Underground Marble exploitation using backfill aiming for the recovery of the remaining pillars

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ABSTRACT

Considering the importance of the natural stone in Portugal, it is important to explore new ways of doing it more efficiently and sustainably. At the Estremoz-Borba-Vila-Viçosa anticline, top quality marble is produced and exported worldwide. This work aims to contribute to the transition for underground exploitation of this resource through the room and pillar method

From previous studies on this topic, this thesis studies the possibility of exploiting the remaining pillars, typical of this mining method, using cemented rockfill (CRF) produced using the waste rock of the quarry.

In a laboratory component the strength and deformability characteristics of the CRF were studied considering two parameters of this material: the particle size distribution and the curing time. From the laboratory results, numerical simulations were performed to investigate the possibility of exploiting the remaining pillars of marble. Two models were developed in different zones of the quarry through the RS2 software based on the finite element method.

It was concluded that with the use of this backfill it is possible to exploit the remaining pillars in specific zones of the underground quarry since some other zones are not stable enough to do so.

In addition, this work also examines the environmental aspect because it applies fundamental principles of Circular Economy with the reuse of waste rock but also because it allows the exploitation of the remaining marble pillars with high economical value. Thus, the amount of waste rock left on the surface is lower and the amount of commercial marble is increased.

Keywords: Cemented Rockfill, Underground quarrying, Particle Size Distribution, Finite Element Method, Marble

1. Introduction

The exploitation of natural stone in Portugal has strong cultural and economic roots, and it takes place in most part of Portuguese territory. Marble exploitations exist in the Estremoz-Borba-Vila-Viçosa anticline at least since 370 B.C. (Lopes, 2007). The anticline is a complex geological structure however by the year of 2020 there were 122 quarries operating at this place (DGEG, 2022) and the final product is top quality marble exported worldwide. Marble is a very profitable resource however its exploitation generates enormous amounts of waste rock that frequently end up as wastes that cause strong visual and environmental impacts (Vagnon et al, 2020).

Sustainability is a tripod since it considers the economical, social and environmental aspect of the industrial processes and only when these factors are balanced one can say that sustainability has been achieved (Purvis et al, 2019). The Circular Economy concept advocates drastically reduced primary resources extraction in favour of secondary material flowing through internal loops (Lèbre et al, 2017).

Considering the quality of Portuguese marble, it is imperative to keep being able to produce this resource which means exploiting deeper into the deposits. To ensure the operations sustainability it is necessary to perform a transition from open pit to underground exploitation, with the room and pillar mining method, making the quarry safer, more profitable and therefore more sustainable (Oggeri et al, 2001).

As mentioned earlier, one of the biggest problems related to marble quarrying is related with the enormous amount of wate rock produced that is afterwards deposited at the surface. The aim of this thesis is to investigate the possibility of exploiting the remaining marble pillars that are left during the room and pillar underground method using cemented rockfill made from the waste rock produced by the quarry. With this technic, based on the Circular Economy principle, more commercial marble would be exploited, and the amount of waste deposited in wastelands would decrease drastically because it would be reused to produce the backfill that replaces the marble pillars as support. With this, the first part of this work was to investigate the strength and deformability characteristics of cemented rockfill. 72 cemented rockfill samples were produced using marble as aggregates and submitted to uniaxial compressive strength and shear strength tests.

With the results obtained in the laboratory work, numerical simulations were made using the RS2 software from Rocsience based on the Finite Element Method. The objective was to investigate about the support capabilities of the cemented rockfill previously manufactured and to look for the best exploitation sequence of the remaining marble pillars.

This thesis comes in line with previous investigation on this topic, in fact, underground marble quarrying in the Estremoz anticline is being studied for more than 20 years (IGM,2000). More recently, Franqueira & Paneiro, (2021) did a 3D stability analysis for this quarry and got very promising conclusions, however, in their model, it was used bibliographic values for the Cemented

Rockfill which can be misleading. Thus, this study aims to contribute to this investigation also by giving more accurate data.

2. Mining Backfill

Backfill is a mining technic used in the mining industry for several decades. It represents the material with no commercial value that is deposited on the empty stopes created by the ore exploitation. Backfill was firstly used to manage the waste rock produced by mines but nowadays it is used to improve the stability of the excavations, reduce surface subsidence and therefore safer work conditions. For this reason, it is common to add binding agents such, generally Portland Cement, to increase strength and support capabilities (Sivakugan et al, 2015). The use of backfill has direct impact on mining projects since there are increasing safety requirements and environmental restrictions regarding waste management and this problem is significantly mitigated when backfill is used since it reuses the waste rock.

There are three main types of backfill (Henderson & Revell, 2015):

- Paste fill
- Hydraulic fill
- Rock fill

The difference between these types of backfill is mostly regarding the particle size that is used which is dependent of the type of exploration carried out in that specific mine and therefore the type of rejected material that comes out of it. The hydraulic fill is a composed of fine particles although the particles below 0,01mm are typically removed. The paste fill is commonly composed by the totality of the rejects from the processing plant. The rockfill can have particles up to 10cm. A common characteristic of all types of backfill material is that it must have low costs regarding its obtention, transport and applicability (Costa e Silva, 2013). For this reason, each mine has its own characteristic backfill considering its waste material which means that there is no backfill that works for every case (Sivakugan et al, 2015).

There are some parameters that are very important to optimize in order to produce cemented rockfill with good strength properties:

- Curing time;
- Cement percentage;
- Particle Size Distribution;
- Water/Cement ratio.

The curing time represents the period when the cement is gaining strength with the development of reactions between the silicates and the water molecules. There are studies that indicate that cements strength increases for months or even years but after 28 days it has already reached about 80%-90% of its final strength (Henderson et al, 2005).

There is no linear relationship between the percentage of cement and the strength of cemented rockfill. Generally, percentages between 5% an 10% of Portland Cement are used although there are other materials with binding properties, like fly ash or pozzolonas, that are often used in the mix dew to its lower cost (Shrestha et al, 2008).

The particle size distribution (PSD) of the aggregates can vary a lot depending on its constitutional materials. The internal structure can be strengthened by reducing the elements that can cause the deterioration of the hydration process and by optimizing the spatial distribution of the particles and therefore reducing its void ratio. A poorly graded PSD can lead to a higher void ratio that will lead to cement particles filling voids instead of working on binding particles of aggregates. The amount of fines in cemented rockfill should be monetarized so that properties like water flow can be controlled. In this topic, the most common form of defining the particle size distribution is the Talbot & Richards equation (Henderson & Revell, 2005):

$$P(d) = (\frac{d}{dmax})^n \times 100$$

On this equation, P(d) represents the probability of the material being finer than sieve opening d. The *d* represents the sieve opening (mm), *dmax* represents the maximum particle size (mm) and *n* is the Talbot index. In Wu et al, (2018) a study was conducted that concluded that the best Talbot index for cemented rockfill was between 0,4 and 0,6 because on this range of PSD there is optimal geomechanic characteristics. Warren et al, (2018) considered that the optimal PSD was found at n=0,5.

The water to cement ratio affects the viscosity of the slug and therefore it has a direct impact on the applicability of the CRF and the ability to fill the entire stope also known for a tight fill situation (Murch, 2018). The optimal water to cement ratio depends on the type of mining method that is used. For a longhole stope the slug should be more fluid so 0,7 – 1,2 are used. When there is no need for that fluidity 0,8 is commonly used (Henderson, 2005).

3. Methods

On this thesis the strength and deformability characteristics of the cemented rockfill made from marble were studied. Afterwards it was investigated if with the applicability of this backfill the recovery rate of the underground quarry would increase due to the exploitation of the remaining pillars. On the laboratory part of this work, two parameter of the cemented rockfill were studied:

- Particle Size Distribution (n=0,4; n=0,5; n=0,6);
- Curing time (7, 14, 28 days).

On the numerical simulations part of this work, two different parts of the underground excavation were studied to know more about its the stability.

On figure 1 there is a diagram of the sequence of this thesis:

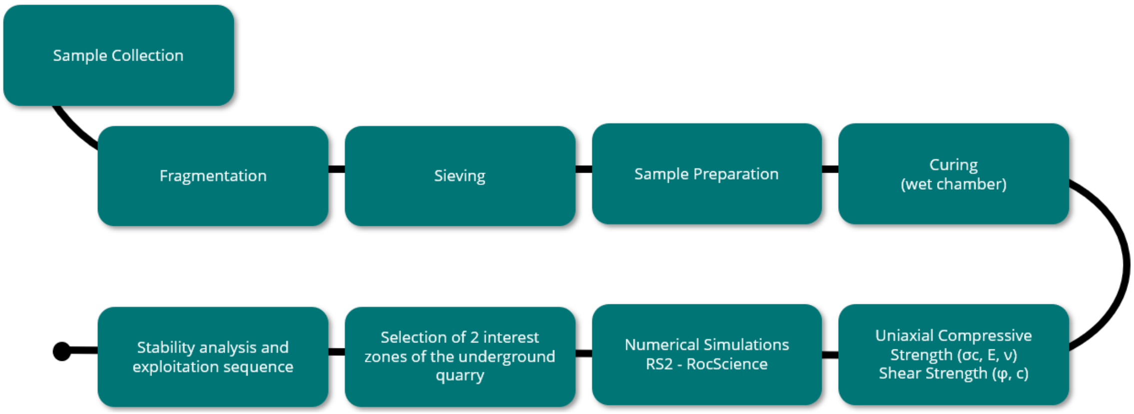

Figure 1 – Thesis stages

The geology of the location where the quarry is corresponds to an anticline with elliptical and symmetrical shape with 45x8km. It has been estimated that the anticline holds 100 x 106 m3 of evaluated marble resources. The quarry operates in open pit method that reaches 156m in depth. The underground excavation has started with the opening of two drifts: one goes directly into the pit and the other one starts from the dome in the SW flank. Therefore the room and pillar excavation will start from the bottom of the pit as shown in figure 2.

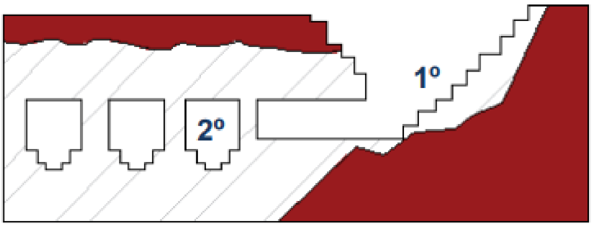

Figure 2 – Transition Open Pit to Underground exploitation

As mentioned before, this thesis is a contribution to an investigation that started by doing geologic investigation about that location. Thus, laboratory and *in situ* tests have been made to define stresses, elastic properties as well as a characterization of the geo-structural conditions. The characterization of the discontinuities was made according to the four slopes of the quarry individually. On table 1 there is a characterization of the families of discontinuities and on table 2 a characterization of the marble from the quarry:

Table 1

Family of discontinuities	Direction	Dip	cohesion (MPa)	Friction angle (º)
1	N50 – 70W	30 – 85º SW/NE	0,14	42,04
2	N10 – 30W	30 – 70º SW	0,25	46,05
3	N30 – 65E	30 – 80 NW/SE	0,31	51,32

Table 2

Property	Tensile Strength (MPa)	Compressive Strength (MPa)	Young's Module (GPa)	Poisson's Ratio	Cohesion (MPa)	Friction Angle (º)
Average	7.31 ± 0.56	69.09 ± 5.77	57.62 ± 5.64	0.24 ± 0.02	11.15	54.67

4. Results and Discussion

After the fragmentation and the sieving of all material, started the process of actually producing the cemented rockfill samples. To know the strength and deformability characteristics of this material, two laboratory tests were made: Uniaxial Compressive Strength test (σc, E, ν) and Shear Strength test (c, ϕ).

Three PSD and three curing times were studied and for each set of samples (same PSD and curing), 4 CRF samples were produced. In total, 72 samples were made. Each sample had 300g of aggregate material, 10% of Portland cement and 0,75 water/cement ratio.

On the following tables (3, 4, 5) are the results of the UCS tests performed on the CRF samples:

Table 3 – UCS test results 7 days curing time

n	Specific weight (kg/m^3)	UCS (MPa)	E (GPa)	ν
0.4	1859.8 ± 5.9	1.667 ± 0.199	5.8 ± 0.3	0.15 ± 0.06
0.5	1925.5 ± 17.4	2.213 ± 0.252	11.1 ± 2.2	0.53 ± 0.05
0.6	1963.4 ± 21.2	3.015 ± 0.644	10.8 ± 1.6	0.24 ± 0.17

Table 4 – UCS test results 14 days curing time

n	Specific weight (kg/m^3)	UCS (MPa)	E (GPa)	ν
0.4	1902.1 ± 18.5	1.769 ± 0.25	10.45 ± 2.15	0.39 ± 0.03
0.5	1945.4 ± 46.9	2.396 ± 0.521	9.85 ± 2.45	0.21 ± 0.03
0.6	1914.4 ± 15.9	2.944 ± 0.367	20.75 ± 0.65	0.31 ± 0.13

Table 5 – UCS test results 28 days curing time

n	Specific weight (kg/m^3)	UCS (MPa)	E (GPa)	ν
0.4	2025.1 ± 114.1	2.954 ± 0.581	14.30 ± 0.30	0.22 ± 0.03
0.5	2059.0 ± 17.0	3.749 ± 0.252	21.85 ± 1.55	0.39 ± 0.10
0.6	2190 ± 46.4	4.667 ± 0.634	31.30 ± 20.00	0.27 ± 0.21

There is a tendence of increasing strength with time regardless of the Talbot index and the samples with the higher Talbot index have a higher strength regardless of the curing time. Even though all samples were prepared with the same method, when analysing tables 3, 4 and 5 there is an increasing specific weight of the samples with the Talbot. Considering that the void ratio and the specific weight are well correlated, it can be noted that the n=0,6 results in samples with better spatial distribution of the particles and therefore with a lower void ratio.

To perform the shear strength test, the samples were loaded with an increasingly normal tension:

- 0.125 σc
- 0.250 σc
- 0.375 σc
- 0.500 σc

On figure _ there is a graphical representation of the set of tests performed on the samples with n=0,5 and 7 days of curing:

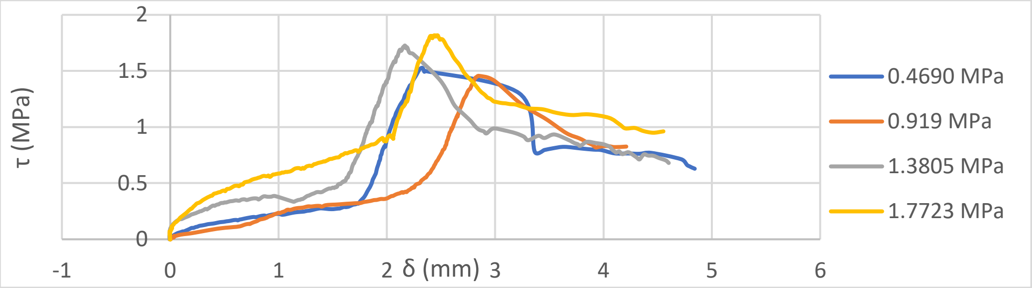

Figure 3 – Shear strength test n=0,5 7 days

As expected, the shear strength increases with the increase of the applied normal load. It can be noted that after failure the samples still show some residual strength. From these results the determination of the cohesion and friction angle was made with the shear strength *versus* normal load graph:

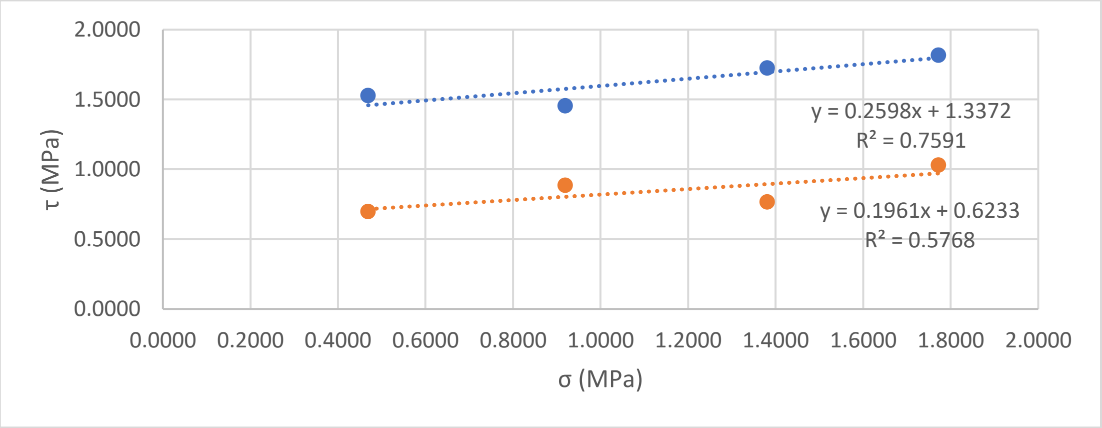

Figure 4 – Shear strength vs normal stress n=0,5 7 days

Based on the Mohr-Coulomb strength criteria the envelopes were determined through simple linear regression. Therefore for this set of samples the cohesion was 1,34 MPa and the friction angle was 14,56º. The remaining results are presented on table 6:

Table 6 – Results of the shear strength test

t cura	n	c (Mpa)	ϕ (º)	c res (Mpa)	ϕ res (º)
7 days	0.4	0.83	6.02	0.36	16.46
7 days	0.5	1.34	14.56	0.62	11.09
7 days	0.6	2.57	27.78	0.51	19.65
14 days	0.4	0.83	7.04	0.44	14.92
14 days	0.5	1.01	24.64	0.88	1.20
14 days	0.6	1.53	18.20	0.75	6.74
28 days	0.4	0.60	8.07	0.27	15.90
28 days	0.5	1.53	22.27	0.35	16.75
28 days	0.6	2.32	11.83	1.16	6.06

The numerical simulations were developed to study the possibility of exploiting the remaining marble pillars with the use of CRF. Since the n= 0,6 was the index that offered higher strength, that was the one used to do the simulations. Two locations of the underground quarry were selected to analyse. The first was further from the open pit excavation influence and the other one was on its zone of influence as shown in figures 5 and 6.

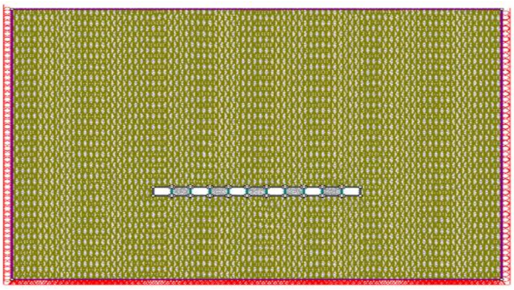

Figure 5 – geometry of the model "cut 1"

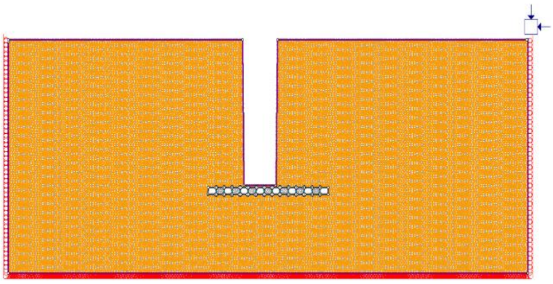

Figure 6 – geometry of the model "cut 2"

On the first case, it was possible to do the exploitation of the pillars even though some instabilities were found in the CRF pillars, the floor and the roof were always stable. In figure 7 there is a representation of the strength factor while exploiting the first two pillars:

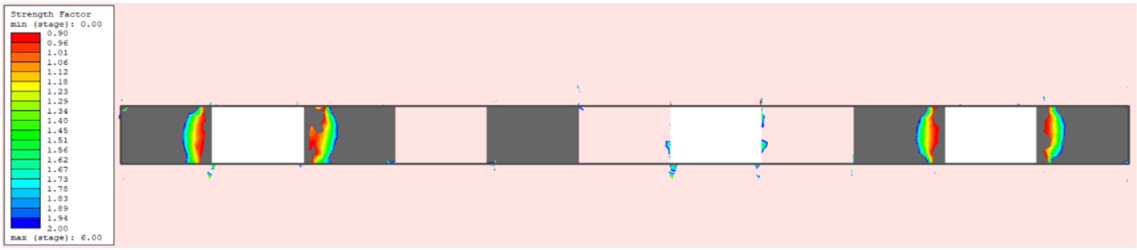

Figure 7 – Representation of the Strength Factor at Cut 1

The failure of part of the pillars happens due to the high main stress caused by the weight of the rock mass above as demonstrated by figure 8.

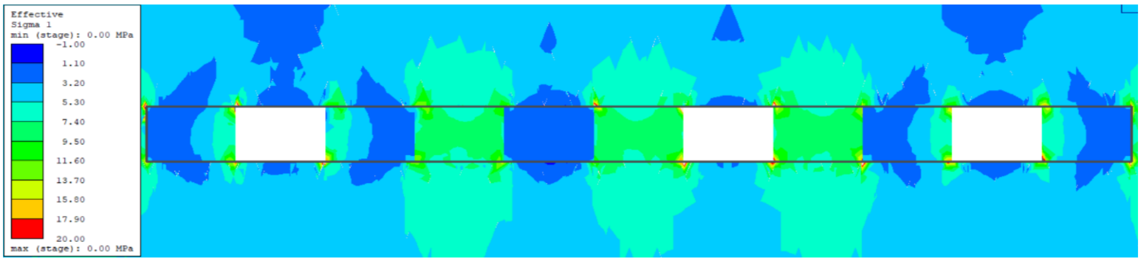

Figure 8 - Representation of the main stress at Cut 1

On the other cut, on the location influenced by the open pit excavation the extraction of the pillars could not be done due to high shear stresses caused by the excavation as the vertical stress is high far from the open pit and as it gets closer to the pit they decrease immensely and generates shear stress. The CRF pillars fail immediately after being placed.

5. Conclusion

Regarding the laboratory work:

- the particle size distribution is a key parameter that must be optimized when making cemented rockfill. The n=0,6 index was the one that presented higher compressive and shear strength, lower void ratio and higher specific weight;
- the curing time didn’t indicate much influence on the shear test results;
- the cemented rockfill mix could be improved by making a large scale testing.

Regarding the numerical simulations:

- it is possible to do the exploitation of the remaining pillars of marble in an underground excavation under the room and pillar method although there are some instabilities they don’t affect the roof and the floor of the chamber;
- Closer to the limits of the open pit excavation where there are concentration of stress the exploitation of the remaining pillars will be more complicated mainly because of the high shear stresses;

Considering marbles cultural and economic importance in Portugal this investigation should be continued. The following works are suggested:

- Repeat the laboratory work using bigger samples;
- Increase the number of samples in each set;
- Increase the cement percentage to determine a way of exploiting the unstable parts of the quarry:
- Carry on with the numerical simulations using 3D modelling with CRF characteristics.

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