A Comparison between a Stationary and a Semi-Mobile Plant for Wet Processing of Crushed Stone

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Abstract: Crushed stone is the most important type of mineral resource in the Republic of Croatia and is mined in more than 350 exploitation fields. Crushed stone is most often used as aggregate for the production of concrete and asphalt, for which it must satisfy high standards, and thus it is necessary to process it. The wet processing technology in semi-mobile plants, which is increasingly frequent in Europe, has thus far not been used in the Republic of Croatia. This paper provides a comparison of the wet processing technology on an older, stationary and a newer, semi-mobile processing plant in the "Oršulica kosa" exploitation field. It also describes the process of waste wash water treatment and the newer high-pressure pre-washing chamber technology. The costs of extracting stone from a stone massif are the same in both cases; therefore, in comparing the two plants, the effect of the cost of transportation and stone processing was also taken into account. An analysis of the cheapest possible transportation showed that for the stationary plant, located at a distance of 1,950 m from the active worksite, the cost of transport was 4.01 kunas per tonne, or 1.7 million kunas per annum, while in the case of the semi-mobile plant this cost was non-existent. As for processing, it appears that the electric energy consumption of the stationary plant is three times higher than that of the new semi-mobile plant, which amounts to a difference of 0.85 million kunas per annum. As for water consumption, it appears that the water consumption of the old stationary plant is approximately ten times greater than that of a new semi-mobile plant, which amounts to a difference of 0.23 million kunas per annum. Taking into account the potential savings of around 2.1 million kunas per annum, the return of the total investment in the new semi-mobile plant should be realized in a relatively short period of 3.5 years. Beside the economic benefit, we should also emphasize the smaller environmental footprint of the new plant, which is evident in the decreased need for adding fresh water to the process, as well as the significantly decreased need for occupying space with settling basins, seeing as the new semi-mobile plant, as opposed to the old stationary one, purifies and recycles wastewater.

Keywords: *mineral processing, crushed stone, mobile processing plants, washing, wastewater treatment*

Introduction

In the Republic of Croatia, crushed stone is mined in more than 350 active exploitation fields. Surface mines (quarries) for crushed stone are the most common in the Republic of Croatia; they account for the largest number of approved exploitation fields and the greatest amount of mined material per annum. Crushed stone is a vital mineral resource for construction and is used in building materials, with the most important being aggregates for concrete construction, aggregates for asphalt construction, aggregates for bituminous mixtures and railroad track lagging. For crushed stone, carbonate (sedimentary) rocks are most often mined, with igneous (silicate) rocks being mined only rarely (Bedeković et al., 2005a). In the Republic of Croatia, crushed stone is processed mainly in stationary plants, using dry and wet techniques. Also of note is the widespread use of mobile plants for dry processing, especially in constructing infrastructure and business and residential buildings. In accordance with the current high standards for the quality of aggregates for the production of concrete and asphalt, along with certain natural properties (such as strength, stability under the effects of weather, and resistance to abrasion and blunt force, which are the result of various geological factors, which humans cannot influence, the produced stone material must have certain properties which humans can influence through the manner of extraction and processing (crushing, screening, dedusting, washing) of the mineral resource. These are the following important properties:

- Specific grain size distribution, as defined by the prescribed limits for individual grain sizes of material,
- Approximately cubic shape of the grain (the shape of the grain is defined as the ration of its largest and smallest dimension; the grains for which this ratio is higher than 3:1 are considered to be of unsuitable shape),
- Maximal purity, i.e. a minimal portion of mud and dust particles (particles smaller than 0.09 mm – filler) (Salopek et al., 2002).

Sometimes the material contains a larger portion of clay particles that need to be separated in processing in order for the aggregate to meet the prescribed standards. In such a case, the standard dry processing technique does not deliver satisfactory results and it is necessary to wash the material, i.e. to use the wet technique. Washing encompasses the processes in which hydraulic techniques are used to achieve a successful separation (release) of the smallest particles, which adhere to each other and to larger grains or connect larger grains to each other, and their subsequent separation from the mineral resource, either by using wash water or through overflow. Washing can be simple (e.g. washing on screens) or complex, using various equipment (e.g. trommel screens, attritors, hydrocyclones, spiral classifiers, classifiers with vanes). The wet process results in a higher-quality product than the dry one, no dust is emitted, and the screening capacity is greater by around 15 %; on the other hand, the downside is wastewater containing mud and clay particles (i.e. suspension) that it produces (Bedeković et al., 2005b). The wastewater needs to be treated, and the mud produced needs to be managed, in order to eliminate a potential harmful effect on humans and environment.

The technology of wet mineral processing on semi-mobile plants, which is becoming increasingly widespread in Europe, has thus far not been used in the Republic of Croatia. There are two basic concepts for wet processing on semi-mobile plants that are show in this paper: the concept in which a high-pressure chamber is used for washing and the concept of washing on screens. In both of these technological concepts, the process of wastewater treatment is crucial. The dolomite exploitation field "Oršulica kosa" near Orahovica, in the Nature Park Papuk, is the first site in the Republic of Croatia where, for the past year, the technology of wet mineral processing on a semi-mobile plant has been used (Vrkljan et al., 1996, 2006, 2011). This paper elaborates on the benefits, mainly economic and environmental in nature, which are achieved through the use of this type of processing technology. It also provides a comparison of the results of using the technology of wet processing on an old stationary plan, which has been used thus far, and the results achieved on a new semi-mobile plant.

Materials and Methods

Stationary processing plant

The existing procedure for mineral processing on a stationary plant is shown on the flowsheet in Fig. 1 and is described in more detail in this paragraph. The mined material is transported to the entrance bin *(1)*, which has a volume of 40 m^3. Exiting the bin, the material passes through the grizzly screen for pre-screening *(3)* with elongated apertures measuring 30 mm. The undersize material (the -30 mm grain size) goes on to be washed on the vibrating screen *(6)*. The oversize material is crushed in the jaw crusher *(4)*, with the output aperture set to 120 mm. After crushing, the material moves on to the primary resonance screen *(5)* with two screening surfaces (with apertures measuring 30 and 60 mm). The oversize material from the primary screen (the 120/60 mm grain size) moves on to secondary crushing in the hammer crusher *(8)* of the BL 6 type, with the output aperture measuring 15 mm. The intermediate grain size from the primary screen *(5)* of 60/30

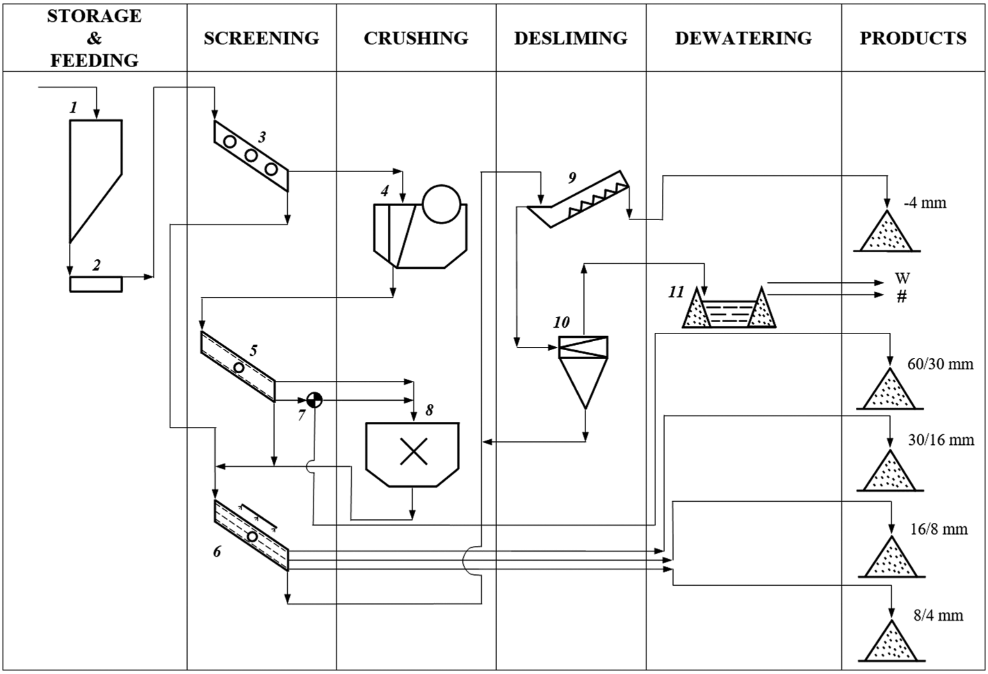

Fig. 1 – Flowsheet of the old stationary processing plant "Hercegovac"

mm can, using the material flow router *(7)*, be directed to secondary crushing with the oversize material or to the final products dump. The undersize material from the primary screen *(5)*, along with the material crushed in the secondary hammer crusher *(8)*, moves on to wet screening on the secondary vibrating screen *(6)* with the screen apertures measuring 16, 8 and 4 mm. After screening, the 30/16 mm, 16/8 mm and 8/4 mm grain sizes are separated as end products in storage. The undersize material from the screen *(6)* (the -4 mm grain size), along with the waste-water from washing, moves on to the spiral classifier *(9)*. The sand from the spiral classifier (the -4 mm grain size) moves on to storage as an end product, while the overflow goes to the retaining reservoir. The overflow from the retaining reservoir ends up in the settling basin *(11)*, while the coarse solids goe on to the hydrocyclones *(10)*. The vortex from the hydrocyclone (the -0.09 mm grain size) moves on to the settling basin *(11)*, while the apex goes back to the spiral classifier *(9)*.

Semi-mobile processing plant

The procedure of mineral processing on a semi-mobile plant (Figure 3) is shown in Fig. 2 and is described in more detail in this paragraph. The process begins by transporting the mineral resource to the entrance bin *(1)*, which has a volume of 36 m³. Above the entrance bin, there is a stationary grizzly *(3)* with apertures measuring 225 mm. The oversize material from the grizzly (+225 mm grain size) goes to storage and is afterwards crushed using the mobile crushing plant Metso LT 105 S *(4)*. The size of the output aperture of the jaw crusher *(4)* of this mobile crushing plant is set to 31.5 mm, which is also the input grain size for the mobile screening and washing plant, the CDE Global M2500 E5X. The process of processing the material from the entrance bin (the -225 mm grain size) begins with screening on the primary single-deck vibrating screen *(5)* P1-36, with a single screening surface measuring 3.60 m². The oversize material from the screen (225/31.5 mm grain size) moves on to crushing in the mobile crushing plant Metso LT 105 S *(4)*. The undersize material from the screen (the -31.5 mm grain size) is combined with the material crushed in the mobile jaw crusher *(4)*, and then they move on to the triple-deck vibrating screen *(6)* P3-75, with a screening surface area of 7.5 m² per deck. All of the grain sizes are also washed on this screen during the screening process. The oversize material from the screen (the 31.5/16 mm grain size) and the two intermediate grain sizes (16/8 mm and 8/4 mm) then go to the appropriate final products dump. One of the special features of the screen is the adjustable incline along the screening surface. The input half of the screening surfaces is placed at an incline of around 11°, while the other, output half is placed at a somewhat greater incline of around 13°. This results in a somewhat shorter retention time of grains on the screen, while retaining the effectiveness of the screening. Another special feature is

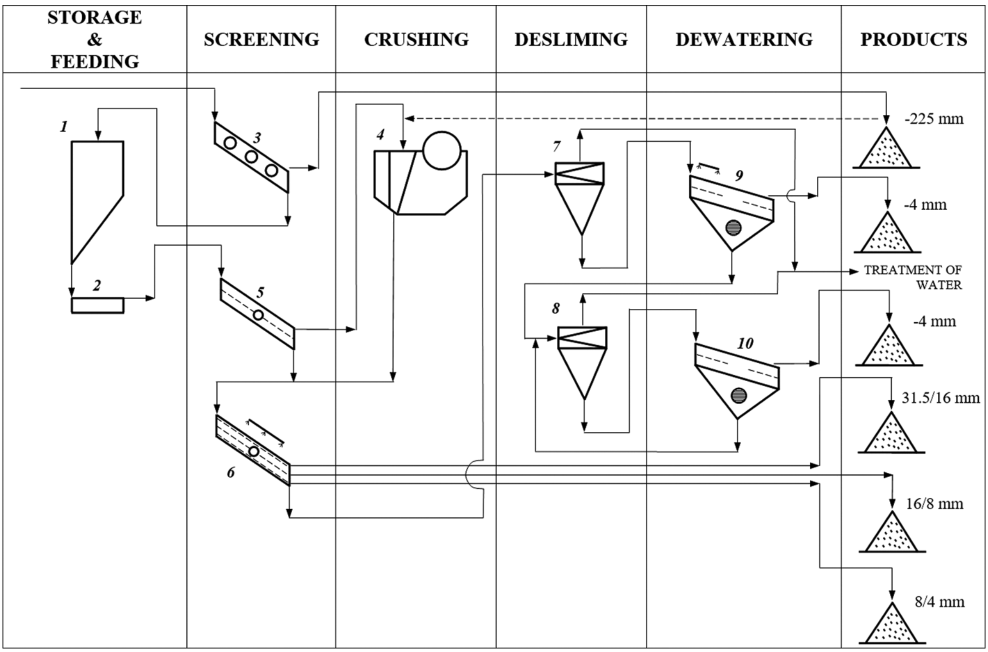

Fig. 2 – Flowsheet of the semi-mobile processing plant

that the last quarter of the screening surface has somewhat larger apertures, which allows for earlier separation of smaller particles and later separation of larger particles, which stay on the screening surface longer and are therefore more thoroughly washed. The nozzles can be adjusted individually (they can turn in different directions, independently from each other, and the pressure can be adjusted for each of them individually, with each having its own valve). The nozzle system is physically detached from the screen, which results in a lower risk of malfunctioning and greater durability. The rubber screen panels prevent an additional loss of water, the ejection of material from the screen, and the soaking of the area around the screen. The screening surface is made of polyurethane so replacing it is quick and simple. The undersize material from the screen *(6)* (the -4 mm grain size) moves on to the retaining reservoir, and from there to the first hydrocyclone *(7)*, with a diameter of 625 mm. The apex from the first hydrocyclone moves on to the dewatering screen *(9)*, where the nozzles for the washing control are also located. The oversize material from the dewatering screen (the -4 mm grain size) goes to final the products dump, while the undersize material, along with the wastewater, moves on to the second hydrocyclone, *(8)* with a diameter of 400 mm. After classification, the coarse solids from the second hydrocyclone goes to the second dewatering screen *(10)*, where the -4 mm grain size is also separated, but with a greater tiny particle content than in the previous hydrocyclone. The overflow from both hydrocyclones goes to the wastewater treatment plant. This plant consists of a flocculant preparation unit and a thickener (sedimentation pool), where the finest particles are sedimented. The overflow from the thickener is clean enough to be reused as wash water.

Fig. 3 – Semi-mobile processing plant M2500 E5X

Wash water treatment

Wash water treatment, i.e. solid-liquid separation, already begins in the hydrocyclones as part of the processing procedure. Although the hydrocyclones are used in this case to reduce the loss of fine particles of the -4 mm grain size to a minimum, they also contribute to eliminating solid particles from the water. Most of the solid particles are separated in the apex from the hydrocyclone and thereby end up in final products dump, while most of the water containing the finest particles (-0,063 mm) is separated in the vortex from the hydrocyclone. These finest particles are then separated in the thickener (sedimentation pool). The separation of the solid-liquid two-phase system has long been the focus of many researchers (Burger et al., 2001, Garrido et al., 2003, Somasundaran et al., 2003, Svarovsky, 1990), who state that the settling of tiny particles follows Stokes's law and depends on the diameter of the particle, the density of the particle, and the viscosity of the medium in which the settling occurs. Seeing as fine particles have a small settling velocity, the process needs to be accelerated by adding a flocculant. In order to avoid a harmful effect on the environment, this plant uses a starch-based polyelectrolyte as a flocculant, which is usually used in the production of potable water. The flocculant preparation chamber consists of three parts. In the first part, clean water enters the chamber; in the second, a flocculant in powder form is added and dissolved in the water; this prepared flocculant then goes to the third part, where it is retained until use. The prepared flocculant solution is added to wastewater in a special container, which results in a reaction between the flocculant and the solid particles in the suspension (Figure 4). The reaction occurs very quickly (around 9 seconds) and is followed by sedimentation in the thickener (sedimentation pool).

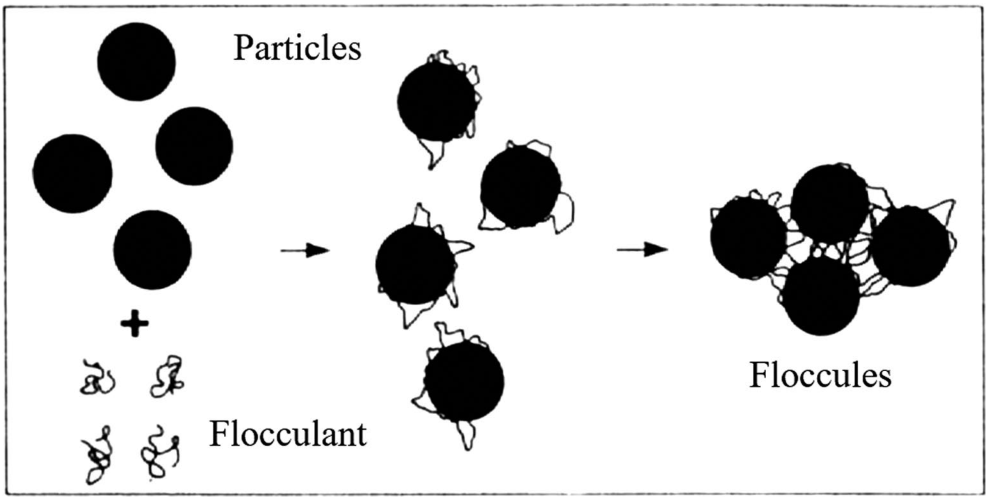

Fig. 4 – Combining of tiny particles into floccules (Bedeković & Stipetić, 2007)

After the addition of the flocculant, tiny particles combine into larger particles, or floccules. Due to their larger diameter, the floccules have a significantly higher settling velocity (the settling velocity increases with the root of the particle diameter) so sedimentation occurs much faster. The overflow from the thickener is clean water which is then reused for mineral processing, while mud settles on the bottom and is occasionally emptied into a settling basin, measuring 85 x 30 x 2.5 m. After it dries sufficiently, the sedimented mud is used to recultivate surface mines and as raw material in the ceramics industry. The capacity of the thickener is 400 m^3/h, while the total water needs of the processing plant amount to 250 m^3/h, from which 221 m^3/h (88.4 %) is acquired through wastewater treatment and 29 m^3/h (11.6 %) comes from adding fresh water into the process.

High-pressure pre-washing chamber

Eliminating fine particles of clay from the material, which stick firmly to larger grains or in agglomerates, is one of the tasks of mineral processing that can be further improved through the use of the high-pressure pre-washing chamber HYDRO-CLEAN®. This chamber is usually implemented into the mineral processing procedure before the usual washing on vibrating screens. The operating principle of the chamber is shown in Fig. 5.

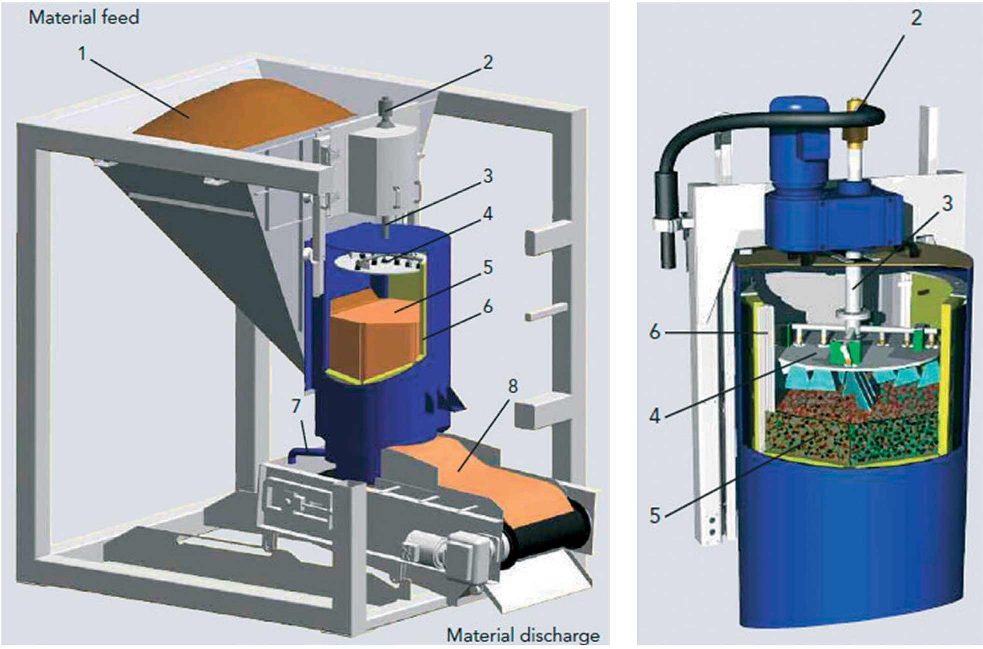

Fig. 5 – The HAVER Hydro-Clean high-pressure pre-washing chamber and a close-up of the washing drum (Haver & Boecker, 2014)

Dry material with a grain size of up to 120 mm, contaminated with fine particles, enters the chamber through the receiving hopper *(1)* and goes to the washing drum with a rotating disc *(4)* which holds high-pressure nozzles. The high-pressure water input *(2)* is located above the drum and reaches the nozzles through the drive shaft *(3)* of the rotor. Due to the high speed of the rotor (100 rpm) and the high water pressure (up to 150 Bar) the material is constantly mixed, which results in friction between individual grains, scattering, swirling and intensive shifting of the material bed *(5)* in the washing drum. The jets of water penetrate into the pores and fissures of mineral particles. Thus, cleaning is the consequence of the impact of the jets of water into individual grains and the mixing of the grains inside the bed. The material is retained in the washing chamber for approximately 3 seconds, during which time the mineral grains are exposed to the high-pressure water jets multiple times. Water containing fine particles passes through the PU filter *(6)* located along the edge of the chamber. The purified water exits through a separate pipe *(7)*, while the washed material falls onto the conveyor *(8)* and exits the chamber in this manner.

Wear and tear inside the device is minimal, as the moving parts (the rotor with the nozzles) are placed outside the flow of the material through the device. Water consumption is small and amounts to 0.1 to 0.2 m^3 per ton of material, so the amount of wastewater produced is small as well. The capacity for material washing is relatively high (up to 320 t/h), while the effectiveness of washing has been confirmed in various industries, such as mining, industrial mineral processing, construction waste recycling, solid waste recycling, etc. Implementing the high-pressure pre-washing chamber into the mineral processing procedure would further improve the purity of the crushed stone.

Results and Discussion

This chapter presents a comparison of the vital technical and economic indicators in the mining and processing of crushed stone in the old stationary and new semi-mobile plant, using the example of the “Oršulica kosa” exploitation field. Crushed stone is a mineral resource which does not have a high market price. Therefore, the costs of the individual technological stages can have a significant impact on the mining and processing of crushed stone. When comparing two different aforementioned variants, the costs of extracting the mineral resource from the stone massif in the stage of removing the overburden, drilling, mining, and loading are the same in both variants. The differences in the costs stem from the different length of the transportation route and the processing technology.

Transportation costs

In regard to transportation costs, the differences stem from the length of the transportation route. The length of the transportation route to the stationary processing plant is 1950 m (Figure 6), while the semi-mobile processing plant is located on the main working plateau of the quarry, where the final products dump will also be located (Vrkljan et al. 2011). This "added cost" of transportation due to the location of the semi-mobile plant will be borne in total by the buyer, but since transportation is the primary activity of buyers in any case, for them these costs will be negligible. From the point of view of the quarry's costs, the acquisition and maintenance of dumpers and trucks which would perform the transportation only in the area of the exploitation field amounts to a significant increase in transportation costs. The planned annual production of crushed stone is 150,000 m^3 in solid rock and the costs of the stationary and the semi-mobile plant will be compared in accordance with this figure. Out of the total annual production, it is scheduled that 60 % of the mineral resource be processed using the wet procedure (stone aggregates for the manufacture of concrete and asphalt).

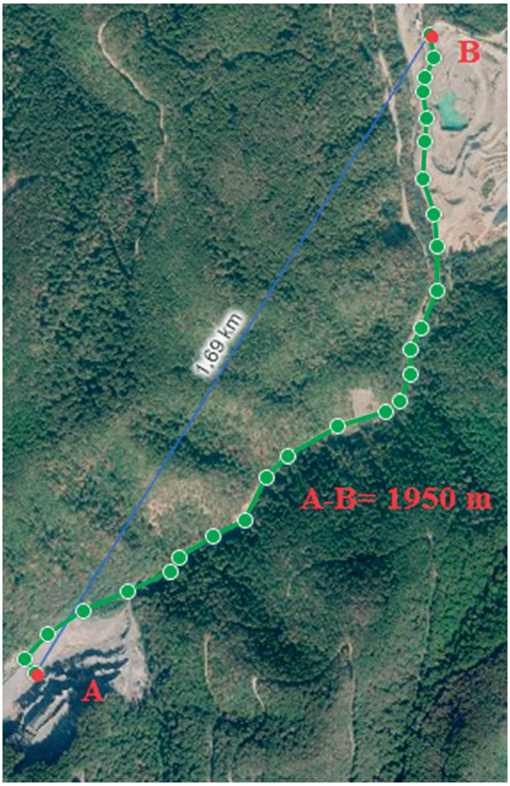

Fig. 6 – Transportation route (A-B) from the "Oršulica kosa" exploitation field to the "Hercegovac" stationary processing plant (ARKOD, 2018)

The transportation length can vary depending on the progress of mining work and the position of the mining sites; in our calculation, the median distance of 1,950 m during the mining period was used. The unit-based transport costs are expressed on an annual level per tonne of end stone products. Experiential data on the cost of a working hour of a Bell 40 dumper, which is used for transportation to the stationary plant, was used in the calculation. Out of the existing machinery in the quarry, the Bell 40 dumper has the greatest skip capacity and is one of the newest machines; if a dumper with a smaller load capacity and/or skip volume were used, the transportation costs would be even greater.

Calculation of transportation cycle t_c

$$t_v=(2 \cdot s_{pr} \cdot 60)/V_d =(2 \cdot 1950 \cdot 60)/23=10.2 \text{ min}$$

$$t_c=t_{ud}+t_v+t_p+t_m+t_{\sim}+t_z=4.1+10.2+1.0+0.5+0.3+0.5=16.6 \text{ min}$$

where t_v is the duration of driving of the full and empty dumper (min); s_{pr} is the average transportation length (km); V_d is the volume of the dumper's skip (m^3); t_c is the duration of the dumper's cycle (min): t_{ud} is the duration of loading the dumper (min); t_p is the duration of emptying the dumper (min); t_m is the duration of manoeuvring the dumper (min); $t_{\sim}$ is the waiting time for loading and emptying (min); t_z is the duration of unexpected delays (min).

Calculation of hourly transport capacity Q_{hd}:

$$Q_{hd}=(60 \cdot G_{ds} \cdot k_v)/t_c=(60 \cdot 36 \cdot 0.9)/16.6 = 117 \text{ t/h}$$

where Q_{hd} is the hourly capacity of the dumper (t/h); G_{ds} is the load capacity of the dumper (t); k_v is the time efficiency coefficient; t_c is the duration of the dumper's cycle (min).

Calculation of effective working hours of the dumper per annum:

$$h_{hg}=(Q_g \cdot \rho) / Q_{hd} = (150\,000 \cdot 2.834) / 117 = 3633 \text{ h}$$

where h_{hg} is the number of effective working hours of the dumper (hours); Q_g is the extraction of crushed stone per annum (m^3); ρ is the bulk per unit of volume of crushed stone (t/m^3); Q_{hd} is the hourly capacity of the dumper (t/h).

Transportation costs per annum:

$$T_{tg}=h_{hg}\cdot T_h=3640\cdot 469.37= 1\ 708\ 252 \text{ kn}$$

where T_{tg} are the transportation costs per annum (kn); h_{hg} is the number of working hours of the dumper per annum (h); T_h is the cost of a working hour for the Bell B40D dumper (kn).

Unit cost of transportation:

$$T_t=T_{tg} / (Q_g\cdot \rho) = 1\ 708\ 252 / (150\ 000 \cdot 2.834) = 4.01 \text{ kn/t}$$

where T_t is the unit cost of transportation (kn/t); T_{tg} are the transportation costs per annum (kn); Q_g is the extraction of crushed stone per annum (m^3); ρ is the bulk per unit of volume of crushed stone (t/m^3).

Costs of processing crushed stone

Mineral processing is performed using machines that run on electricity; therefore, the costs of processing are expressed through electric energy consumption. Moreover, seeing as this is wet processing technology, along with the electric energy consumption, the costs of water consumption also need to be taken into account.

The electric energy costs were calculated for both the stationary and the semi-mobile plant. The input data for the calculation were reduced to the hourly capacity of the plant and electric energy consumption per hour.

Rate of electric energy consumption:

The "Hercegovac" stationary plant	The M2500 semi-mobile plant
$N_{el.}=P_{el.} / Q_h = 400/80 = 5$	$N_{el.}=P_{el.} / Q_h = 250/150 = 1.67$

Unit cost of electric energy:

The "Hercegovac" stationary plant	The M2500 semi-mobile plant
$T_{el.j}=T_{el.}\cdot N_{el.}=1\cdot 5= 5$ kn/t	$T_{el.j}=T_{el.}\cdot N_{el.}=1\cdot 1.67= 1.67$ kn/t

where $N_{el.}$ is the rate of electric energy consumption (kWh/t); $P_{el.}$ is the electric energy consumption (kWh); Q_h is the plant capacity (t/h); $T_{el.j}$ is the unit cost of electric energy (kn/t); $T_{el.}$ is the cost of electric energy (kn/kWh); $N_{el.}$ is the rate of consumption (kWh/t).

We have already mentioned that due to the properties of the mineral resource, a wet processing procedure is used; it is, therefore, necessary to add the cost of water to the costs of crushed stone processing. Thus, what follows is the calculation of the costs of water for the stationary and the semi-mobile processing plants.

Rate of water consumption in processing:

The “Hercegovac” stationary plant	The M2500 semi-mobile plant
$N_v=P_v / Q_h = 160/80 = 2\ m^3/t$	$N_v=P_v / Q_h = 30/150 = 0.2\ m^3/t$

Unit cost of water:

The “Hercegovac” stationary plant	The M2500 semi-mobile plant
$T_{vj}=T_v \cdot N_v=0.5 \cdot 2= 1$ kn/t	$T_{vj}=T_v \cdot N_v=0.5 \cdot 0.2= 0.1$ kn/t

where N_v is the rate of water consumption (m^3/t); P_v is the water consumption (m^3/h); Q_h is the plant capacity (t/h); T_{vj} is the unit cost of water (kn/t); T_v is the cost of water (kn); N_v is the rate of consumption (m^3/t).

From the first set of results, we can see that the unit cost of transportation to the “Hercegovac” stationary processing plant amounts, at best, to 4.01 kn/t, while with the semi-mobile plant this cost is non-existent, seeing as it is located on the main work plateau of the quarry.

From the calculation of the processing costs, we can see that using the M2500 semi-mobile plant, as opposed to the old “Hercegovac” stationary plant, it is possible to achieve savings in the unit cost of electric energy of 3.33 kn/t of processed crushed stone. Despite a greater mineral processing capacity, the use of new technologies and tighter performance, i.e. reduced transportation of resources within the plant and, thereby, reduced load, result in a significant decrease in electric energy consumption.

Additional savings will be achieved through reduced maintenance costs, which would be accrued with the stationary plant due to its age and the worn-out condition of the equipment. Savings can also be achieved in the number of necessary jobs, seeing as one worker-operator is sufficient for the new semi-mobile plant, while the older plant required more workers due to its large size and surface area.

From the calculation of the processing costs, we can see that it is possible to achieve savings in the unit cost of water of 0.9 kn/t. Given the significant increase in capacity of the new semi-mobile plant and the recirculation of wastewater, the consumption of fresh water entering the system has been reduced tenfold. In addition, the process of washing employed thus far was done by purifying the water through sedimentation in large settling basins. By using the new semi-mobile plant and the system for wastewater treatment, the existing settling basins will be replaced by a single, smaller settling basin. Therefore, despite the costs of purchasing flocculant and maintaining the wastewater treatment plant, there will be a significant decrease in the costs related to maintaining large settling basins, as well as a decrease in the space that is used up by them.

The projected production of crushed stone in the "Oršulica kosa" exploitation field per annum is 150,000 m^3 in solid rock. Out of this amount, 60 % is planned to be used for the production of aggregate for the manufacture of concrete and asphalt, while the remaining 40 % would be sold as mixtures or ballast. Therefore, with a bulk per unit of volume of 2,834 t/m^3, the production of aggregate per annum (P_g) in the semi-mobile processing plant would amount to:

$$P_g = 150\ 000 \cdot 2.834 \cdot 0.6 = 255\ 060 \text{ t}$$

In order to determine the time period in which there would be a return on investment through savings, it is necessary to compare the total investments with the savings per annum. Therefore, Tables 1 and 2 present an overview of the costs of investment and the pertaining savings.

Table 1 – Savings per annum

Savings parameter	Savings in unit cost kn/t	Production per annum t	Savings per annum kn
Transportation	4.01	255 060	1 022 790
Water	0.90	255 060	229 554
Electric energy	3.33	255 060	849 349
		Total:	2 101 693

Table 2 – Costs of investing in a semi-mobile processing plant

Type of investment	Amount, kn		
Purchasing the plant	6 375 000		
Setting up the plant	375 000		
Preparing the ground surface	187 500		
Installing electricity and water at the exploitation field	187 500		
		Total:	7 125 000

Based on the data in Tables 1 and 2, we can calculate the time required for the return on investments through savings:

$$G_p = U_i / U_u = 7\ 125\ 000 / 2\ 101\ 693 = 3.39 \approx 3.5 \text{ years}$$

where U_i is the total amount of investment; U_u are the total savings; G_p is the number of years for the return on investments.

Conclusions

Crushed stone is a mineral resource that does not have a high market price, which makes it more susceptible to the effects of extraction costs. The method of mining the stone from the stone massif is the same in both of the compared variants; thus, there is no difference in cost in that stage of extraction. Based on the comparison of the results on the crucial technical and economic indicators manifested in the stationary and the semi-mobile plants in processing crushed stone, the following conclusions can be derived.

A significant advantage of the semi-mobile plant is that it can be brought to any location and can thus virtually eliminate the transportation costs within the exploitation field, as opposed to the stationary plant, to which the material needs to be transported for processing. The calculations show that the median transportation cost to the stationary plant during extraction amounts to 4.01 kn/t. Thus, with a median transportation length of 1,950 m to the stationary plant and an effective production capacity of 150,000 m^3 in solid rock, by using a semi-mobile plant, it is possible to achieve direct savings of 1.7 million kunas per annum on average.

The largest consumer of electric energy in the quarry is the processing plant. The unit cost of electric energy in the stationary plant is three times higher than that of the semi-mobile plant (5 kn/t compared to 1.67 kn/t). By using the semi-mobile plant, it is possible to achieve savings in electric energy consumption amounting to approximately 0.85 million kunas per annum.

Seeing as we deal with a wet processing procedure, water consumption has also been taken into account. The unit cost of water in the stationary plant is ten times higher than in the semi-mobile plant (1 kn/t compared to 0.1 kn/t). Savings in water necessary for processing when using the semi-mobile plant amount to approximately 0.23 million kunas per annum.

Taking the aforementioned savings into account, we can conclude that by using the new semi-mobile plant instead of the old stationary one, it is possible to achieve savings of approximately 2.1 million kunas per annum. Considering the total investment cost is approximately 7.1 million kunas, the return on investment should be realized in a relatively short period of 3.5 years.

Besides the aforementioned direct economic benefit, we should also emphasize the environmental benefits. The new semi-mobile plant is equipped with a system for purifying and recirculating wastewater and works with a minimal addition of fresh water into the system, amounting to 29 m^3/h (11.6 %), while the mud that is a by-product of purifying the water contains far less moisture than the mud created in the stationary plant. Another consequence of the greater amounts of wastewater in the old stationary plant was a larger surface area occupied by settling basins, while that surface area is significantly decreased when using the new semi-mobile plant. The mud created during the processing is used for recultivating quarries or is sold as a raw material for the ceramics industry. From all of the above, we can conclude that using the new semi-mobile plant will significantly decrease the production costs of crushed stone and will decrease the environmental impact of production.

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