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An Applied Study on the Debris Recycling in Tunnelling

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Abstract: Problem statement: A simple calculation has shown what the impact of muck created during the construction of a hypothetical 50 km long and 100 m^2 cross section tunnel could be on the environment: around 8 million cubic meters would have to be discharged as waste material. One solution to such a problem could be to recycle (almost a part) the earth material, that is, the muck and debris that are excavated from the tunnel face. **Approach:** In order to verify the possibility of using some different breakers from the ones used in the handling plant on the studied tunnel-access, some tests were performed in the DITAG laboratory at the Politecnico DI Torino. **Results and Conclusion:** Different cut dimensions were considered in the recycling of the muck material from the tunnel excavation using TBMs. The obtained material, mixed with natural sands and gravels according to various hypotheses, corresponds to the dimensional requirements for the shotcrete and concrete aggregates. The optimal solution should be the mixture of the best fines produced by TBM, the products of the broken rock and some percentage of natural sands and gravels. The final choice will depend on economic factors and obviously also on the particular features in the work sites.

Key words: Environment, tunnels, debris recycling, treatment of rock material, tunnel boring machine, shotcrete, concrete aggregates

INTRODUCTION

In recent years, the demand of sands and gravels for the construction of public works, including the construction of transport infrastructures in Europe, has increased to a greater extent (Cardu *et al*., 2009; Longo and Oreste, 2010; Banzato *et al*., 2011; Oreste, 2009; Fuoco and Oreste, 2009). This has involved for increasing exploitation of alluvial quarries. At the same time, more and more attention has been paid to reducing the impact on the environment to a minimum.

A simple calculation has shown what the impact of muck created during the construction of a hypothetical 50 km long and 100 m^2 cross section tunnel could be on the environment: around 8 million cubic meters would have to be discharged as waste material.

One solution to such a problem could be to recycle (almost a part) the earth material, that is, the muck and debris that are excavated from the tunnel face (Bellopede *et al*., 2011).

Obviously, some specified prerequisites the tunnel muck has to reach by means of the selection and handling operational phases, with the aim of being used as aggregates with a mean dimension of up to 16 mm, free of micas, fines and clayey particles, for the production of the shotcrete or the concrete for the tunnel lining.

Underground soil exploitation will be used more and more in the coming years throughout Europe. Because of the presence of mountain ranges, such as the Alps in the North and the Apennines, which run all along its length, Italy has always been one of the countries with the highest concentrations of tunnels: it is sufficient to consider the number of already existing tunnels that are longer than 500 m, which add up to a total of about 850 km and an additional 150 km of tunnels (updated in November 2009) are under construction. There are 750 km of existing railway tunnels lines that are longer or equal to 50 m, 130 km under construction and 170 km at the draft stage. It is important to recall that there are more than 150 km of underground metropolitan tunnels in Italy which will be increased with the addition of new sections to enlarge the already existing lines or the construction of new infrastructures (Naples, Rome, Turin, Brescia, Catania, Milan).

The study of the material handling plant of the rock materials obtained from the face excavation of a Alpine tunnel-access is particularly interesting because of the problems that had been faced and solved, to examine the possibility of making a profit from the rock produced in the tunnel excavation, in order to avoid dumping the rock in waste sites.

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MATERIALS AND METHODS

The studied Alpine incline tunnel-access has been foreseen for a future long railway tunnel, to increase the excavation heads. The incline ends in an adit, which crosses the principal tunnel and constitutes the starting point of the works. The incline length (around 4000 m) and the 70-80 m^2 cross section, implies a volume of muck of about 500000 cubic meters: a muck handling plant, is therefore of fundamental importance to reduce the volume of the rock material that will be discharged to the waste sites.

The rocks encountered in the studied tunnel-window are essentially altered dolomites, quartzites and Permo-Trias micaceous schists. The D and B method was used for the excavation. The muck was first of all selected by a geologist who classified it into three main groups: (1) rock material suitable for concrete aggregates; (2) waste material that will be dumped; (3) material with intermediate characteristics, which is sent to a special deposit with the possibility of reusing it as ballast or road ground material. The first group was then submitted to a first breaking using a primary jaw breaker at the tunnel face to obtain a smaller debris dimension than 250 mm. This product was then transported by means of a belt to the processing plant which is composed of: (1) a separation tower; (2) a section for breaking and sieving the rock material; (3) a plant for processing the sands, slurries and water.

The first class material is sent to a primary sieve that separates the material into three classes: (a) a dimension > 250 mm, which is stored in a silo for possible further breaking operations; (b) material with a dimension between 25 and 250 mm; (c) material with a dimension < 25 mm, which is sent to the waste deposit site. Any possible iron residues are removed during the transportation on the belt.

A synthetic scheme of the selection plant is as follows:

- 1st Class>60 mm is sent to the secondary breaker
- 2nd Class 25-50 mm goes to the tertiary breaker; the tertiary sieve is fed by this product
- 3rd Class 8-25 mm is sent either to the tertiary sieve, or to the tertiary breaker
- 4th Class< 8 mm is sent to the tertiary sieve
- 5th Class<4 mm is sent to the sand and slurry processing plants

In the sand processing plant, two cyclones that cut the products to dimensions of around 0.03 mm to eliminate clays are fed by class 0-4 mm, mixed with water. The product skimmed off by the cyclones is sent to the slurry processing plant. The gross product of the cyclones passes through two sieves with 2 mm openings. The up product is sent to the sand storage plant; the gross product is recycled back to the breaker and sieving plant.

A cyclone in the slurry processing plant divides the material into two class: 0- 800 μm and 800-2000 μm, which is sent to a draining sieve and then to the sand storage or to the waste (only the part exceeding the request of the concrete plant supply). The 0-800 μm class goes to a hydro-classifier that eliminates the finest particulates (<60 μm), which are sent to the waste site, after decantation in a Dorr type tank and the 60-800 μm fraction is drained and then dried and sent to the sand storage.

Aggregate characteristics of shotcrete and concrete: In order to verify the possibility of recycling the tunnel muck material in the shotcrete and concrete production, it is necessary to know the required characteristics for the aggregate component (Thalmann *et al*., 2003; Olbrecht and Studer, 1998). Shotcrete and concrete aggregates can be divided into sand and gravel on the basis of the grain dimensions. Some other substances are then introduced into the concrete mixture such as the water, the most important and some quantities of fluidifiers makers and setting accelerators. The sieving dimension of the aggregates has to conform to certain distribution laws, i.e. the Bolomey and Fuller. The Bolomey sieving curve takes into account a parameter (A) that depends on the required concrete workability (Table 1).

A key aspect that must be considered in the evaluation of the possible use of muck from the excavation of tunnels is that aggregates need high strength against alkali. This is because of the phenomenon that is known as the “alkali-silica reaction” (or ASR). This phenomenon represents a form of chemical degradation of concrete that is triggered by the presence of aggregates which are characterized by a particular mineralogical composition.

The alkali-aggregate reaction is generally associated with the presence of alkali (sodium and potassium) in the cement and amorphous or poorly crystalline silica in some aggregates.

Cement contains small quantities of alkali (Na_2O and K_2O) (due to the clay component) which after hydration form a hydroxide solution:

$$Na_2O + H_2O \rightarrow 2NaOH$$
$$K_2O + H_2O \rightarrow 2KOH$$

Reactive aggregates react with hydroxyl ions (OH-) associated with alkali and give rise to expanding products.

Table 1: Values of the parameter A in the Bolomey sieving curve in function of the origin and of the concrete workability

Aggregate origin	Moist earth	Semi-fluid and plastic	Fluid-very fluid
Alluvial deposit	8	10	12
Breaker	10	12	14

As a result of the reaction, an alkaline silicate gel appears on the surface of the granules and this gel, if dampened with water, swells and develops a pressure between the grains and the cement paste.

This process is slow and the expansion occurs during concrete hardening; the increase in intergranular pressure can lead to localized swelling and cracking of the concrete, thereby ruining it. A white liquid gel (sodium silicate) escapes from the irregularly shaped cracks. Cracking is usually followed by the detachment of a small circular portion of the concrete surface area (pop-out), because of the swelling of the reactive aggregates.

Although the exact alkali-aggregate reaction mechanism is not fully understood, some basic parameters that contribute to the progression of the destructive phenomenon have been identified.

The alkali-aggregate reaction occurs as rapidly and intensely as the increase in:

- The sodium and potassium content in the aqueous phase which fills the capillary pores of the cement paste: A content in excess of 3 kg m^3 is considered dangerous
- The relative humidity of the environment
- The quantity of amorphous and cryptocrystalline siliceous aggregates
- If any of these three conditions is missing, the phenomenon will not occur and there will be no apparent damage (Gertsch *et al*., 2000)

RESULTS

Breaker tests: In order to verify the possibility of using some different breakers from the ones used in the handling plant of the studied tunnel-access, some tests were performed in the DITAG laboratory (Department of Land, Environmental and and Geo-technology Engineering) at the Politecnico di Torino.

Some breaking tests were carried out on quartzite specimens obtained from the site processing installation using a AD80N2 type laboratory Hazemag breaker, that has the following characteristics: feed opening: 100x100 mm; rotor diameter: 250 mm; dimension of reliefs: 300 mm; distance between plates and reliefs between 10 and 25 mm; maximum capacity: 350 kg h^{-1}; installed power: 2.2 kW, rotation speed of the rotor: 2800-3500 rev. p.m.

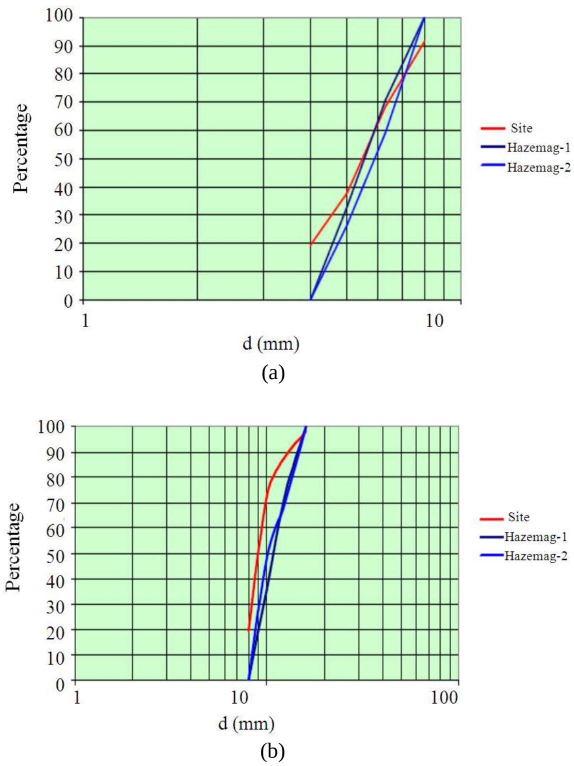

Fig. 1: (a) (up): Comparison of the site sieving curves products with the Hazemag products 1 and 2 in the 4-8 mm range; (b) (down): Comparison of the site sieving curves products with the Hazemag products 1 and 2 in the 8-16 mm range

Two tests were carried out, both with distance of 25 mm between the plates and relieves. The first with a rotation speed of the rotor at 3500 rev p.m. (product 1); the second one with a rotation speed of 2800 r. p.m. (product 2). An improvement of the shape of the quartzite grains was obtained from these tests, which became particularly suitable for shotcrete or concrete production. Obviously a larger number of tests will be necessary to confirm this result.

The debris produced with the aforementioned method were subjected to sieving test analysis. The results are shown in Fig. 1, with a comparison with the site sieving products.

The TBM as first breaker: In the prevision of the use of TBMs for the excavation of long and deep tunnels, an analysis of the debris produced in the TBM excavation work, was carried out. The TBM could in fact be considered as a primary breaker in the rock handling process for shotcrete or concrete production (Tuncdemir *et al*., 2008).

Table 2: Values of the constant c and n of the Rosin-Rammler sieving curve calculated for an average TBM product, of rocks of medium strength, crystalline rocks and Hazemag product respectively

	Medium strength rocks	Crystalline rocks	Hazemag Products
c	1.68	1.52	1.97
n	0.30	0.58	1.00

The geometric characteristics of the excavated material is affected by the excavation method that is used; muck obtained from Tunnel Boring Machines (TBMs) is more difficult to reuse for concrete than muck obtained from drill and blast excavations, as the typical form of the granules that are produced is lamellar and these grains tend to form horizontal planes during the concreting phase (Innaurato *et al*., 2007). Furthermore, they trap some of the water in the mixture, causing a consequent degradation of the final structure. The surface roughness and the presence of sharp edges improve the bond between the aggregates and concrete, but reduce the workability and require a greater quantity of water and cement and therefore increased costs.

From various sieving curves of the rock materials produced by TBMs and quoted in literature, the modified Rosin-Rammler sieving law (Eq.1), which is the most commonly used for the jaw breaker, was applied and the sieving curve that averages the various sieving curves of the TBMs production was found by means of the least squares law Eq. 1:

$$R_u = e^{-\frac{u}{1-u}\cdot n} \cdot c \tag{1}$$

where, R_u is the sieving up product, $u = x/x_m$ and x and x_m are the ordinary dimension and the maximum dimension of the rock particles, respectively; c and n are some constants that can be experimentally calculated. These curves can be considered as typical for the rock products of TBMs, from which it is possible to obtain the optimal composition for the dimensional distribution of the aggregates to be used for concrete or shotcrete production.

The same procedure has been followed with the products of the Hazemag breaker on the quartzite obtained from the site plant of the studied tunnel-window. The constants found in this case are shown in Table 2.

The rock material produced by the TBM generally presents a typical continuous dimensional distribution of grains from 0.001 to around 31.5 mm. On the other hand, the TBM grains are generally long and flat and therefore unsuitable for concrete production without a previous selection and handling. Only the largest parts could be separated and then broken up, for example with an Hazemag breaker.

Table 3: Percentages of the rock material to be handling on the basis of the hypothesis examined in the text

Material dimension	% (of the total)
Fines (< 4 mm)	51.88
Class 4-31.5 mm	48.12

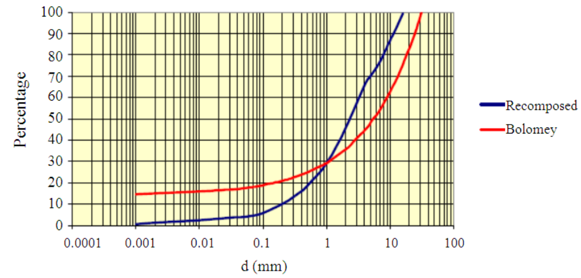

Fig. 2: Comparison of the Bolomey sieving curve (red curve) with the one of the recomposed material (blue curve)

In a first attempt a cut dimension of 4 mm was essayed. Firstly, the sieving curves of the finest material (< 4 mm) and the one of the largest dimensions were reconstructed from the total sieving curve of the rock produced by TBM. It is of fundamental importance that the Hazemag breaker can assure the rock grains have a suitable shape for the largest dimensions of the rock material. This crushed material can be finally added to the fines produced by the excavation machine to form the aggregates for the concrete.

The subdivision of the percentages of < 4 mm dimension and the largest dimension is shown in Table 3 on the basis of what is obtained by selecting into two parts the TBM production. Starting from these values, it is possible to recompose the material produced by the TBM and from the breaker in a single class. A sieving curve of the recomposed material is thus obtained, which is compared with the Bolomey curve shown in Fig. 2. Some differences between the sieving curve of the recomposed material and the Bolomey curve can be noted, in particular for the fine fractions (< 1 mm).

The final material composition can be modified into three different operational modes: (1) mixing the reconstructed product (TBM and Hazemag product) with sand and gravel; (2) mixing different percentages of fines produced by the TBM and the Hazemag products; (3) mixing the fines produced by the TBM with Hazemag products and some fractions of sand and gravel.

The 0-4 mm fraction for the sand and the sum of the 4-8 and 8-16 mm classes of the material produced in the tunnel-window site plant for the gravel were used as reference classes.

Table 4: Obtained optimal mixture between the original broken rock product and sand and gravel (operat. mode 3)

Material	(%)
Recomposed broken material	35
Gravel	60
Sand	5

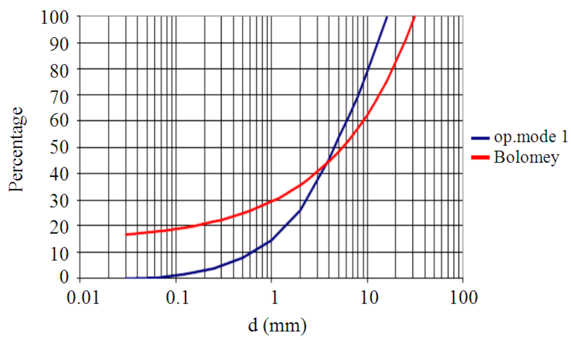

Fig. 3: Comparison between the optimal composition (blue curve) and the Bolomey sieving curve (red curve), according to operational mode 1

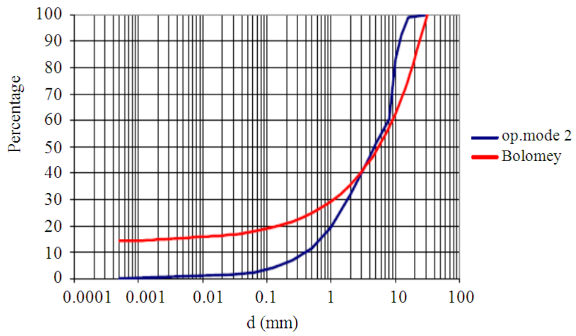

Fig. 4: Comparison between the optimal composition (blue curve) and the Bolomey sieving curve (red curve), according to operational mode 2

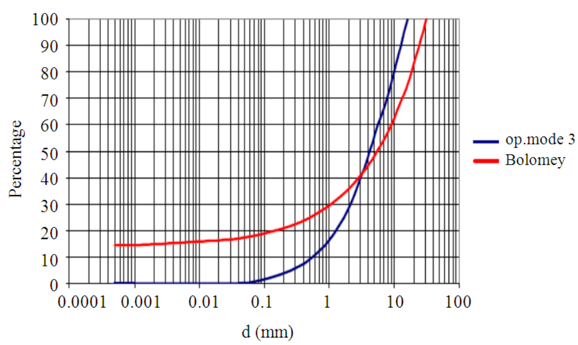

Fig. 5: Comparison between the optimal composition (blue curve) and the Bolomey sieving curve (red curve), according to operational mode 3

The three different sieving curves were been then again compared with the Bolomey curve. The comparison shows a noticeable difference between the three sieving curves and the Bolomey curve (Fig. 3-5).

A comparison was then made with the Fuller curve: as previously mentioned, this curve is based on the full assemblage of the rock grains, versus the creation of a low workability concrete. This will not be a problem when the produced aggregates will be used for the realisation of the lining segments.

The comparison shows that the approximation between the previously mentioned three sieving curves and the Fuller law is better than the Bolomey law, above all for the finest aggregates.

The obtained optimal mixture between the original broken rock product and the sand and gravel is shown in Table 4.

DISCUSSION

Changing of the cut dimension: From the above analysis it is possible to observe a noticeable difference between the sieving curves obtained from the mixture of the various products according to the three hypothesis that were made and the Bolomey and Fuller reference curves. A new analysis was then carried out, choosing 2 mm as the cut dimension. All the analysis were then repeated in the same manner previously as described.

From the obtained results it is possible to draw some conclusions: if the cut dimension of 4 mm is chosen, the lowest difference between the rock products and the sieving curves of reference is shown for the Fuller curve, in particular under hypothesis 3, that is, summing the best mixture of the fines produced by the TBM and the broken products of sand and gravel, according to the sieving products obtained in the tunnel-window site plant.

If the chosen cut dimension is 2 mm, the lowest difference is shown for the Bolomey curve. The optimal solution should therefore be the one corresponding to operational mode 1, that is, the mixture of the fines produced by the TBM with the products of the breaking operation, without any further addition.

With reference to the volumes of rock material that has to be bought from the market, the optimal solution should be the mixture of the best fines product of the TBM and the products of the broken rock (operational mode 1). The final choice will depend on economic factors and obviously also on the particular features in the work sites.

CONCLUSION

Over the past forty years, the construction of public works has been increasing considerably all over the world and particularly in Europe in order to improve the mobility of people and goods. Underground soil exploitation will be used more and more in the coming years throughout Europe. The availability of a large quantity of excavated material, which can be recycled as aggregates for concrete for the construction of retaining walls and for the lining of tunnels, can be expected.

The construction of several long tunnels will produce large amounts of excavated material and, at the same time, will produce a high demand for aggregates for the required linings. If the excavated material is considered as a waste rather than a possible resource, the double problem arises of having to resort to non-renewable resources (extracted from quarries) and of having to find areas for the disposal of the unused muck, with the consequent environmental impact.

The research that is presented in this study has taken into consideration a site rock material handling plant of an alpine tunnel-access for the possible reuse of the muck obtained from the excavation face.

Obviously the results of this research should be confirmed or revised, when the geologic and lithologic studies on the tunnel layout are known and a more detailed analysis will allow one to be more precise on the rock volumes to be reused and on the equipment to be used to guarantee the best results either from an economic and technical point of view.

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