MINING SCHEDULING OF GYPSUM EXPLOITATION BY TERRACE MINING METHOD: AN ECO-SUSTAINABLE ALTERNATIVE

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Abstract

One of the main objectives of the production sequencing in a mining is the maximization of the Net Present Value, combined with a sequence of mining development that seeks better operational flexibility of the mine while at the same time guarantees the goals of production and quality of the ore. In this context, the present article proposes a mining sequencing methodology for the Terrace Mining method for the Ponta da Serra gypsum mine, located in the region of Araripe, Pernambuco, Brazil. For this, it was held the dimensioning of equipments for the stripping operation (excavators and trucks) according to the required production. The results show that the proposed sequencing model for gypsum mining allows the reduction of costs in the stripping operation and the rehabilitation of the mined area, implying an eco-sustainable environmental approach to mining sequencing so that the exploited terraces serve the waste deposition with significant benefits associated with reducing environmental impact without compromising the goals of productivity and economic competitiveness.

Keywords: Gypsum; Mining scheduling; Terrace Mining; Sustainability.

SEQUENCIAMENTO DE LAVRA PARA A EXPLOTAÇÃO DE GIPSITA PELO MÉTODO TERRACE MINING: UMA ALTERNATIVA ECO-SUSTENTÁVEL

Resumo

Um dos principais objetivos do sequenciamento da produção em uma mineração é a maximização do Valor Presente Líquido, aliado a uma sequência de desenvolvimento da lavra que busque melhor flexibilidade operacional da mina e ao mesmo tempo garanta as metas de produção e qualidade do minério. Neste contexto, o presente artigo propõe uma metodologia de sequenciamento de lavra para o método Terrace Mining para a mina de gipsita Ponta da Serra, localizada na região do Araripe, Pernambuco, Brasil. Para tal, realizou-se basicamente o dimensionamento dos equipamentos para a operação de decapeamento (escavadeiras e caminhões) de acordo com a produção requerida. Os resultados mostram que o modelo de sequenciamento proposto para a mineração de gipsita possibilita a redução de custos na operação de decapeamento e a reabilitação da área minerada, implicando em uma abordagem ambiental eco-sustentável para sequenciar a lavra de forma que os terraços explotados sirvam para a deposição do estéril com significativos benefícios associados à redução do impacto ambiental sem comprometer as metas de produtividade e competitividade econômica.

Palavras-chave: Gipsita; Sequenciamento da mineração; Terrace Mining; Sustentabilidade.

1 INTRODUCTION

A global challenge in the coming years will be environmentally friendly and financially attractive exploitation of non-renewable resources to meet the growing demand of increasingly consumerist society. Currently, open-pit mining contributes significantly in the production of mineral goods [1].

The open pit mining can be defined as a surface excavation for the removal of minerals of economic interest. It can be used for the exploitation of metal and nonmetallic mineral deposits near the surface, usually with depths less than 150 m. The volume of the deposits may vary from a few tons to million tons [2].

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Tecnol. Metal. Mater. Miner., São Paulo, v. 15, n. 2, p. 175-181, abr./jun. 2018

175

Mining in multiple benches or Open Pit Mining is a mineral exploitation method through which the deposit is accessed by means of digging of a large opening on the surface, called pit, to expose the ore. The operation of this mining method starts with a small pit and develops to a higher one. This proceeds until the final configuration of the mine called final pit, be achieved. These sequences of pits are called "pushbacks" [1].

A variation of the Open Pit mining method is the Terrace Mining, which is applied to mineral deposits which have thicker overburdens or when the footwall of the ore has a steeply dip. In this method, the waste material can be transported into the pit areas where the ore has already been exploited. The Terrace Mining works with multiple benches for both the ore and to the overburden material. The whole mine moves through the deposit, but not necessarily in a single stage, it is not a single stage operation. The number of benches is a function of the excavation depth (height of the benches 10 to 15 meters and from 1 to 32 benches in the form of a terrace). The waste material is deposited at 180° from the front work (taken back) in places where the ore has already been exploited [3].

The open pit mining method of simple benches is traditionally used by the mining industry in the Gypsum Pole of Araripe, located in the State of Pernambuco, Brazil [4]. Successive cuts of benches need to deepen the mine requires the movement of large volumes of soil and waste from the overburden for the deployment and operation of the mine, besides of generating large dumps with waste material removed from the mine. The mining by Terrace Mining allows the deposition of overburden removed from the upper layers of the deposit within the formed cuts in previous stages of mine development, which makes the method more attractive environmentally and economically.

The sequencing of production, *scheduling*, is a making decision process carried out regularly which plays an essential role in industry. A scheduling effective of production has become a necessity in today's competitive environment, being of great importance to achieve goals and efficient use of resources [5].

The scheduling in open pit mines is an important stage of mine planning, since it determines the raw materials to be produced annually over the life of the mine, evaluates the operation value of the enterprise, and contributes to the sustainable use of mineral resources. Find an optimal scheduling is a complex task that involves large data sets and multiple restrictions [6].

However, besides of technical and economic criteria, a demand that has been increasingly required in the scheduling mining is meeting the environmental constraints of the mine. From the seventies, environmental protection came to have greater importance in making decisions on the scheduling, which caused serious changes in the mineral industry. This development has generated a change of view on the role of mining in society: the mining activity came to be understood as a form of temporary soil use, not end use as it was in the past, and companies in the sector began to think in the environment at all stages of mining, with the implementation of activities directed to revegetation, landscaping, soil improvement and regional socio-economic development [7].

However, in the last decade, there was a significant increase in global demand for mineral commodities. This fact initiated many efforts to increase the productive capacity of the mining sector, both in terms of production infrastructure, and the research of new mineral resources. In this context, there is a needed to expand production of operating mines, as well as opening of new projects.

Every new mining project or expansion of an existing one requires the acceptance of environmental agencies. Thus, every new project or change in waste material disposal projects also depends on environmental licensing. This situation introduces additional uncertainty on the scheduling, since the disposal of overburden material by expanding current deposits or through the creation of new projects will depend upon the approval of the entire legal procedure implementation of licensing in a timely manner to meet the mine plan requirements.

This way, the main objective of this work is to show a mine scheduling methodology for gypsum mines to serve as a model for other orebodies, based on the gypsum deposits of the Araripe region, Brazil, through the mining method Terrace Mining, which allows to take into account a sustainable environmental approach in order to anticipate the exhaustion of the pit aiming the disposal of waste material within the pit respecting technical, economic and environmental parameters.

2 MINING METHODS IN PLASTERER POLE OF ARARIPE

The fundamental difference between the methods currently in use in mining gypsum, Open Pit Mining (Figure 1) and Terrace Mining, concerns especially on the form of overburden disposal from casting, since the gypsum's mining procedure is identical.

Also are found differences regarding geometry of the pit and, waste and ore haul roads, which in Terrace Mining are separated, whereas in Open Pit Mining the same approach is used in both transport (waste and ore).

In terms of mining scheduling, the fundamental difference is that in Terrace Mining, the cuts are made perpendicularly to the approaches and parallel to the provided area for deposition of material from overburden through backfilling method.

They are needed independent access for movement of ore and waste, disposed at the pit limit, connecting the casting front with waste dump, which is made in a previously mined area, and the gypsum front of work to the external environment, as described in the Figure 2.
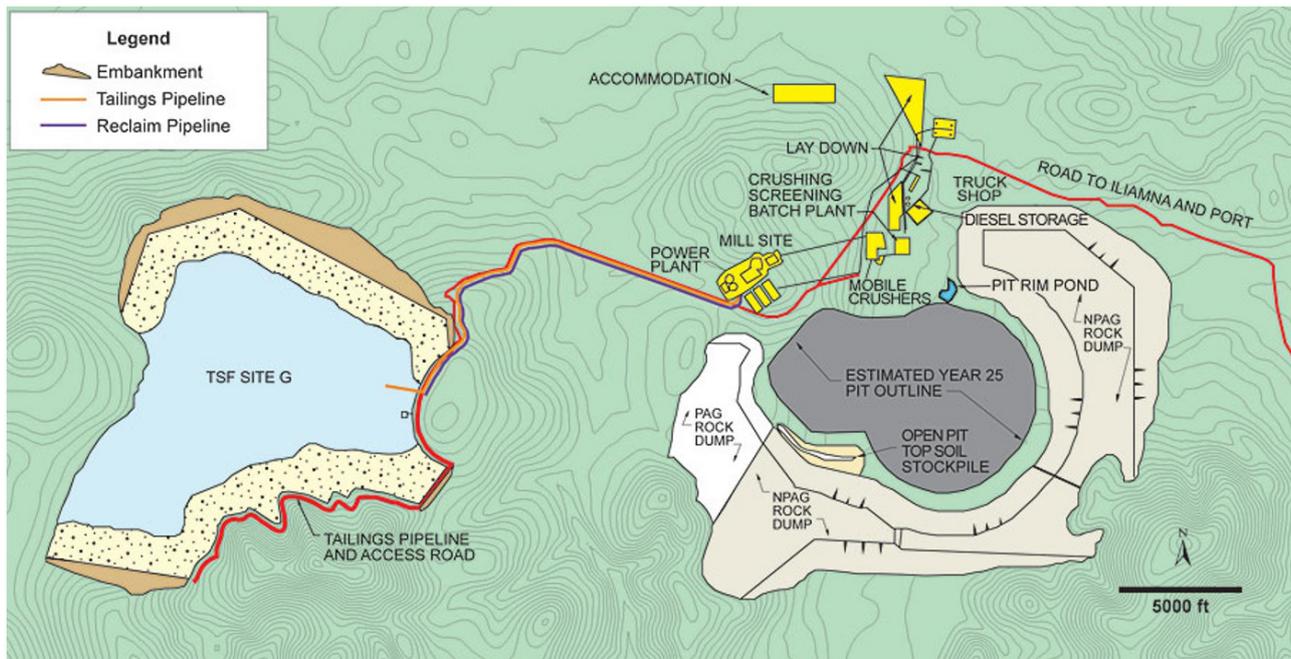
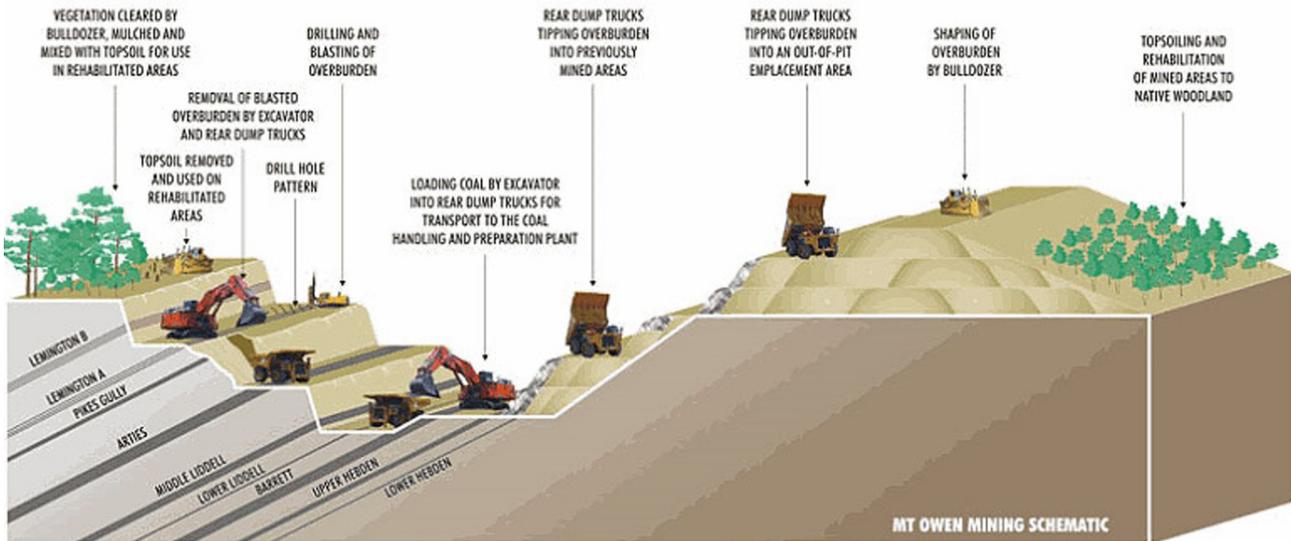**Figure 1.** Typical layout of an Open Pit Mining. Source: Northern Dynasty Minerals Ltda. [8].

Figure 2. Typical layout of Terrace Mining Method. Source: Gaukoartifact [9].

The overburden excavation (casting) is greatly simplified by the absence of the need for construction and operation of a waste dump for disposal of overburden, reducing traffic in external approaches, the transport distances of overburden and favoring the environmental recovery process of the mined area. They are also found economic benefits due to less need for trucks to transport of waste and reduction of distances.

3 UNIT OPERATIONS IN GYPSUM MINING WITH TERRACE MINING

The gypsum mining in the mining method of Terraces is composed of several unit operations, which will be described below.

Firstly need to be built all mine infrastructure works, for the exploitation, specifically, the access roads to the mine and sites of this infrastructure (offices, storages spaces etc.).

Then the vegetation removal of the surface must be performed, so that you can reach the capping of the deposit. This operation is usually performed with bulldozers, with the help of chains, if necessary, wheel loaders for loading material into trucks, also used in this operation.

Once released the surface of the overburden, it can be performed the casting operation, which consists in excavating the overburden material that cover the ore, for the release of this one. This operation can be performed with: bulldozers, hydraulic excavators, trucks, draglines and wheel loaders. At the same time which is carried out the casting operation, are constructed accesses to the ore. Only the first cut excavated on this operation is deposited in the form of outside dump, since the ore does not present any free face yet. The remaining cut to be executed, in this method, is deposited in the mined out area of the pit.

The mining of ore is usually done with the unit operations of drilling, blasting, loading and transportation of ore. For this, are used drills rigs, wheel loaders, hydraulic excavators and trucks.

In the mining of gypsum and, in the mining method Terrace Mining, environmental rehabilitation occurs concurrent with the mining, this means that the material from overburden stripping operation is deposited in the pit as the ore mining occurs.

4 SCHEDULING MINING

4.1 Dimensioning of the Overburden Excavation Equipment

The mining scheduling in the Terrace Mining starts by extending the side access for transport of waste from the overburden, generally carried out through two benches of about 8-15 m of high, connecting the overburden excavation levels with the respective deposition levels within the mining, in areas already exhausted by gypsum mining.

The advance in gypsum mining fronts is performed in parallel, in a perpendicular direction to the cuts, both to that are being developed as well as to that are being filled with waste. Figure 3 shows this procedure.

The width of the cuts at the overburden benches must be set according to the size of excavation equipment (hydraulic excavator), compatible with the type of transport truck and scaled depending on the local stripping ratio and producing desired ore.

Assuming a production of 25,000 tons/month of gypsum and based on the data of the Figure 4, can be obtained the amount of gypsum produced monthly, considering a density of 2.3 m³/ton (Equation 1).

$$Volume\,of\,Gypsum = 25,000\,ton\,/2.3\,ton.m^{-3} = 10,000\,m^3 \quad (1)$$

Thus, the required area of gypsum to be worked each month is given by Equation 2:
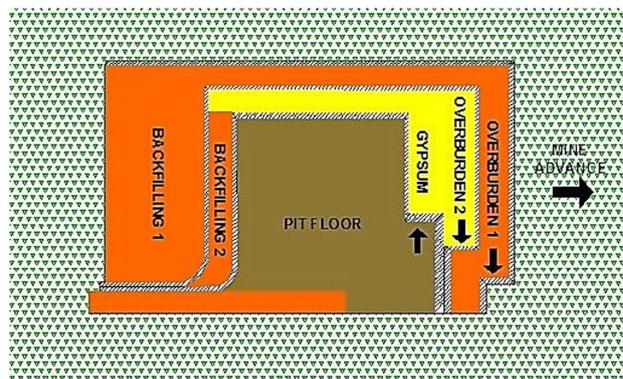

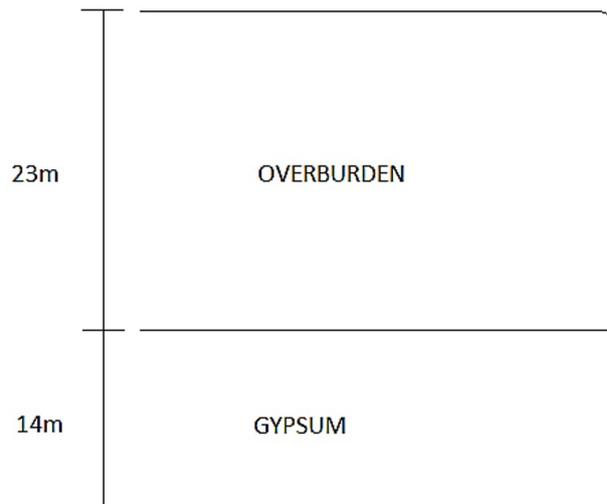**Figure 3.** Advance mining scheme in Terrace Mining.

Figure 4. Gypsum and overburden average layer thickness.

$$Area\,of\,gypsum\,/\,month = 10,000\,m^3\,/14\,m = 715\,m^2\,/\,month \quad (2)$$

The width of the cuts in the stripping of overburden operation will be equal a one dual haul road. Considering a dump truck of 16 m³, the vehicle width is 2.50 m, and then the cut will have a width of 10 m approximately (Equation 3), as shown in the scheme of the Figure 5.

$$Cutting\,width = 3.5\,x\,2.5 = 8.75\,m\,(it\,was\,considered\,10\,m) \quad (3)$$

For this cutting width, there is the need of the monthly advance given by Equation 4:

$$Monthly\,advance\,(gypsum\,and\,overburden) = 715\,m^2\,/10\,m = \\ 71.5\,m\,/\,month \quad (4)$$

Assuming an average width for the gypsum ore of 150 meters approximately, each cut to be executed will have a lifetime around 2 months (Equation 5).

$$Lifetime\,of\,the\,cut = 150\,/\,71.5 = 2\,months \quad (5)$$

178

Tecnol. Metal. Mater. Miner., São Paulo, v. 15, n. 2, p. 175-181, abr./jun. 2018
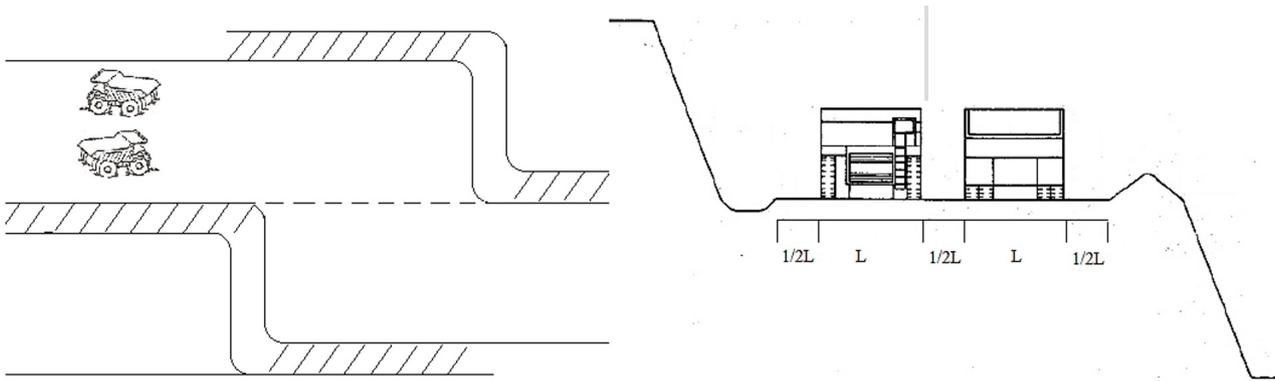
Figure 5. Model for sizing the width of roads in mining.

In stripping of overburden operation, aiming to meet the ore exposure needs and considering a stripping ratio average of (23 m³ / 14 m³) 1.64: 1 m³ / m³, and cutting width of 10 m with an average height of 10 m for each bench (Figure 6), the excavation equipment required for the operation can be dimensioned, based on the daily productivity calculated as shown.

The volume to be dismounted by excavator monthly is given by the Equations 6 and 7:

$$1° \ bench = 715 \, m^2 \ x10 \, m = 7,150 \, m^3 \qquad (6)$$

$$2° \ bench = 715 \, m^2 \ x13 \, m = 9,295 \, m^3 \qquad (7)$$

totalizing 16,445 m³/month. Assuming an average swelling of 60%, a volume of waste stilted to be excavated and transported is given Equation 8:

$$V_w = 16,445 \, x1.6 = 26,312 \, m^3 \ / \ month \qquad (8)$$

The excavator working regime is summarized in the Table 1:

The Equation 9 is applied to determining the hourly productivity of excavation equipment, which allows the determination of the minimum size of the bucket:

$$P_h = \left(60 \, x \, 60 \, x \, C_e \, x \, E_f \, x \, V_c\right) / \left(t_c \, x \, C_g\right) \qquad (9)$$

Considering an average time of 40 seconds for cycle of the excavator, it is possible to estimate the minimum size of the bucket, as demonstrated by the Equation 10:

$$Hourly \ productivity = \left(26,312 \, m^3 \ / \ month\right) /$$
$$\left(8h \ / \ day \ x \, 22 \, days \ / \ month\right) = 149.5 \, m^3 \ / \ h \qquad (10)$$

Then, the bucket capacity is given by the Equation 11:

$$V_c = \left(149.5 \, x \, 40 \, x1.1\right) / \left(60 \, x \, 60 \, x \, 0.65 \, x \, 0.75\right) = 3.7 \, m^3 \ / \ cycle \qquad (11)$$

Systematically can work with 2 hydraulic excavators on the overburden, one on the top bench (h_b = 10 m) and the other on the lower bench (h_b = 13 m). Using the same
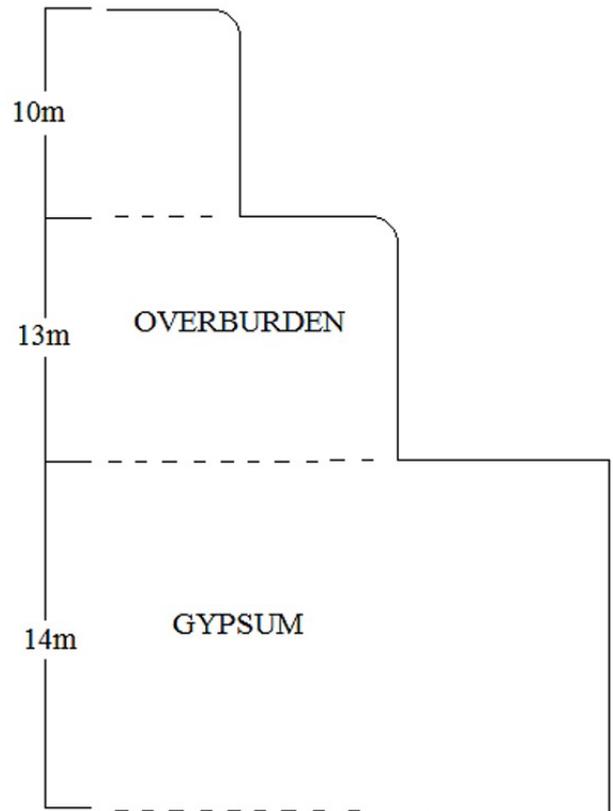

Figure 6. Dimensions of the planned benches for Terrace Mining.

Table 1. Excavator work regime

Hours/day	8 h/day
Bucket factor - C_e	0.65
Turning coefficient - C_g	1.1
Efficiency - E_f	0.75
Cycle time	40 s

scaling formulation, it's desired the following minimum buckets capacities (B_c) given by Equations 12 and 13 for the upper bench, and 14 and 15 for the bottom bench, using the monthly productivity of each excavator to:

For the upper bench (Equations 12 and 13):

$$P_{h\,Sup.} = \left(\frac{11,440\,m^3 /}{month}\right) / \left(\frac{8\,h\,/\,day\,x22\,days\,/}{month}\right) = 65\,m^3\,/\,h \quad (12)$$

$$B_c = (65\,x\,40\,x\,1.1)\,/\,(60\,x\,60\,x\,0.65\,x\,0.75) = 1.63\,m^3\,/\,cycle \quad (13)$$

For the bottom bench (Equations 14 and 15):

$$P_{h\,Sup.} = \left(\frac{11,440\,m^3 /}{month}\right) / \left(\frac{8\,h\,/\,day\,x22\,days\,/}{month}\right) = 65\,m^3\,/\,h \quad (14)$$

$$B_c = (84.5\,x\,40\,x\,1.1)\,/\,(60\,x\,60\,x\,0.65\,x\,0.75) = 2.11\,m^3\,/\,cycle \quad (15)$$

The volume of waste produced for each section will be the values obtained by the Equations 16 and 17:

$$V_{b1} = 715\,m^2\,x\,10\,m\,x\,1.6 = 14,440\,m^3\,/\,month \quad (16)$$

$$V_{b2} = 715\,m^2\,x\,13\,m\,x\,1.6 = 14,872\,m^3\,/\,month \quad (17)$$

totalizing 26,312 m³/month, as already shown.

4.2 Dimensioning of Transport Equipment

According to the layout intended for operation, it has an average transport distance in the overburden bench:
Top bench: 145 m.
Lower bench: 125 m.
Considering the transport distances above and the average speed of 20 km/h, one can determine the total cycle time for transportation. The maneuver times and routes can be seen at Table 2.

The charging time, for the top and lower benches, considering the hydraulic excavator of 1.75 m³ on the top bench 1 and 2.23 m³ at the lower bench 2, a cycle time of 40 seconds, and trucks of 16 m³ it was determined by the Equations 18 and 19:

$$Top\,bench: t_{cycle} = 16\,/\,1.75\,x\,40" = 365.7 = 6\,minutes \quad (18)$$

$$Lower\,bench: t_{cycle} = 16\,/\,2.25\,x\,40" = 284.4 = 5\,minutes \quad (19)$$

And the trucks cycle time, regardless of the maneuvers, is given by Equations 20 and 21:

$$Top\,bench: 145\,m\,/\,\left(\frac{333\,m\,/}{min}\right) = 0.4354\,seconds = 0.5\,minute \quad (20)$$

$$Lower\,bench: 125\,m\,/\,\left(\frac{333\,m\,/}{min}\right) = 0.3753\,seconds = 0.5\,minute \quad (21)$$

The Table 3 shows the total cycle time of the overburden stripping operation of the excavator-truck set:

The number of trucks needed to carry out the stripping provided in the mine can be calculated from the productions required for casting operation, which are respectively 11,440 m³ to the top bench and 14,872 m³ to the bottom bench, as already showed.

Table 2. Maneuver times and route

Load / maneuver	1 min
Going route	145 / 125m
Discharge / maneuver	1 min
Back route	145 / 125m

Table 3. Total cycle time of the overburden stripping operation

	Load / maneuver	Going route	Discharge / maneuver	Back route	Total
Bench 1	7	0.5	1	0.5	9
Bench 2	6	0.5	1	0.5	8

The average productivity of the truck, considering the calculated cycle times can be obtained from the Equation 9, as described in the dimensioning of the excavator: Therefore, for the top bench, the productivity is given by Equation 22:

$$P_{h\,Sup.} = (60\,x\,0.75\,x\,0.85\,x\,16)\,/\,9 = 68\,m^3\,/\,h \quad (22)$$

And to the lower bench 2, the truck productivity is given by the Equation 23:

$$P_{h\,Inf.} = (60\,x\,0.75\,x\,0.85\,x\,16)\,/\,8 = 76.5\,m^3\,/\,h \quad (23)$$

Taking into account the compatibility between the load times and travel time it has need for trucks to the casting operation, as demonstrated by the Equations 24 and 25:

$$N^{\circ}_{sup.} = (9\,/\,7)\,x\,(0.85\,/\,0.75) = 1.457 = 2\,trucks \quad (24)$$

$$N^{\circ}_{inf.} = (8\,/\,6)\,x\,(0.85\,/\,0.75) = 1.511 = 2\,trucks \quad (25)$$

5 CONCLUSIONS

Both mining methodology, *Open Pit Mining* and *Terrace Mining*, allow a good operating performance of gypsum mining. The first method is applied in the region by local custom or tradition, whereas the companies in the region are generally small, and do not invest, or have done little, in technical studies, in order to find more profitable alternatives for the extraction of this mineral good.

The gypsum of Araripe region lying under a layer of clay, and therefore, for access to the ore the clay need to be excavated. The difference between these two mining methods is on the casting operation, i.e., the excavation of the clay layer. The adoption of Terrace Mining provides the reduction of transport costs in the casting operation, since the waste material is now deposited directly into the pit while the mining of gypsum occurs. In addition, there is the elimination of maintenance costs of waste dumps, needed in *Open Pit* mining, and costs with the acquisition of new areas for construction of these dumps.

180

Tecnol. Metal. Mater. Miner., São Paulo, v. 15, n. 2, p. 175-181, abr./jun. 2018

The purpose of mine planning in this transition between the two mining methods, from *Open Pit* to *Terrace Mining*, is to select and dimension the equipment of casting operation, define the geometry of the benches in overburden, design backfills inside the mined pit and the access roads, in order to achieve the desired production by the company.

Thus, the planning of gypsum mining with *Terrace Mining* is an important stage of gypsum mining, since it determines all the above mentioned parameters, providing:

- Reduction of costs in the casting operation, due to less need for trucks and smaller distances at the operational methodology of *Terrace Mining*;

- Environmental rehabilitation of the mined area, with backfill being done inside the pit, avoiding the need for landfills for disposal of waste outside the mined area;

- Reforestation of the grounded area enabling thus a future use of the mined area;

- Implementation a more competitive and environmentally friendly mining for the region.

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