minerals

IMPACT FACTOR 2.818

CITESCORE 3.7

Article

Performance Analysis of HRC™ HPGR in Manufactured Sand Production

Júlio Cesar Figueiredo de Almeida, Homero Delboni, Jr., Rafael Bento, Alfredo Reggio and Everson Cremonese

Special Issue
Process Mineralogy, Plant Practice and Developments in Mineral Processing

Edited by
Prof. Dr. Laurindo De Salles Leal Filho, Prof. Dr. Homero Delboni Júnior and Prof. Dr. Arthur Pinto Chaves

MDPI

https://doi.org/10.3390/min13020222

minerals

Article

Performance Analysis of HRC™ HPGR in Manufactured Sand Production

Júlio Cesar Figueiredo de Almeida [1,2,*], Homero Delboni, Jr. [2], Rafael Bento [3], Alfredo Reggio [2] and Everson Cremonese [2]

[1] Metso Outotec, Sorocaba 18087-101, Brazil
[2] Department of Mining and Petroleum Engineering, University of Sao Paulo, Sao Paulo 05508-070, Brazil
[3] Itaquareia Ind. Ext. de Minérios (Itaquareia Mining), Mogi das Cruzes 08780-970, Brazil
* Correspondence: julio.almeida@mogroup.com or eng.julioalmeida@usp.br; Tel.: +55-159-9804-6053

Abstract: The costs related to comminution in the mineral industry are significant, thus representing the main challenge for optimizing such a process. During the last few decades, the technology of High-Pressure Grinding Rolls (HPGR) has been consolidated as an important alternative for comminution circuits, due to the relatively low operational cost, as well as a relatively high energy efficiency. Due the initial high capital costs, HPGR applications are limited to high-capital projects. However, Metso Outotec has recently developed a relatively low-cost HPGR equipment mainly applied to aggregates segment. Accordingly, this work aims to evaluate the performance of HRC™ HPGR in the production of manufactured sand, based on surveys carried out in an existing industrial plant. The performance assessment indicates that the HRC™ was an adequate alternative for manufactured sand production. The analysis also includes the comparisons of the resulting products based on Brazilian Standards for sands used in concrete and filters.

Keywords: HPGR; manufactured sand; comminution; HRC™; aggregates

check for updates

Citation: de Almeida, J.C.F.; Delboni, H., Jr.; Bento, R.; Reggio, A.; Cremonese, E. Performance Analysis of HRC™ HPGR in Manufactured Sand Production. *Minerals* **2023**, *13*, 222. https://doi.org/10.3390/min13020222

Academic Editor: Thomas Mütze

Received: 19 December 2022
Revised: 14 January 2023
Accepted: 30 January 2023
Published: 2 February 2023

1. Introduction

A combination of environmental restrictions, together with technical and economic feasibility aspects, is increasingly restricting the production of natural sand relatively close to the main consumers. New mines are thus facing long transport distances, which may extend the overall costs by as much as 2/3 [1,2].

An alternative to such a scenario is to produce manufactured sand, which is sand produced using a crushing method, from rocks or tailings resulting from either gravel or even natural sand production. Such applications are increasing the growth of the manufactured sand market, in view of the technical and environmental restrictions faced by the traditional methods of sand production that involve the extraction of this material from riverbeds [3–5].

In addition, various authors [6–8] have evaluated the use of manufactured sand in concrete and mortar, instead of simply using it for replacing natural sand.

The growing demand for manufactured sand leads to a demand for a product that may result from either fine crushing or coarse grinding. The relatively high metal consumption requirements, i.e., as ball media and/or liners, is an economic challenge in both cases, which also include the prerequisite of low capital costs.

Under such a scenario, Metso Outotec developed the HRC™, an HPGR technology specifically for such an application [9].

Since its introduction in 2011, the use of HRC™ is progressively increasing in the Brazilian and global industrial operations dedicated to aggregate segment, which include manufactured sand production. Currently, there are more than 70 types of HRC™ equipment applied to aggregate segmenting, and some of these applications are located in Brazil [9,10].

One such industrial operation was surveyed for assessing HRC™ performance, as well as evaluating the obtained product according to Brazilian Standards of sand for use in concrete and sand for filters.

1.1. Objective

This work aims to evaluate the performance of HRC™ in manufactured sand production. The performance is evaluated in terms of capacity, energy consumption and quality of obtained product.

1.2. HRC™

In 2015, Mesto Outotec introduced new models of their HRC™ HPGR equipment, specifically for aggregate segment, referred to as HRC™ Aggregates [9]. Figure 1 shows a photograph of an HRC™8 installed in an industrial plant.

Figure 1. HRC™ Aggregates installed in an industrial operation.

The HRC™8 was designed for relatively low throughputs and medium–low specific grinding force, which result in lower weights and low cost compared to the full size Metso Outotec HPGR equipment with similar dimensions (HRC™800), the latter being typically used in applications that demand a higher specific grinding force. Table 1 shows the technical specifications and the main differences between the HRC™8 and HRC™800 models [9].

Table 1. HRC™ technical specifications.

	HRC™800	**HRC™8**
Weight of equipment (kg)	16,000	11,000
Installed power (hp)	2 × 150	2 × 100
Diameter and length of rolls—D × L (mm)	800 × 500	800 × 500
Grinding specific force limit (N/mm^2)	4.5	2.5
Nominal speed with 60 Hz frequency (RPM)	32	32
Feed Top Size limit (mm)	32	32
External dimensions—length × width × height (m)	2.5 × 4.3 × 2.5	2.4 × 3.5 × 1.6

With a lower weight, installed power, maximum limit of specific grinding force, external dimensions and cost of mechanical components, the HRC™8 costs 30% to 35% that of the HRC™800 model. The relatively low capital cost of HRC™8 is particularly adequate for industries processing low-value material, such as aggregates for civil construction [9].

1.3. HRC™ Operating Indices

The main indices associated with HPGR operation are listed in the following Equations [11,12].

$$SP = \frac{F}{1000 \times D \times L} \tag{1}$$

where SP is the specific pressure (N/mm^2), F is the force (kN), D is the roll diameter (m), and L is the roll width (m).

$$SE = \frac{P}{Q} \tag{2}$$

where SE is the specific energy (kWh/t), P is the power (kW), and Q is the throughput of solids (t/h).

$$SC = \frac{Q}{D \times \ L \times V} \tag{3}$$

where SC is the specific capacity (ts/hm^3), and V is the roll peripheral speed (m/s).

1.4. Itaquareia Mineral Processing Plant

The Itaquareia mineral processing plant installed in Mogi das Cruzes, Sao Paulo state, Brazil, was selected for conducting the experimental work here described.

Mining is carried out with a combination of excavation and hydraulic jets in open pits, from which the pulp is pumped through centrifugal pumps to the processing plant. The first processing stage includes a static scalping screen equipped with a 15 mm aperture metallic mesh, whose oversize is used to pave roads within the industrial area, whereas the undersize is directed to a large storage tank. The material reclaimed from the storage tank is pumped to a vibrating screen equipped with three decks, equipped respectively with 7.0 mm, 3.5 mm and 1.5 mm mesh apertures. Depending on the granulometric range, the screen products are referred as follows:

- Coarse gravel (−15 mm + 7.0 mm);
- Fine gravel (−7.0 mm + 3.5 mm);
- Coarse sand (−3.5 mm + 1.5 mm);
- Medium sand (−1.5 mm).

In the past, all four screen fractions have been produced and commercialized by Itaquareia as final products. However, in periods of low market demand, coarse sand was stockpiled on the site, making it a potential environmental issue for the company over the years, and making "coarse sand" an environmental liability in this operation. This situation was resolved by introducing a comminution unit in the processing plant, essentially including an HRC™ unit with smooth rolls, together with a dedicated horizontal screen. Figure 2 shows the current Itaquareia process flow sheet.

As shown in Figure 2, the Coarse Sand fraction is transported via dump trucks from the primary screening area to the HRC™ feed bin. A dedicated apron feeder controls the feed rate to the HRC™ unit, whose product is directed to a second bin. Material from the second bin is either a final product or further screened on a double-deck horizontal screen, with 1.18 mm and 0.60 mm mesh screens. The top deck oversize is referred to as block sand, which is specifically used in the building blocks market, while the bottom deck oversize is referred to as filter sand. The bottom deck undersize is further recirculated to the primary screen feed, as part of this plant's strategy for reusing process water.

Even though the coarse sand is currently the main feed in the HRC™, the equipment was also evaluated for fine gravel processing.

Figure 3 shows the Itaquareia HRC™ industrial processing plant located in Mogi das Cruzes, Sao Paulo—Brazil.

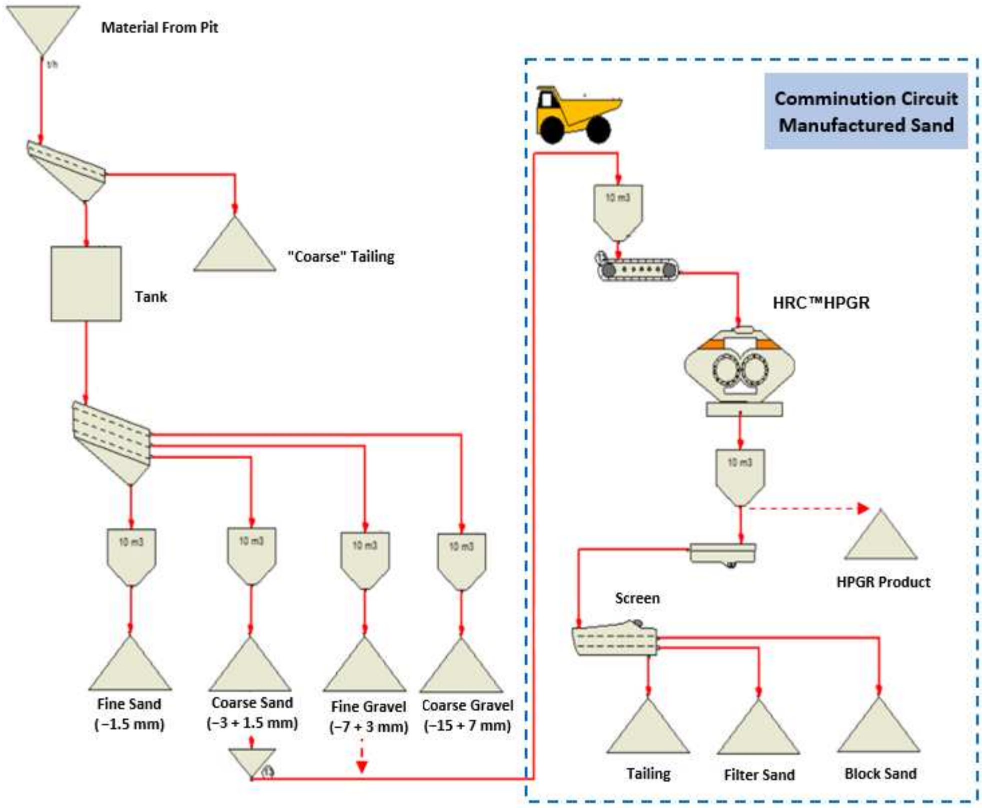

Figure 2. Itaquareia processing plant flow sheet.

Figure 3. Itaquareia HRC™ industrial plant.

2. Experimental

2.1. Method

The procedural method for assessing the HRC™ performance in the Itaquareia-manufactured sand processing plant included a survey campaign in the circuit, followed by sample processing and characterization, together with assessing selected capacity and energy consumption indices.

The sampling campaign included five surveys in the Itaquareia HRC™ circuit. The obtained samples were processed in the Metso Outotec laboratories in Sorocaba, São Paulo state, Brazil, to determine size distributions, bulk and flake densities, as well as moistures. Further testing was carried out at University of Sao Paulo laboratories specifically for chemical analysis and abrasion testing. The overall procedure adopted in this work is summarized in Figure 4.

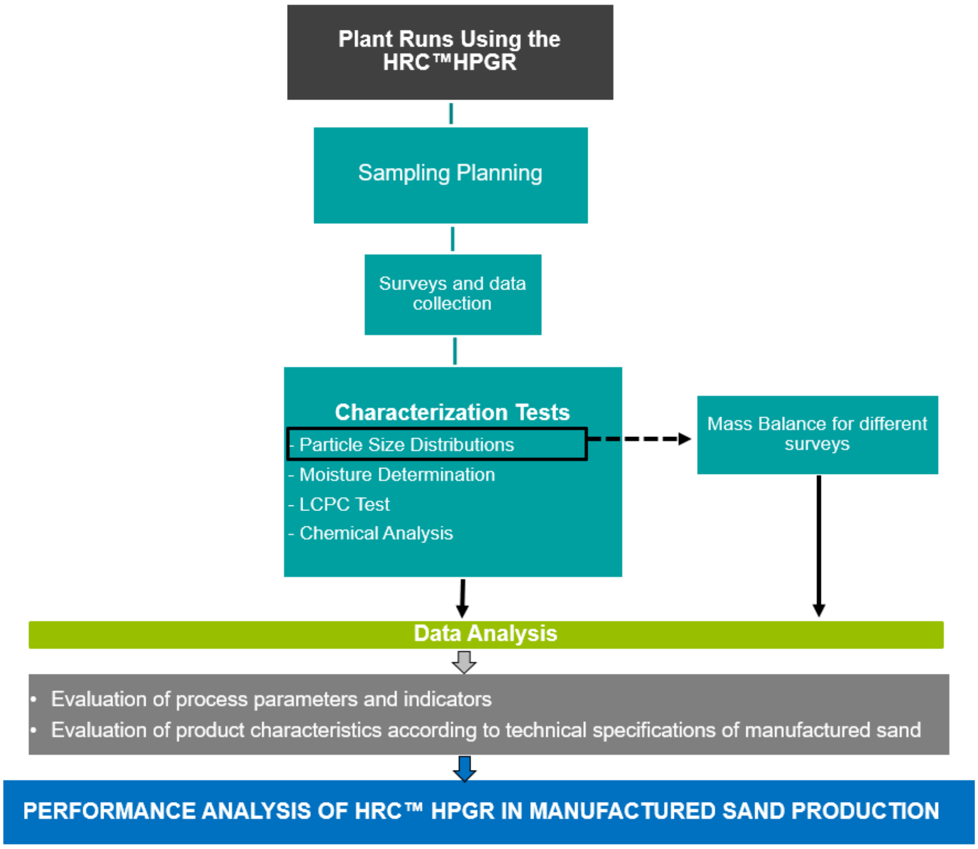

Figure 4. Method adopted for assessing the performance of HRC™ in the Itaquareia industrial processing plant.

2.2. Sampling Campaign

The sampling campaign carried out at the Itaquareia industrial processing plant included five full surveys in the HRC™ circuit. They comprised two different types of feed using three levels of specific grinding pressures, as described in Table 2.

Table 2. Summary of surveys carried out at Itaquareia HRC™ circuit.

Survey	Type of Feed	Specific Grinding Pressure (N/mm^2)
1	Fine Gravel	1.0
2	Fine Gravel	1.8
4	Coarse Sand	1.8
5	Coarse Sand	1.8
6	Coarse Sand	2.1

Surveys 4 and 5 were carried out under the same conditions to assess the reproducibility associated with adopted procedures. Figure 5 shows the Itaquareia comminution circuit flowsheet as well as the selected sampled streams; the latter is further described in Table 3.

Table 3. Sampling point dentification.

Sampling Point	Description
1	HRC feed
2	HRC discharge
3	Screen feed
4	Screen top deck oversize
5	Screen bottom deck oversize

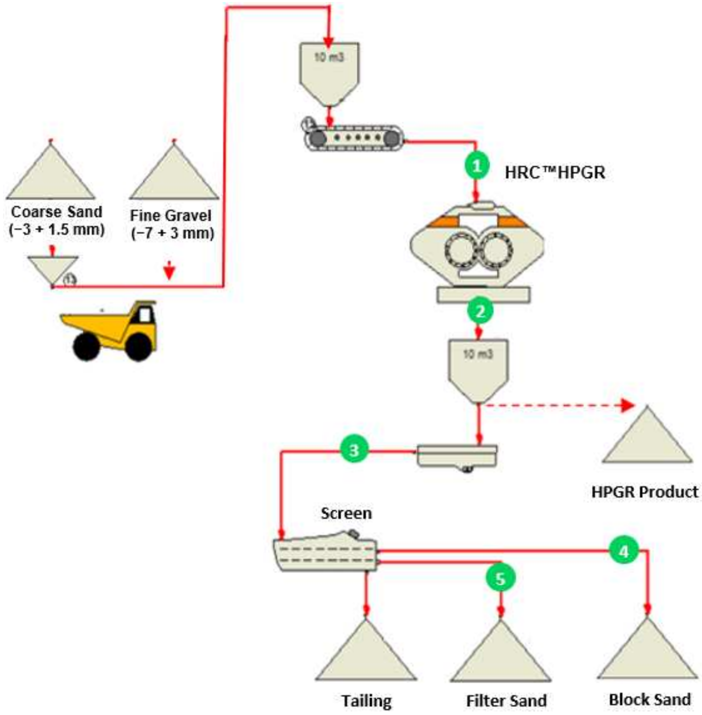

Figure 5. Itaquareia comminution circuit and sampled streams.

The procedure adopted in each survey involved an initial emptying of both silos before filling them with the selected test material. At the beginning of each test, the HRC™ was adjusted to the particular roll pressure and operated until a steady-state condition was achieved, essentially when a feeder speed was established that maintained a stead silo level. During the steady-state operation period, data were obtained from the control system through the HMI (Human–Machine Interface), and included the power draw and roll speed for each roll, together with specific energy.

At the end of this period, the whole system was shut down and samples were collected around the points indicated in Table 3. For this, tools such as shovels, brooms and specific containers for sample storage were used. Due to the access difficulties, the undersize from the bottom screen deck was not sampled.

Since this version of the HRC™8 model does not have an automatic/real-time gap monitoring system, samples from flakes contained in the HRC™ discharge were carefully separated for measuring the HRC™ operating gap through the use of a pachymeter. The flakes were not compact enough to require a deagglomeration step. The flake deagglomeration happened only with the natural handling of this material along the downstream steps of the process. This premise was confirmed through site visits, discussions with operators and the handling of this material during testing.

3. Results and Discussion

In this section, the results obtained from the survey campaign and sample treatment are presented, together with associated analysis. Mass balancing was followed by HRC™ performance indices and additional characterization tests. The last part included a detailed analysis of the products obtained in each survey carried out at the Itaquareia HRC™ industrial plant.

3.1. Mass Balance

The mass balance procedure adopted in all five surveys consisted initially of calculating the solid flow rate in the screen bottom deck undersize, based on all other solid flowrates obtained throughout the circuit. Based on such an estimation, the size distribution of the screen bottom deck undersize was calculated. Even though such a method may be regarded as mass reconciliation, it resulted from the practical limitation in surveying the bottom deck screen undersize. Such a situation is relatively frequent in industrial plants in the aggregate industry. Table 4 shows the solid flow rate associated with each stream in each survey as the mass balanced. The same values are presented in a graphic form in Figure 6.

Table 4. Mass balance results—solids flow rate.

	Solids Flow Rate (t/h)					
Survey	**HPGR Feed**	**HPGR Product**	**Screen Feed**	**Screen Top Deck O/S**	**Screen Bottom Deck O/S**	**Screen Bottom Deck U/S**
1	47.2	47.2	47.16	26.0	8.3	12.8
2	46.3	46.3	46.31	24.2	8.5	13.6
4	35.5	35.5	35.50	13.9	10.2	11.4
5	35.7	35.7	35.71	14.8	9.7	11.2
6	33.1	33.1	33.06	13.5	8.7	10.8

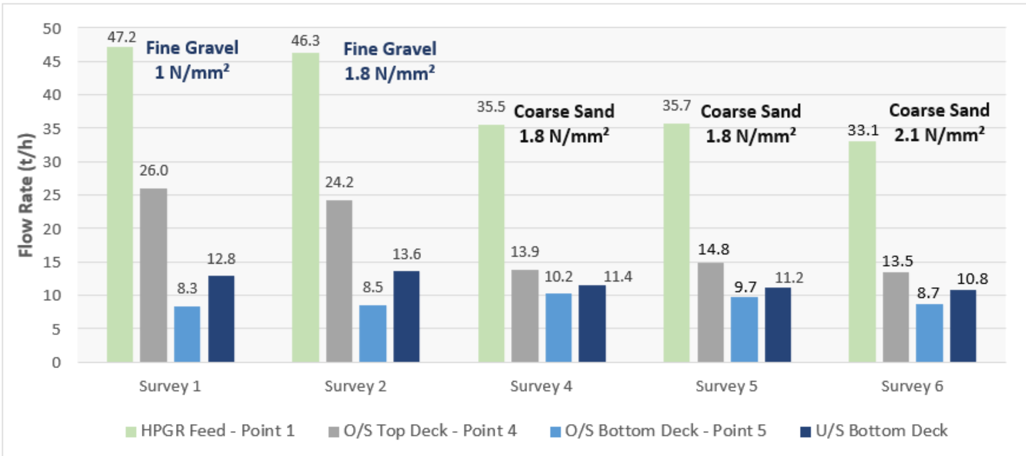

Figure 6. Summary of mass balance results.

Size distributions resulting from mass balance are shown and discussed in detail in the following sections, where each one is compared with the Brazilian standards for sand products. Table 5 shows the summary of mass balanced size distributions indices, such as HRC™ feed and product P_{80} and P_{50}.

Table 5. Mass balance results—feed moisture, bulk density and particle size distribution indices.

Survey	Feed	Specific Pressure (N/mm^2)	Feed Moisture (%)	Bulk Density (g/cm^3)	Feed P_{80}-F_{80} (mm)	Product P_{80}-P_{80} (mm)	Feed P_{50}-F_{50} (mm)	Product P_{50}-P_{50} (mm)
1	Fine Gravel	1.0	7.9	1.73	4.28	2.81	2.53	1.36
2	Fine Gravel	1.8	7.9	1.72	4.22	2.60	2.39	1.27
4	Coarse Sand	1.8	4.6	1.65	2.34	1.78	1.57	0.95
5	Coarse Sand	1.8	4.5	1.63	2.27	1.74	1.52	0.95
6	Coarse Sand	2.1	4.7	1.65	2.29	1.73	1.55	0.93

Tables 5 and 6 indicate higher HRC™ throughput associated with fine gravel feed as compared with coarse sand, even though the former showed a coarser feed size distribution as compared with the latter. The comparison is consistent with both F_{80} and F_{50} parameters, since the resulting products follow the same tendency, i.e., coarser for fine gravel feed as compared with coarse sand feed.

Table 6. Summary of operating conditions and main performance indexes.

Survey	Feed	Specific Pressure (N/mm^2)	HRC™ Feed (t/h)	Specific Capacity (ts/hm^3)	Specific Energy Consumption (kWh/t)	Flake Density (g/cm^3)	Operating Gap (mm)	RR_{80} *	RR_{50} **
1	Fine Gravel	1.0	47.2	174	3.27	2.06	18.7	1.52	1.87
2	Fine Gravel	1.8	46.3	170	3.49	2.14	17.7	1.63	1.89
4	Coarse Sand	1.8	35.5	131	3.53	2.03	14.3	1.31	1.65
5	Coarse Sand	1.8	35.7	131	3.51	2.02	14.4	1.30	1.60
6	Coarse Sand	2.1	33.1	122	3.58	2.06	13.1	1.32	1.67

* Reduction ratio (F_{80}/P_{80}). ** Reduction ration (F_{50}/P_{50}).

In terms of P_{80} and P_{50}, the increase in specific pressure is relatively small. Accordingly, fine gravel showed a P_{80} change from 2.81 mm to 2.60 mm as the specific pressure was increased from 1.0 N/mm^2 to 1.8 N/mm^2, while for coarse sand, the P_{80} changed from 1.74 mm to 1.73 mm as specific pressure was increased from 1.8 N/mm^2 to 2.1 N/mm^2. The latter change in P_{80} may be considered negligible.

3.2. HRC™ HPGR Performance Indices

The main indices calculated for each survey are summarized in Table 6.

Table 6 shows a significant reduction in the specific capacity for coarse sand feed, as compared with fine gravel feed, resulting from the smaller feed rate of the latter in comparison with the former. Interestingly, the specific energy consumption values were similar for both fine gravel and coarse sand feed, thus indicating a relative compensation by the respective HRC™ power draw, i.e., higher throughputs were associated with relatively higher power draw, and smaller throughputs were associated with relatively smaller power draw.

Table 6 also indicates similar flake densities for all tests. The reduction ratios were higher for fine gravel as compared with coarse sand tests, both in terms of P_{80} (RR_{80}) and P_{50} (RR_{50}). As observed in the size distributions, neither the RR_{80} nor the RR_{50} index were significantly affected by the specific pressure.

3.3. Additional Characterization Tests

Table 7 shows the grades of selected elements, as obtained by chemical analysis using the lithium tetraborate fusion method.

Table 7. Chemical analysis results.

Feed ID	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O (%)
Fine Gravel	88.3	5.97	1.55	0.11	0.13	<0.10	0.23	3.5	0.11	<0.10
Coarse Sand	91.3	4.65	1.34	0.14	<0.10	<0.10	0.21	3.14	<0.10	<0.10

The chemical analysis results show high contents of SiO_2 for both samples, in this case higher than 88%, indicating high-quality products [13]. Although the contents of SiO_2 indicate good-quality products, further investigation is recommendable to avoid possible harmful alkali–silica reactions later in the concrete due to this content of Al_2O_3.

The abrasiveness of a combined feed sample of fine gravel and coarse Ssnd was assessed through the Macon test, also referred as LCPC—Laboratoire Central des Ponts et Chausses. The value of 1184 g/t classifies the sample as very abrasive, and this result is in accordance with the reference values indicated for quartz sand [14].

3.4. Product Characteristics

The products obtained in the surveys were compared with respective Brazilian Standards of manufactured sand and the required parameters.

The first comparison was carried out with both HRC™ discharge and block sand product, the former thus representing the HRC™ direct product (Point 2—Table 2), whereas the latter corresponded to the screen top deck oversize product (Point 4—Table 2). These two products were thus compared with Standard ABNT NBR7211, a Brazilian reference for fine aggregates (sand) used in concrete, which includes that this material must meet the following parameters:

- Particle size distribution—usable zone, as well as lower and upper limits;
- Fineness modulus—referred to as the sum of percentages accumulated in 9.5, 6.3, 4.75, 2.36, 1.18, 0.600, 0.300 and 0.150 mm aperture screens divided by 100, i.e., cumulative percentage retained on specific sieves, divided by 100;
- Limit of 5% passing through a 0.075 mm screen aperture;
- Presence of clay and/or friable materials [15].

In addition to these parameters being mentioned by this standard, several authors highlight the criticality and influence of such parameters in the quality of sand for concrete [16–18].

The second comparison was carried out with the filter sand product, corresponding to the screen bottom deck oversize (Point 5—Table 2). In this case the product of each survey was compared with Standard ABNT NBR11799, a Brazilian reference for filter materials (filter sand), which must meet the following:

- 100% passing through a 4.78 mm aperture screen;
- Free from dust, clay and organic materials;
- Effective size—referred to as 10% passing size, in mm;
- Uniformity coefficient—referred to as the ratio between the 60% passing size and the 10% passing size [19].

This standard does not indicate the specific values of the effective size and uniformity coefficient, and mentions that the required values must be established by the consumer market (end costumer).

The product analysis is here described in terms of a chart containing the lower and upper limits according to the Brazilian Standard ABNT NBR7211 for fine aggregates (sand) used in concrete. An additional table is included in each case for assessing through a color scale every single aspect as listed in the ABNT NBR7211 and ABNT NBR11799 standards. The color scale indicates whether the materials are outside of, or partially, almost fully or fully within the standards, as shown in Figure 7.

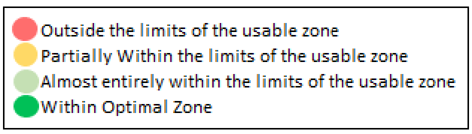

Figure 7. Color scale adopted in the analysis.

Figure 8 and Table 8 show that HRC™ feed was inadequate for the concrete and filter uses, whereas Table 8 indicates that the HRC™ product's size distribution was partially within the limits of the usable zone for use as sand in concrete, while being inadequate for filter sand.

Even though the block product was inadequate for both concrete and filter, the filter sand product almost fully met the specifications of a fine aggregate for concrete, as well as being fully suitable for filter sand.

Here too, Figure 9 and Table 9 show that the HRC™ feed was inadequate for concrete or filter uses. Table 9 indicates that the HRC™ product's size distributions were almost entirely within the limits of the usable zone for use as sand for concrete, while being for filter sand.

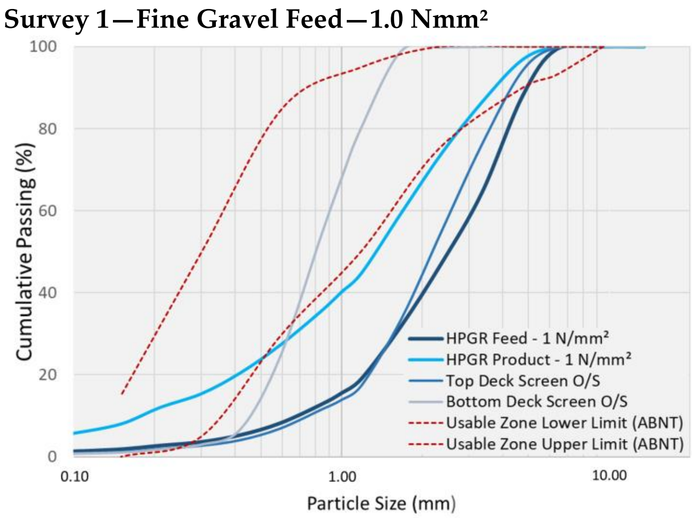

Figure 8. Survey 1 size distributions and limits for use as sand for concrete.

Table 8. Survey 1 product analysis.

	Survey 1—Feed Fine Gravel, Pressure 1N/mm^2							
	Standard NBR 7211—Agreggates for Concrete (Aggregate Fine)					Standard NBR 11799—Filtering Material (Sand for Filters)		
Sampling Points	**Fineness Modulus**	**Fineness Modulus Classification**	**Material −0.075 mm (%)**	**Presence of Clay and Friable Materials**	**Particle Size Distribution**	**Material −4.8 mm (%)**	**Free from Dust, Clay, Organic Material**	**Effective Size and Uniformity Coefficient**
HPGR Feed	3.81	Out of Usable Zone	0.93	Not identified	Outside the limits of the usable Zone	87.83	Yes	Adequate
HPGR Product	3.08	Within Usable Zone	4.29	Not identified	Partially Within the limits of the usable Zone	96.91	Yes	Adequate
Block Sand	3.78	Out of Usable Zone	0.57	Not identified	Outside the limits of the usable Zone	94.09	Yes	Adequate
Filter Sand	2.91	Within Usable Zone	0.55	Not identified	Almost entirely within the limits of the usable Zone	100	Yes	Adequate

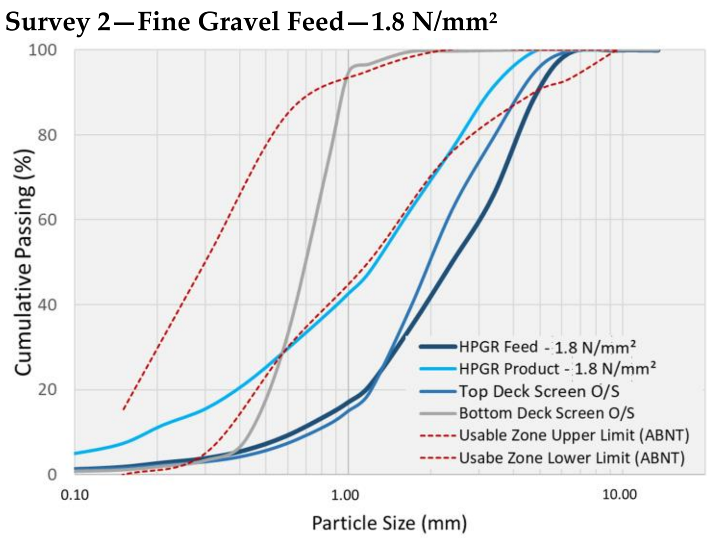

Figure 9. Survey 2 size distributions and limits for use as sand for concrete.

Table 9. Survey 2 product analysis.

	Survey 2—Feed Fine Gravel, Pressure 1.8 N/mm^2							
	Standard NBR 7211—Agreggates for Concrete (Aggregate Fine)					Standard NBR 11799—Filtering Material (Sand for Filters)		
Sampling Points	**Fineness Modulus**	**Fineness Modulus Classification**	**Material −0.075 mm (%)**	**Presence of Clay and Friable Materials**	**Particle Size Distribution**	**Material −4.8 mm (%)**	**Free from Dust, Clay, Organic Material**	**Effective Size and Uniformity Coefficient**
HPGR Feed	3.77	Out of Usable Zone	0.90	Not identified	Outside the limits of the usable zone	88.63	Yes	Adequate
HPGR Product	3.01	Within Usable Zone	3.69	Not identified	Almost entirely within the limits of the usable zone	99.57	Yes	Adequate
Block Sand	3.75	Out of Usable Zone	0.80	Not identified	Outside the limits of the usable zone	94.6	Yes	Adequate
Filter Sand	2.68	Within Optimal Zone	0.53	Not identified	Almost entirely within the limits of the usable zone	100	Yes	Adequate

As per Survey 1, the block product was inadequate for both concrete and filter. Conversely, the filter sand product's size distribution was almost entirely within the limits of the usable zone, while being fully suitable for filter sand.

The Figure 10 shows the Particle Size Distribution for the survey 4 and limits for use as sand for concrete and the Table 10 shows the product analysis for this survey.

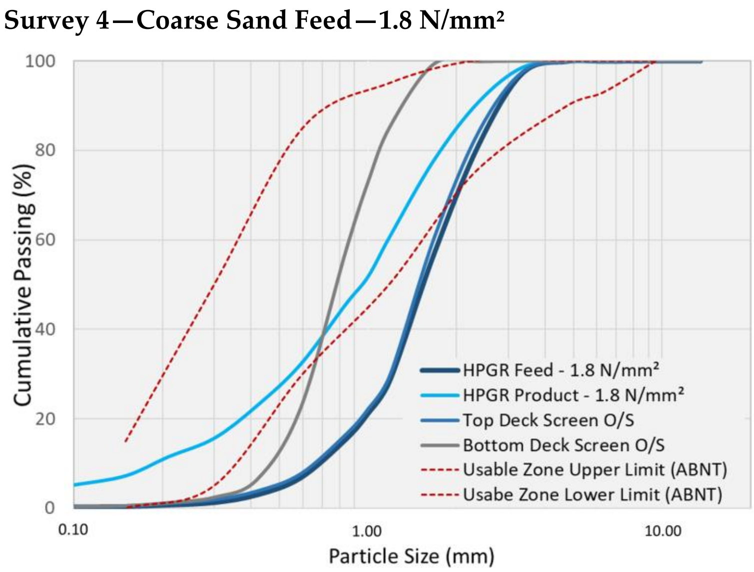

Figure 10. Survey 4 size distributions and limits for use as sand for concrete.

The combination of coarse sand feed and a specific pressure of 1.8 N/mm^2 was quite efficient, since such products met the main parameters required by the corresponding standards. The HRC™ product was adequate for use as a fine aggregate for concrete, in addition to being almost entirely adequate according to the specifications for filter material.

Although the block sand product was inadequate for concrete, it practically met all specifications for filter sand. Conversely, the filter sand product was almost entirely adequate according to the specifications for fine aggregate for concrete, as well as being a fully adequate filter material.

The Figure 11 shows the Particle Size Distribution for the survey 6 the Table 11 shows the product analysis for this survey.

Table 10. Survey 4 product analysis.

	Survey 4—Coarse Sand, Pressure 1.8 N/mm^2							
	Standard NBR 7211—Agreggates for Concrete (Aggregate Fine)					Standard NBR 11799—Filtering Material (Sand for Filters)		
Sampling Points	**Fineness Modulus**	**Fineness Modulus Classification**	**Material −0.075 mm (%)**	**Presence of Clay and Friable Materials**	**Particle Size Distribution**	**Material −4.8 mm (%)**	**Free from Dust, Clay, Organic Material**	**Effective Size and Uniformity Coefficient**
HPGR Feed	3.63	Out of Usable Zone	0.17	Not identified	Outside the limits of the usable zone	99.94	Yes	Adequate
HPGR Product	2.84	Within Optimal Zone	3.64	Not identified	Entirely within the limits of the usable zone	99.82	Yes	Adequate
Block Sand	3.60	Out of Usable Zone	0.21	Not identified	Outside the limits of the usable zone	99.89	Yes	Adequate
Filter Sand	2.89	Within Optimal Zone	0.22	Not identified	Almost entirely within the limits of the usable zone	100	Yes	Adequate

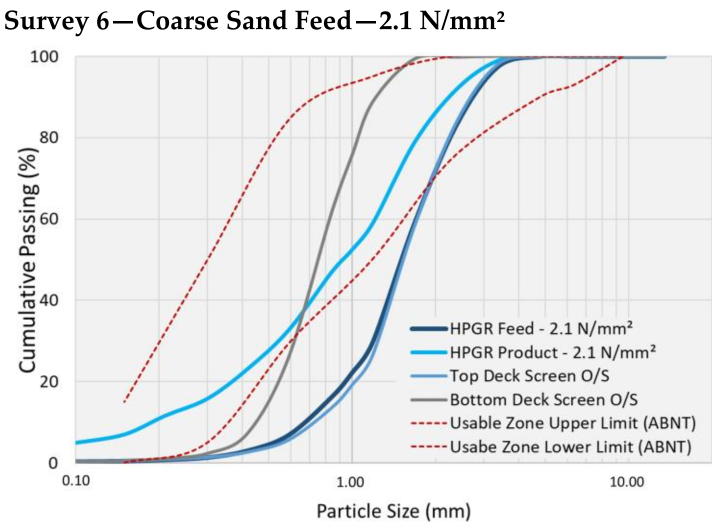

Figure 11. Survey 6 size distributions and limits for use as sand for concrete.

Table 11. Survey 6 product analysis.

	Survey 6—Coarse Sand, Pressure 2.1 N/mm^2							
	Standard NBR 7211—Agreggates for Concrete (Aggregate Fine)					Standard NBR 11799—Filtering Material (Sand for Filters)		
Sampling Points	**Fineness Modulus**	**Fineness Modulus Classification**	**Material −0.075 mm (%)**	**Presence of Clay and Friable Materials**	**Particle Size Distribution**	**Material −4.8 mm (%)**	**Free from Dust, Clay, Organic Material**	**Effective Size and Uniformity Coefficient**
HPGR Feed	3.62	Out of Usable Zone	0.21	Not identified	Outside the limits of the usable zone	99.97	Yes	Adequate
HPGR Product	2.85	Within Optimal Zone	3.55	Not identified	Entirely within the limits of the usable zone	100	Yes	Adequate
Block Sand	3.66	Out of Usable Zone	0.27	Not identified	Outside the limits of the usable zone	99.92	Yes	Adequate
Filter Sand	2.83	Within Optimal Zone	0.14	Not identified	Almost entirely within the limits of the usable zone	100	Yes	Adequate

Increasing the specific pressure to 2.1 N/mm^2 resulted in even better results as compared with Survey 4. In this case, the coarse sand feed resulted in an HRC™ product that was fully adequate for use as either concrete or filter. Conversely, the filter sand product was almost entirely adequate according to the specifications for concrete, while fully adequate for use as a filter material.

4. Conclusions

The use of HRC™ for manufactured sand production was assessed in an industrial operation through a dedicated survey campaign, which included two full surveys for two different feed materials. In each case, two specific pressures were tested for assessing both HRC™ performance indices and product characteristics, as compared with the respective Brazilian standards.

The selected products for evaluation were not only the HRC™ discharge screened at both 1.8 mm and 0.60 mm, but also the HRC™ discharge only, the latter thus representing a single-pass (open circuit) operation.

For fine gravel feed, the results indicate adequate product characteristics according to filter sand specifications, as obtained in the screen bottom deck oversize (−1.8 mm + 0.60 mm) for both 1.0 N/mm^2 and 1.8 N/mm^2 specific pressure operations. The former showed a specific energy consumption of 3.27 kWh/t, while the latter resulted in a mere 7% increase (3.49 kWh/t) in this index. The specific capacities (m-dot) were also very close—respectively 174 and 170 ts/hm^3.

In the case of coarse sand feed, the results indicated adequate product characteristics according to concrete sand and filter sand specifications. The former was obtained directly from the HRC™ discharge, whereas the latter resulted from the screen bottom deck oversize (−1.8 mm + 0.60 mm). Operating specific pressures of 1.8 N/mm^2 and 2.1 N/mm^2 showed similar results according to the respective specifications. The former showed a specific energy consumption of 3.53 kWh/t, while the latter resulted in practically the same value (3.58 kWh/t) in this index. Specific capacities (m-dot) were also very close—respectively 131 and 122 ts/hm^3.

In the case of the Itaquareia industrial operation, the use of HRC™ resulted in not only economic benefits, but also in positive environmental aspects, as former tails, mainly coarse sand, are currently converted into products within specifications for use as both concrete sand and filter sand.

Recommendations for further investigations include the influence of speed in the HRC™ performance, as well as assessing roll-wearing caused by such an abrasive material. Additionally, although the particle shape characteristic is not required by the mentioned Brazilian Standard, it is suggested that future studies should include the evaluation of this parameter.

Author Contributions: Conceptualization, J.C.F.d.A.; formal analysis, J.C.F.d.A. and H.D.J.; investigation, J.C.F.d.A. and H.D.J.; methodology, J.C.F.d.A. and H.D.J.; project administration, J.C.F.d.A.; resources, J.C.F.d.A., R.B. and E.C.; supervision, H.D.J.; validation, H.D.J.; writing—original draft, J.C.F.d.A.; writing—review and editing, J.C.F.d.A., H.D.J., R.B., A.R. and E.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Special thanks to Itaquareia Group, for allowing and strongly supporting the development of this study. The encouragement, pioneering vision and research support culture of the Itaquareia Group directly contributed to the realization of this work. Thanks to Rafael Bento and the team at Itaquareia Unit 6 for their collaborative spirit and strong support in the surveys. Thanks to the LCT and LTM laboratories at the University of São Paulo, represented here by Maurício Bergerman, Carina Ulsen and Guilherme Nery. Special thanks also to Metso Outotec for encouraging and actively collaborating with the development of this work, represented here by Juan Frausto Gonzalez and Suzanne Lynch-Watson. Additional thanks to the Metso Outotec teams of sales, technical support, application and development of the HRC™ HPGR in the area of Aggregates, represented here by Everson Cremonese, Marcelo Motti, Anderson Brini, Alfredo Reggio, Caroline Raymundo, Willer Ito and Thiago F. Silva.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. La Serna, H.A.; Rezende, M.M. Aggregates for Civil Construction. ANM National Mining Agency. 2009. Available online: https://www.gov.br/anm/pt-br/centrais-de-conteudo/publicacoes/serie-estatisticas-e-economia-mineral/outras-publicacoes-1/8-1-2013-agregados-minerais (accessed on 16 September 2022).
2. Aguirre, A.B.; Hennies, W.T. Logistic for Aggregates (Gravel and Sand) in Large Urban Centers. *REM Rev. Esc. Minas* **2010**, *63*, 639–644. Available online: https://www.scielo.br/j/rem/a/Mwp8SLtyySTKYFJJh7zXKqN/?format=pdf&lang=pt (accessed on 15 September 2022). [CrossRef]
3. Neville, A.M. *Concrete Properties*, 2nd ed.; Pini: São Paulo, Brazil, 1997.
4. Drago, C.; Verney, J.C.K.; Pereira, F.M. Effect of using crushed sand on Portland cement concrete. *Rem: Rev. Esc. Minas Ouro Preto* **2009**, *62*, 399–408. (In Portuguese)
5. Cabral, K.O. Influence of artificial sand from the crushing of granite-gneiss rock on the properties of conventional concrete in the fresh and hardened state. In *259 Postgraduate Program in Civil Engineering*; Federal University of Goiás: Goiás, Brazil, 2007. (In Portuguese)
6. Buest, G.T. Study of the replacement of fine natural aggregates for fine aggregates crushed in Portland cement concrete. In *Postgraduate Program in Civil Construction*; Federal University of Paraná: Curitiba, Brazil, 2022. (In Portuguese)
7. Almeida, S.L.M.; Pereira, A.F.R. Obtaining Artificial Sand from the Vigné Quarry. In Proceedings of the Technical Communication of XII JIC—Scientific Initiation Day-CETEM, Rio de Janeiro, Brazil, 7–8 July 2004. (In Portuguese).
8. Lodi, V.H.; Prudêncio Júnior, L.R. Technical and economic feasibility of using crushed sand in Portland cement concrete in the Chapecó region—SC. In Proceedings of the Workshop-Performance of Building Systems, Chapecó, Brazil, 14 November 2006. (In Portuguese).
9. Pedrosa, F.J.B. *High Pressure Grinding Rolls as an Alternative to Electrofused Aluminum Oxide Comminution: An Evaluation of the Simplification Potential of a Circuit*; University of São Paulo, Polytechnic School: São Paulo, Brazil, 2019. (In Portuguese)
10. Raymundo, C.; (Metso Outotec, Sorocaba, São Paulo, Brazil). Personal communication, 2023.
11. Schönert, K. A First Survey of Grinding with High-Compression Roller Mills. *Int. J. Miner. Process.* **1988**, *22*, 401–412. [CrossRef]
12. Morley, C. High pressure grinding rolls: A technology review. In *Advances in Comminution*; Kawatra, S.K., Ed.; SME: Littleton, CO, USA, 2006; pp. 15–39.
13. Souza, M.T.; Cesconeto, F.; Arcaro, S.; Raupp-Pereira, F.; Oliveira, A. Characterization of Quartz Sands from the State of Mato Grosso do Sul for Industrial Applications. *Cerâmica* **2014**, *60*, 569–574. (In Portuguese) [CrossRef]
14. Thuro, K.; Singer, J.; Kaesling, H.; Bauer, M. Determining Abrasivity with the LCPC Test. In Proceedings of the 1st Canada-US Rock Mechanics Symposium-Rock Mechanics Meeting Society's Challenges and Demand, Vancouver, BC, Canada, 27–31 May 2007.
15. ABNT. *NBR 7211: Aggregates for Concrete-Specification*; ABNT: Rio de Janeiro, Brazil, 2005. (In Portuguese)
16. Miranda, L.F.R.; Selmo, S.M.S. Part II—Analysis of the effect of materials finer than 75μm under accelerated aging performance. *Constr. Build. Mater.* **2006**, *20*, 625–633. [CrossRef]
17. Montija, A.F.C. Aspects of the experimental variability of the concrete strain modulus test. 2007. 261 f. In *Post Graduate Program of Civil and Urban Engineering*; University of São Paulo: São Paulo, Brazil, 2007.
18. Gauhar, S.; Rafiqul, A.T.; Syed, M.J. Optimization of Gradation and Fineness Modulus of Naturally Fine Sands for Improved Performance as Fine Aggregate in Concrete. *Procedia Eng.* **2016**, *145*, 66–73.
19. ABNT. *NBR 11799: Filter Material—Sand, Anthracite and Gravel*; ABNT: Rio de Janeiro, Brazil, 1990. (In Portuguese)