roll surface and increases the wear rate [19, 22, 23]. In a case study, it was reported that the moisture content within the range of 2–4% has the best performance in the comminution process [21], and another research showed that 3–5% is proper for pre-grinding of fine iron ores [24].

Also, controlling HPGR motors and their load-sharing handle can decrease the wear rate of the rolls, and it can be monitored with continuous observation of operation and measurement in routine maintenance procedures and shutdowns [25, 26]. Feed characteristics such as particle size distribution play a prominent role in HPGR performance. The top size of HPGR's feed depends on the operating gap

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and roll diameter, and it is typically determined to be about 1.5 times bigger than the operating gap [27]. In general, the maximum wear and concaving rate of rolls occur in the middle areas of the rolls [18]. The applied force on the central area of HPGR roll surfaces is much higher than the edges, and it causes to increase in the wear rate remarkably on the central area of the roll surfaces [23, 28, 29]. Asymmetrical feeding on the different areas of the rolls is deleterious for HPGR [30, 31], and it probably increases the wear rate of rolls. It is obvious that inhomogeneous feeding of HPGR which is originated from material segregation can be defined easily as reserve mixing or demixing [32], and it has a considerable effect on wear rate of rolls. Segregation can happen from the belt conveyor to the feeding bin which is present in the HPGR circuit. Segregation is mainly due to physical properties including environmental conditions, handling parameters, and particulate materials [33]. Some researchers used specific software like DEM to model the segregations patterns and have a better understanding about it [34]. Rodriguez et al. showed that the skew can decrease the wear intensity of rolls which is an essential way to maintain rolls for a longer working period of time and decrease the effect of segregation on the rolls [35]. Also, it has shown that the size range of materials is the most controlling factor in the segregation phenomenon [35]. Although different effective parameters on HPGR rolls were objective in previous investigations, no one focused on how asymmetrical feeding can affect HPGR performance. In this research, material segregation on the HPGR feed belt conveyor and its influence on the wear rate of roll surfaces in a plant scale are investigated and represent the applied solution to increase the performance of the HPGR rolls and lifetime and reduce the segregation.

2 Materials and Methods

This investigation used several technical methods to monitor the HPGR's efficiency and present solutions to improve its performance. Particles size analyses were used to compare the feed and product of HPGR. Also, sampling was carried out to stabilize process production. Furthermore, the control room data was utilized to provide a good insight into the process and apply for data analysis stage.

After monitoring, collecting reliable data, and conducting analyses, the corrective measurements were implemented to improve performance.

2.1 HPGR Circuit

The case study plant produces over 2 million tons of iron ore concentrates per year. Figure 1 shows the general process flowsheet of the plant. In this plant, the HPGR mill works as pre-grinding equipment to prepare the ball mill feed, and it works in a closed circuit with a wet double-deck vibrating screen. The screen has three products: screen underflow (− 6 mm), which is fed to the hydrocyclones, screen middle product (− 50 + 6 mm), which is recycled to HPGR

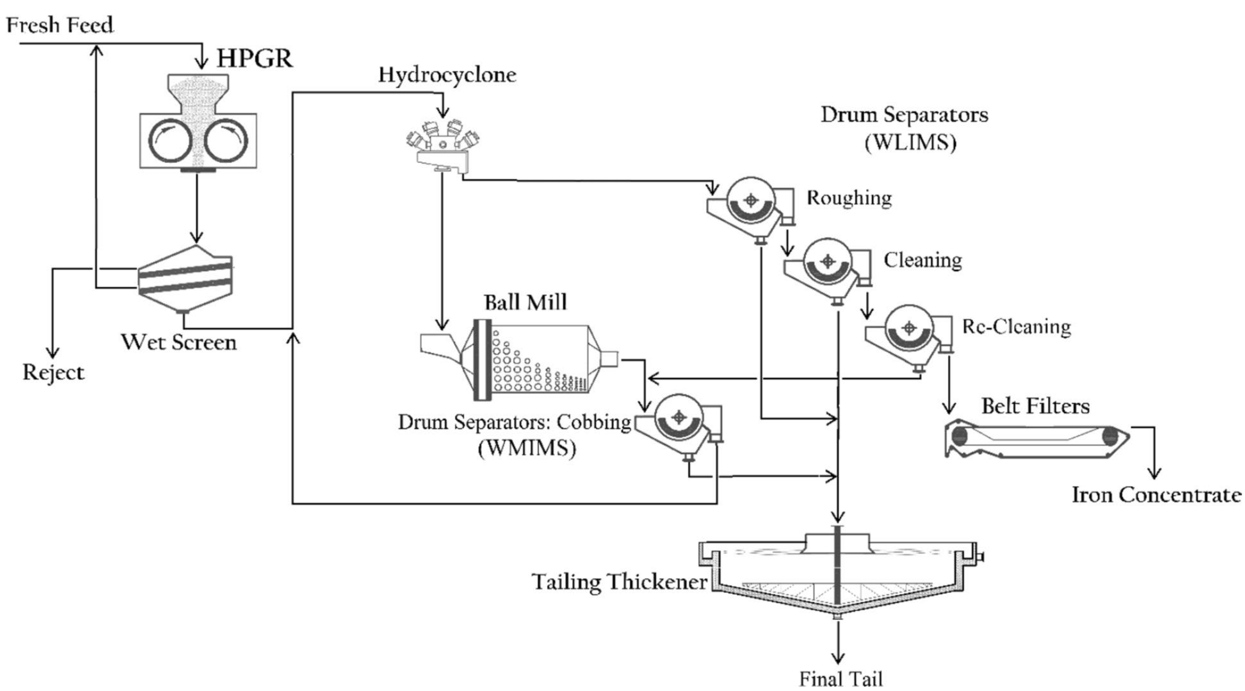


Fig. 1 The simplified process flowsheet of the case study plant. Reprinted with permission from [21]

Table 1 Physical and chemical composition of fresh feed sample

Average chemical analysis (%)	
Fe_{total}	50.3
FeO	20.6
Al_2O_3	2.4
CaO	2.5
MgO	3.8
TiO_2	0.22
SiO_2	10.3
S	1.7
P	0.1
Physical properties	
F_{100}	50 mm
F_{80}	37 mm
Average Bond Index	13–15 kWh/t

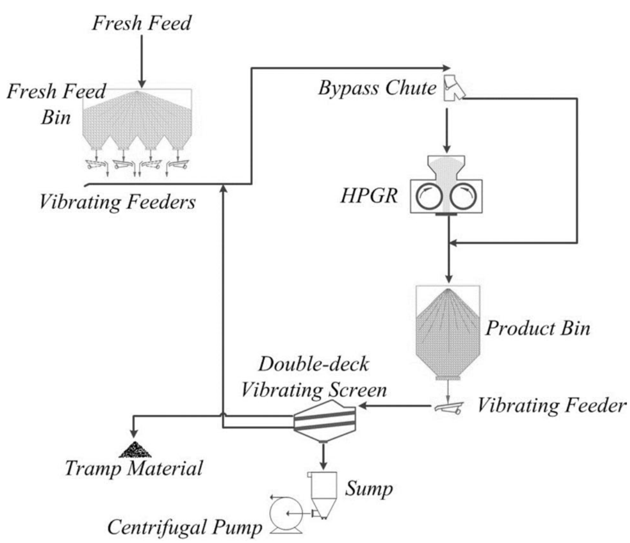


Fig. 2 A schematic view of the HPGR circuit

for regrinding as the circulating load, and the screen reject (+ 50 mm), which include very coarse particles and metal scraps. Table 1 represents the average chemical composition of the fresh feed. In Table 1, F_{100} is defined as feed top size, and F_{80} accounts for a screen aperture size that 80% of particles are finer than it.

Figure 2 demonstrates a schematic view of the HPGR circuit, and the technical data are presented in Table 2. The roll surface is made of forged steel and protected by tungsten carbide studs.

2.2 Operating Conditions of HPGR

The long-term plant audit was performed as a procedure to detect the operating and feeding conditions of the HPGR and the effect on the HPGR performance. In this regard, HPGR operation gap, wear rate, fresh feed rate, and circulating load were measured. Moreover, inspections included (1) reviewing the operating manuals of equipment, (2) considering the standard operating adjustments of equipment, (3) data gathering from the equipment observations, and (4) analyzing, proposing, and implementing the improvement solutions. Table 3 shows the operating parameters of HPGR.

3 Results and Discussion

Based on the HPGR audition and mentioned operating conditions in previous sections, there are several reasons for the non-uniform and excessive wear of the roll surface. To focus on the influence of the material segregation of the HPGR's feed, the effective parameters on the segregation such as non-uniform distribution of HPGR feed on the belt conveyor, inappropriate particle size distribution of HPGR feed, and non-standard operating parameters are discussed.

Table 2 The technical data of installed HPGR, vibrating screen, and de-agglomeration bin

HPGR		Double-deck vibrating screen	
Throughput capacity	900 t/h	Throughput capacity	900 t/h
Operating pressure	230 bars (Max.)	Aperture: upper deck	50 and 14 mm
		Aperture: lower deck	6 mm
Feed moisture	≤ 5%	Screen length	9 m
		Screen width	2.5 m
Feed size: F_{100}, F_{80}	50, 37 mm	Inclination	Dual slope, 25/15 deg
Specific pressing force	Maximum 4 N/mm^2	**De-agglomeration bin**	
Roll diameter	1.5 m	Capacity	200 ton
Roll width	1.2 m	Diameter	8 m
Roll speed	9–23 rpm	Height	5.2 m
Drive rating	2 × 745 kW	Feeder	900 t/h
Variation range of circumferential roller speed	0.75–1.8 m/s		

Table 3 The operating conditions of HPGR

Hydraulic pressure (bar)	170–180
Specific pressing force	3.1–3.3 N/mm^2
Zero gap (mm)	25
Fresh feed rate (t/h)	420–440
Fresh feed + circulating load (t/h)	600–680
Power consumption (kW)	800–900

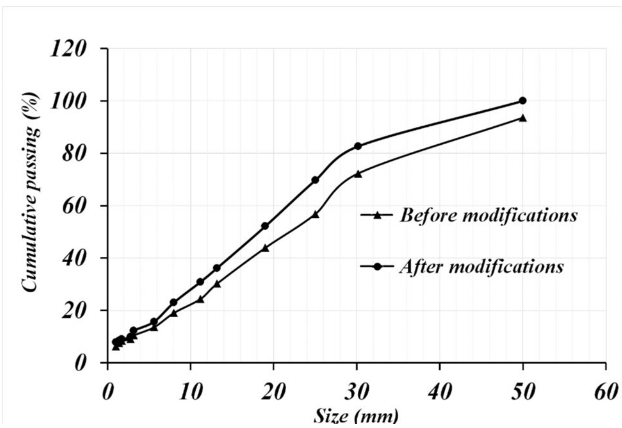


Fig. 3 The average PSD of HPGR's feed in two 3-day periods before and after implementing modifications at the upstream crushing plant

3.1 Inappropriate Particle Size Distribution (PSD) of HPGR's Feed

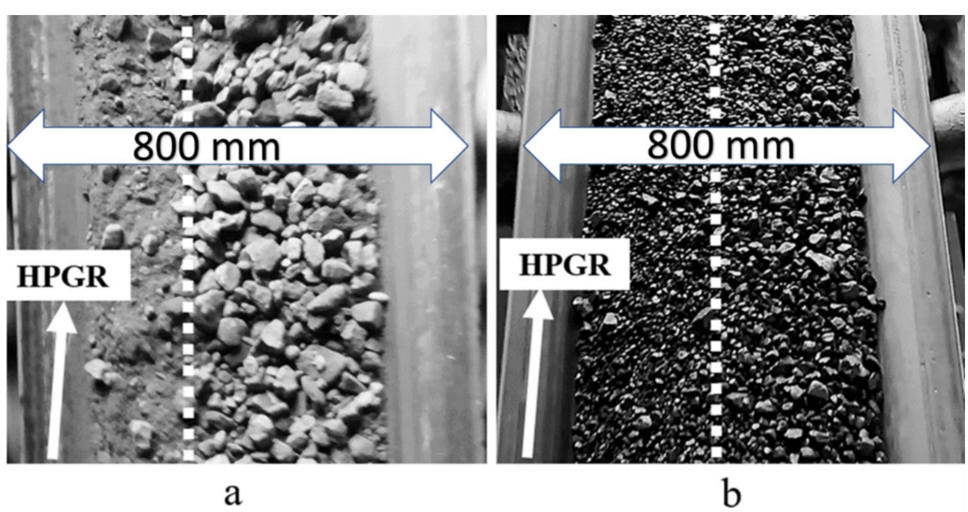
According to design data, F_{100} and F_{80} of HPGR's feed should be 50 and 30 mm, respectively. It was realized that inappropriate F_{100} and F_{80} of HPGR's feed as well as the presence of coarse particles in feed significantly reduced the equipment throughput and increased the wear rate of the roll surface.

Figure 3 shows the average PSD of the HPGR feed during operation in two 3-day periods before and after corrections. The coarse top size of the HPGR feed and the narrow size distribution of particles in the range of − 50 + 3 mm are problematic. Before modifications, the F_{80} of the HPGR feed was about 37 mm, and more than 6% of the HPGR's feed was coarser than 50 mm. To reduce HPGR's feed size, it was seen beneficial to reduce the aperture size of the screen at the upstream crushing plant and before the HPGR circuit from 50 to 40 mm to remove the coarse particles from the process and produce a finer feed for the downstream HPGR. After that, the F_{80} of the HPGR's feed was reduced to 29 mm, and all particles were finer than 50 mm which seemed to have a positive effect on the reduction of wear rate on the roll's surface.

3.2 Non-uniform Distribution of HPGR's Feed on the Belt Conveyor

HPGR feed comprises fresh feed (crushed iron ore) and the circulating load of a wet double-deck vibrating screen. The fresh feed is firstly transferred from the daily bin on the belt conveyor using two vibrating feeders under the daily bin. Then, the circulating load of the wet screen (coarse particles > 6 mm) is added to the fresh feed through a chute on the belt conveyor. The long-term auditions from the feed belt conveyor showed a non-uniform distribution of particles at the cross-section of the belt conveyor (Fig. 4). The coarse particles are gathered on the right side of the belt conveyor, while the fine particles are placed on the left side of the central axis of the belt conveyor. The results boost this hypothesis that this segregation has a negative effect on HPGR rolls, and the wear rate in the different sections of roll surfaces is different.

Fig. 4 Non-uniform distribution of particles on the cross-section of belt conveyor. **a** Fresh feed. **b** Fresh feed and circulating load of double-deck screen



During operation, samples were taken from two sides of the HPGR feed belt conveyor, and the PSD of HPGR's feed is shown in Fig. 5.

The results of the plant observations showed that the wear rate of the roll surface at the drive side was more than the non-drive side of the rolls. The non-uniform wear of the roll surface is related to the HPGR feeding conditions (Fig. 6). The circulating load chute of the screen guides material to one side of the belt conveyor, and it causes material segregation on the belt conveyor. As evident in Fig. 5, the PSD of the materials through the cross-section of the belt conveyor is different, and this non-uniform distribution of the materials continues to the HPGR hopper. Consequently, the PSD of materials on the cross-section of the roll's surface is different with materials on the roll's surface at the drive side coarser than the materials at the non-drive side, and it leads to the different and non-uniform wear rate. The wear rate of fixed and float rolls was measured, and it was on average 5 mm per million tons of iron ore feeding. To solve the segregation issue in the HPGR's fresh feed, it was suggested to always set the level of the materials in the fresh feed bin above 50%. Also, the screen circulating load chute was modified to guide the materials in the center of the belt conveyor. Figure 6 shows the new HPGR roll and its surface after about 12,000 working hours.

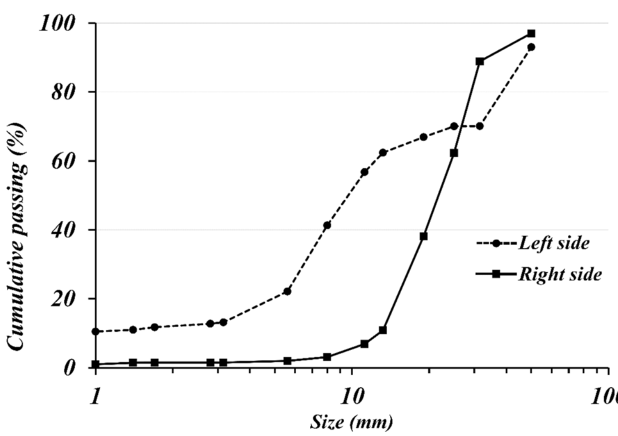


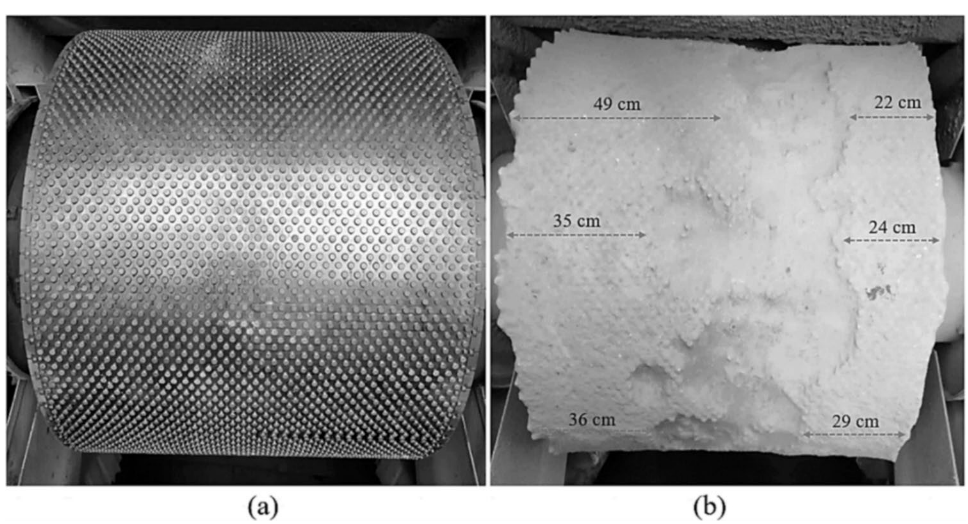
Fig. 5 Particle size distribution of HPGR's feed on the cross-section (left and right sides of the central axis of the belt conveyor) of the belt conveyor

One special ruler was used to monitor the wear pattern on the rolls surface. These measurements were carried out on 1600, 2700, 5200, 9000, and 12,000 working hours. Figure 7 shows the wear pattern over time, and it was understood that the wear rate on the rolls surface is uneven. As the deep concaves were appeared after 9000 working hours on the rolls surface, the wear measurements on the rolls surface were limited to this step.

The daily fresh feed bin of the plant can store about 3600 tons of crushed iron ore to provide a stable feeding condition. The process surveys indicated that the segregation phenomenon happens inside the fresh feed bin. Figure 8 presents the rate of different streams at the HPGR circuit concerning the level of materials inside the daily fresh feed bin. When the level of materials is under 40%, the segregation phenomenon increases, and the F_{80} of fresh feed becomes coarser. Notably, the level of the daily bin was collected from the control room employing ultrasonic sensors, and the rate of fresh feed and circulating load were obtained from the conveyor belt's scale. Also, the F_{80} of each stream was determined by sampling and sieving analyses.

The coarser fresh feed produces the course HPGR product, and it increases the screen's circulating load. Therefore, the wear rate of the HPGR roll surface increases. As a result, the level of materials inside the daily bin should be kept above 50% during operation to avoid accruing the segregation phenomenon of the fresh feed (Fig. 9).

Fig. 6 A new HPGR roll (**a**) and HPGR roll after 12,000 working hours (**b**)



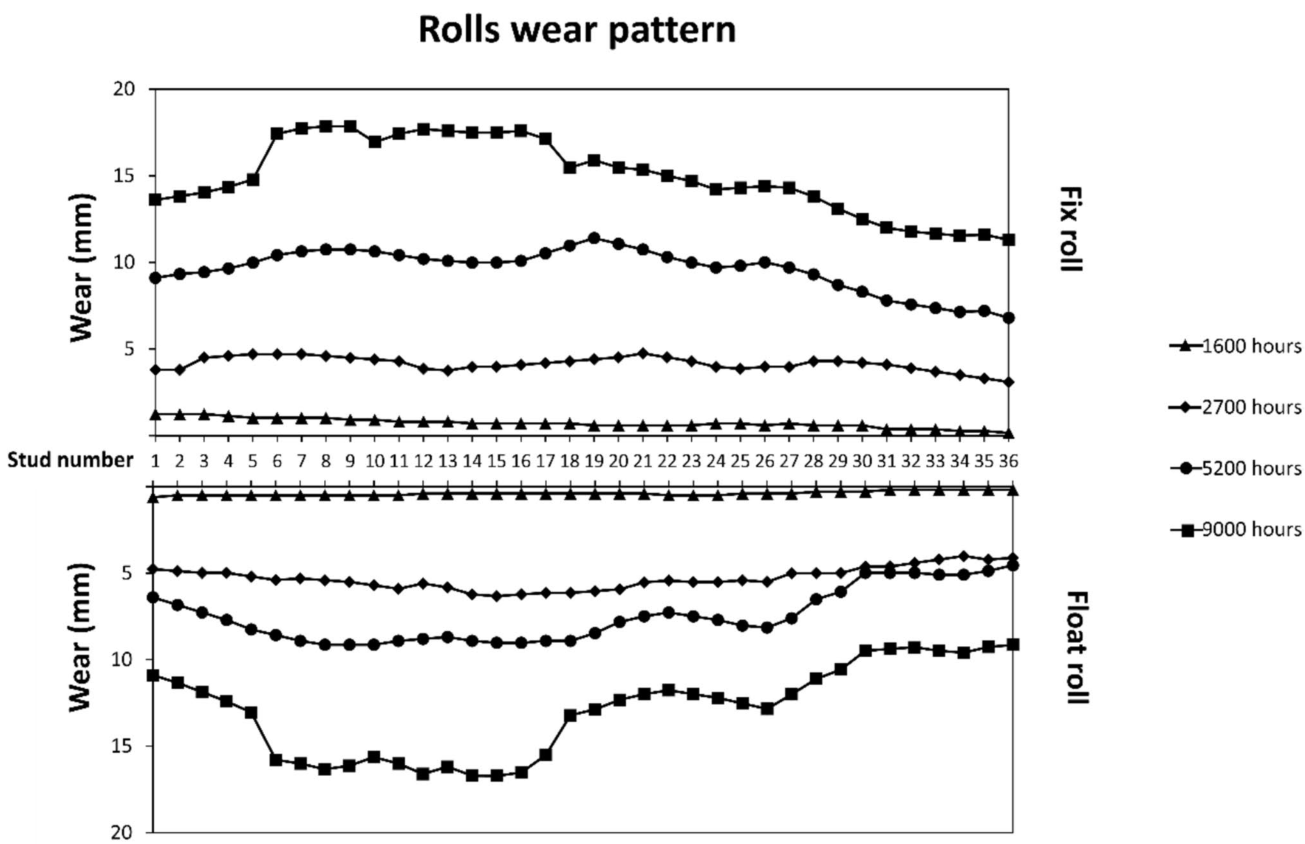


Fig. 7 Wear pattern of rolls after 1600, 2700, 5200, and 9000 working hours

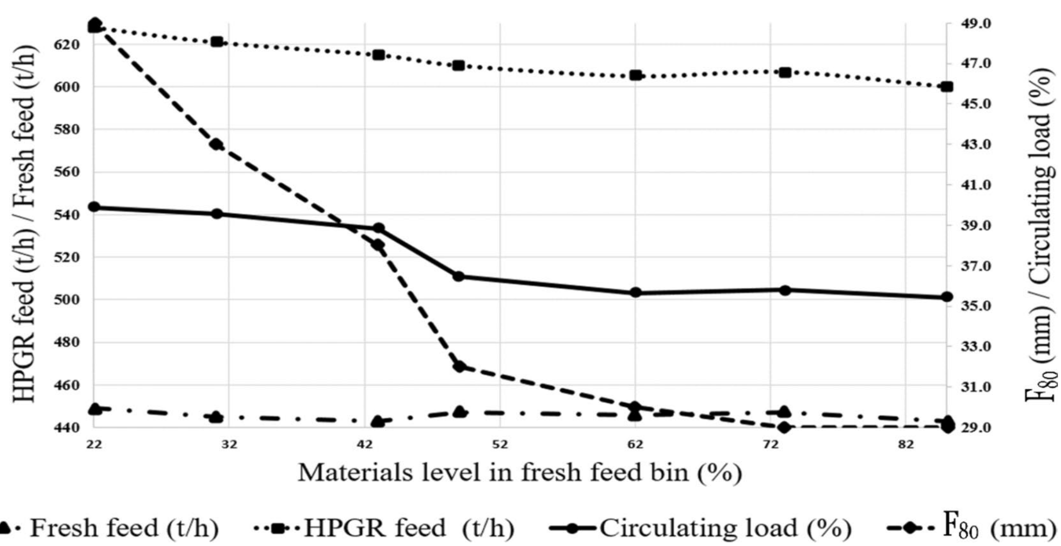


Fig. 8 The effects of materials level in the daily bin on F_{80} of fresh feed and screen's circulating load

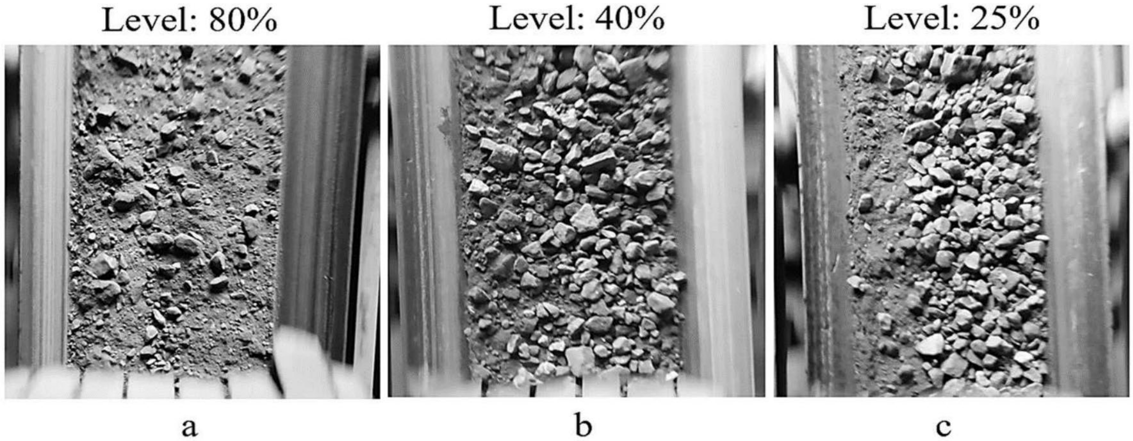


Fig. 9 Segregation of fresh feed on the belt conveyor for three different material levels inside the daily bin

3.3 Low Moisture Content of HPGR's Feed

To achieve the best performance at HPGR grinding operation, the moisture content of HPGR's feed should be adjusted at the range of 2–4% [14, 21]. At the case study plant, wet screening of HPGR's product increases the moisture content of HPGR's feed from less than 0.5% to about 2%, and it helps to form the protective layer on the surface of the rolls. It should be mentioned that the high moisture content of HPGR's feed (usually more than 5%) is also problematic [36, 37], and it may cause slippage of materials on the roll surface and increase the wear rate. Figure 10 depicts the presence of protective layers on the surface of the rolls.

In this research, one of the solutions to increase the moisture content of the fresh feed was to install some water spray nozzles on the HPGR's feed belt conveyor. The long-term auditions showed that this action is not completely practical, and there are still some bottlenecks to increase the moisture content of HPGR's feed.

3.4 HPGR Reduction Ratio (F_{80}/P)

The reduction ratio which is defined as the proportion of F_{80} to P_{80} is an indicator to show the efficiency of the comminution process. The investigations on the reduction ratio of HPGR showed that HPGR comminution efficiency during the last 6 months of the roll's lifetime reduces due to the wear of the roll's surface over time. However, readjusting the gap between rolls can somehow prevent it. In addition, the concave wear shape on the surfaces of the rolls allows the materials to pass through without sufficient size reduction. The reduction ratio is measured and presented in Fig. 11. Notably, during this working period, other operating parameters such as pressure and feed rate were maintained in the mentioned range in Table 3.

The changes in the reduction ratio affect the circulating load and the rate of material rejection from the wet screen. At the end of the roll's lifetime, the efficiency of the HPGR reduces because of extended concaves on the roll's surfaces, and the HPGR product has coarser particles. The coarser

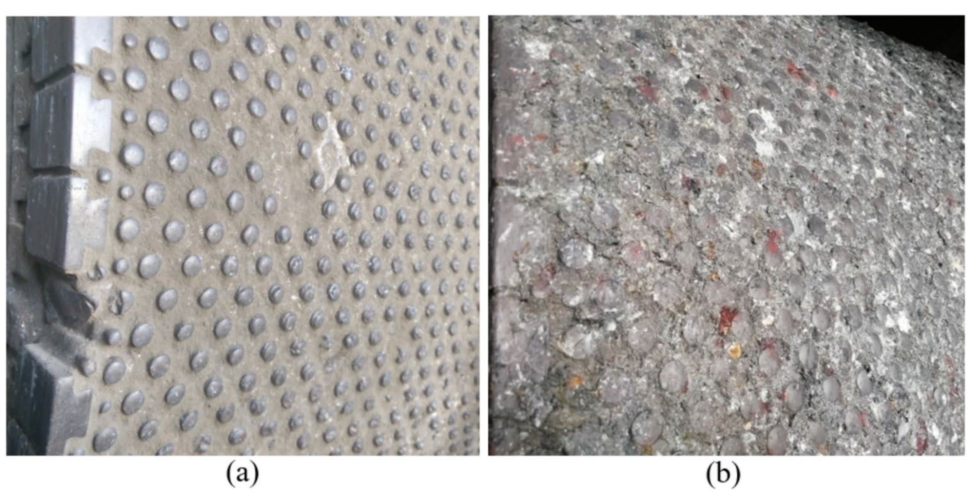


Fig. 10 **a** The protective layer on the surface of the roll. **b** Inappropriate protective layer due to insufficient feed moisture. "Reprinted with permission from [21]"

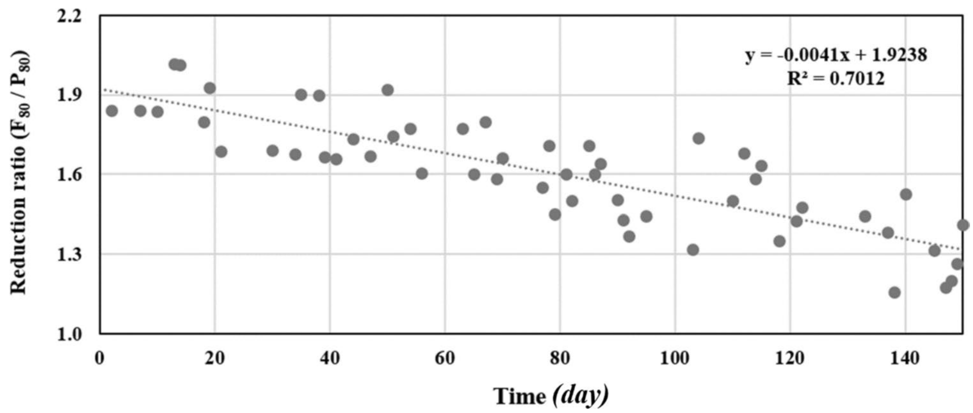


Fig. 11 The reduction ratio (F_{80}/P_{80}) of HPGR over the last 6 months roll's lifetime

particles at the HPGR output mean higher circulating load and rejection rates. The screen circulating load compared with fresh feed showed that it increased from 37 to 55% during the last 6 months of operation. Also, at the same time, the rejection rate compared with the fresh feed rose from 1.5 to 3.5%. A view of the roll's surface before and after extended concaves is shown in Fig. 12.

4 Conclusion

In this paper, the effects of materials segregation on feeding conditions and the performance of HPGR were investigated. The main reasons for the asymmetrical wear on the roll surface were (a) the segregation phenomenon that happens due to the non-uniform distribution of materials on the belt conveyor, (b) the narrow size distribution of HPGR's feed, and the presence of coarse particles in it. By changing the aperture size of the screen at the upstream crushing plant from 50 to 40 mm, the coarse particles inside HPGR's feed were removed, and the F_{80} decreased from 37 to 29 mm as well. To avoid segregation in the daily bin, the bin level was kept higher than 40% during operation. Furthermore, the circulating load chute of the HPGR's screen was modified to guide all materials to the center of the belt conveyor to have a uniform distribution of materials for the HPGR.

The moisture content of the HPGR feed was about 2% which is not suitable for optimum operation and forming a protective layer of materials on the roll surface to prevent excessive wear of the roll surface. To increase the moisture content, spray water nozzles on the belt conveyor were used, but the results showed that this action was not effective in raising the moisture content of materials. The results showed that after about 12,000 working hours, the circulating load of HPGR's circuit increased from 37 to 55%, while the rejection of materials increased from 1.5 to 3.5%. It is strongly recommended to do further investigations on the prediction of the roll's lifetime with different pressure levels and set the best pressure regarding the economic view. Also, finding a solution to increase the feed moisture content in an appropriate way is an attractive field of study.

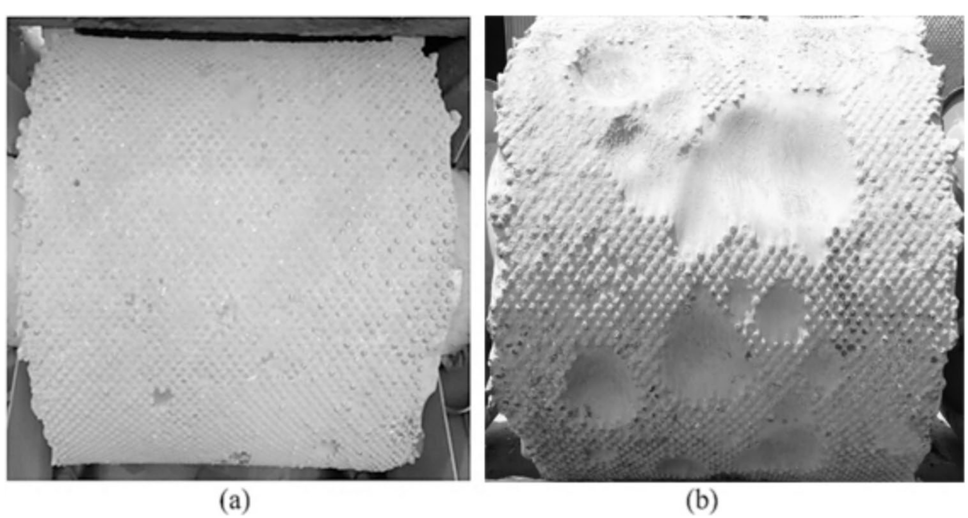


Fig. 12 Rolls surface before (**a**) and after concaves (**b**)

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Declarations

Conflict of Interest The authors declare no competing interests.

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