Study of Strength Behaviour and Deformability Characteristics of Paste Fill with Addition of Recycled Rubber

Diana Marques Dias 1

1 Instituto Superior Técnico, Universidade de Lisboa, Portugal

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* dianamias4@gmail.com

Abstract

At a time when the mining industry is committed to ensure industrial growth by increasing the eco-efficiency of all operations, the use of other solid wastes, in this case, rubber tires, along with mining tailings, is considered relevant. In order to guarantee the support functions in the underground stope performed by the traditional backfill, promoting thus the storage of materials in the underground, avoiding this way their deposition on the surface.

This document aims to study the strength, behaviour and the mining backfill deformability, in this case paste, with recycled rubber powder addition, making this way room for further research on this type of solutions.

For this, an experimental work was carried out, which consisted in laboratory tests program development with mixtures composed of tailings (from the Zinkgruvan and Neves-Corvo mines), Portland cement, water and rubber, in order to analyse the strength properties and deformability of these new materials.

It was possible to verify that the compressive and tensile strengths decrease with the addition of rubber. However, Young's modulus has decreased and Poisson's ratio has increased, which shows greater ease in accommodating deformations. There was also a decrease in the Strain Energy Storage Index, indicating a decline in the tendency to trigger rockbursts. On the other hand, the yield stress increased, which means greater paste strength to flow.

Finally, it is extremely important to continue this study in order to infer the applicability of these new materials in an industrial context.

Keywords: Paste Backfill; Recycled Rubber; Strength; Deformability; Strain Energy Storage Index; Rockbursts.

1. Introduction

The mining industry has a crucial role in modern society, being responsible for the extraction of indispensable minerals for its technological development.

Underground exploration plays a very important role in mineral production. The increase of the exploration depth forces the excavations safety requirements to be ever greater.

In order to increase the stability of the excavations, support and reinforcement methods are used.

The increase of the exploration depth forces the excavations safety requirements to be ever greater. The backfill is a passive, artificial support method that performs a strength action in response to the deformation of the stope walls and allows the transmission of stresses, promoting the stability of the massif through the control of its decompression.

During the exploration processes, huge amounts of material are produced without any economic value, tailings, if not used for backfill, are deposited on the surface, representing a potential environmental threat.
Currently, the policies for implementing a “circular economy” aim to produce more, at a lower price, in an eco-efficient way, that is, to produce with less resources consumption and less waste generation, therefore less environmental impacts.

Aware of the importance of the theme, the mining industry is increasingly committed to reducing its ecological footprint.

One of its strategies implemented for many decades is the use of tailings, resulting from the processing of ores, as the main constituent of paste fill. Generally, supplementary materials are introduced in these mixtures, such as pozzolans and additives, in order to improve their strength properties.

Concomitantly, the development of the automotive or motorized market and the global economy has led to a huge increase in tire consumption (European Tyre & Rubber Manufacturers’ Association, 2015). One of the most worrying environmental problems worldwide is end-of-life tires, since they are made up of complex drainage rubbers (Pedro, 2011). In order to face this problem, different solutions have been implemented for their final destination, in order to prevent the abandonment and burning of these materials.

The most economical and environmentally advantageous solution for the management of these residues is their recycling (European Tyre & Rubber Manufacturers’ Association, 2009), namely by adding rubber from tires in some industrial products, such as asphalt pavements, mortars and concrete, thus improving their performance (Barbosa et al., 2013).

However, there are no known studies on the behaviour of mining backfill with the incorporation of rubber powder.

The aim of this dissertation was to study the strength properties and the deformability of these new materials.

1.1. Rubber

Tires are one of the solid wastes of most concern, since the development of the automotive, or motorized market, and the global economy has increased their use and accumulation. It is estimated that in the world 1500 million tires are manufactured annually and almost 1000 million are discarded, more than 50% being deposited in landfills or garbage without any treatment (Thomas et al., 2015).

As a way to counter the harmful use of landfills and tire burns, several methods of reuse and recycling have been proposed (Liu et al., 2016). The main solutions found were: energy production; pyrolysis; retreading; reuse; and recycling.

In recent years, industries are taking on the challenge of encompassing the sustainability of waste use and the production of more environmentally friendly raw materials, making waste recycling an integral part of waste management policies in most countries (Onuaguluchi & Panesar, 2014).

The use of recycled rubber reduces environmental pollution and saves natural raw materials, being a very economically advantageous solution (Raghavan et al., 1998; Son et al., 2011; Lv, 2015). The use of rubber particles can help in the production of materials with new characteristics, improving their performance (European Tyre & Rubber Manufacturers’ Association, 2009). According to Xue & Cao (2017) 21% of used tires are recycled for civil engineering applications, for additives in asphalt pavements (McQuillen et al., 1988; Svec & Veizer, 1996; Specht, 2004) and concrete (Eldin & Senouci, 1993; Topçu, 1995; Fedroff et al., 1996), with reference to potential uses for rubber-modified cement mortars (Raghavan, et al., 1998; Turatsinze et al., 2005; Uygunoglu & Topçu, 2010).

1.2. Mining Backfill

The excavation creates empty spaces that alter the state of virgin tension, that is, the tensions existing in the massif before any activity is carried out. This excavation leads to the redistribution of the state of tension and its decompression, with the possibility of gradual fracturing phenomena in the vicinity of the cavity. Thus, part of the energy stored in the massif is consumed, through deformation of the massif, keeping the rest stored in the ground.
Rockbursts translate into a more or less violent and sudden release of energy stored in the rock mass, causing fracturing (Brady & Brown, 2005) and, sometimes, the collapse of excavations, which is why they represent one of the main hazards induced by mining. The different intensities and frequencies of the occurrence of these events, depend on numerous factors, which can translate, in some cases, into simple fractures in the massif and in other cases cause disastrous effects, affecting the exploration fronts, equipment and/or workers (Marta, 2018).

In order to minimize the consequences resulting from the excavation processes, support and reinforcement methods are used. This leads to a reduction in the fracture zone and the risk of rockbursts, contributing to a decrease in their magnitude and frequency. Concomitantly, the use of support minimizes the deformation of the excavation profile and helps to prevent sagging, thus increasing the potential opening time of the excavation and improving regional and local stability, in order to guarantee safety (Potvin et al., 2005). The use of sustenance reduces the disturbed surrounding area and allows the application of several blasting methods, of which those that use backfill stand out.

The backfill as a support has the function of creating artificial pillars, ceilings and / or artificial work platforms, providing the exploration of a greater number of neighbouring fronts. In addition to these functions, the recovery of rejected material that would otherwise be stored abroad stands out. In this way, there is a rehabilitation costs reduction, as well as the time spent on it, ensuring continued exploration and the mine’s smooth operation, allowing new advances in safety stope fronts.

The mining backfill is an artificial support method, being one of the most effective support techniques developed, with the main function of ensuring long-term regional and local stability and limiting the excavations exposure (Bilro, 2018). Operationally, the backfill helps in limiting the convergence of the stope walls, in relieving tensions in areas of high concentration, in the dissipation of seismic energy (Brown, 2004), in reducing the importance of falling rock blocks and contributes for the minimization of subsidence and collapse of the terrain (Potvin et al., 2005).

There are several types of mining backfill. Its selection essentially depends on several variables, such as the function to be performed by it, the type of material available, the geomechanical characteristics of the embedding rock and the blasting method. The types of backfill most used in underground explorations are waste fill, hydraulic and paste fill.

2. Experimental Work

Mixtures were carried out in order to verify the influence of the increase of rubber powder in Uniaxial Compressive Strength, Tensile Strength and deformability in paste fill samples. In order to compare the parameters under study, three percentages of rubber were established (0%, 5% and 10% solids by weight).

Thus, specimens for Uniaxial Compressive Strength tests and determination of the deformability parameters and specimens for tensile tests for each percentage were performed, being tested after curing periods of 7 and 28 days.

In the mixing process there was a big change in the consistency of the generated paste, so it was interesting to have a preliminary study of the material’s rheology by determining the yield stress of the material with the Fall Cone Test.

It should be noted that all laboratory activities were carried out at the Geomechanics Laboratory of the Instituto Superior Técnico (GEOLAB), in Lisbon.

2.1. Preparation of paste fill mixture

In order to verify the influence only of the addition of recycled rubber it was defined that the mixtures would contain 20% water and 80% solids by weight, of which 2.5% are Portland cement (constant parameter in all samples) and the tailings varied with the percentage of defined rubber, being partly replaced by this, as explained in Figure 1.
The tailings used in the experimental campaign were obtained in the underground polymetallic solid sulfide mines of Neves-Corvo, in Portugal, and of Zinkgruvan, in Sweden. Both tailing samples were collected in the disc filters of the paste fill plants of each mine and transported inside barrels, which were sent to the Geomechanics Laboratory of the Instituto Superior Técnico (GEOLAB), in Lisbon, Portugal, where they were studied. Portland cement, provided by SOMINCOR, type CEM II / AL 42.5 R, from Loulé, is marketed and transported by CIMPOR - Cimentos de Portugal, SGPS, SA. It was decided to use tap water.

As for the recycled rubber, 100% vulcanized tire rubber was used, provided by BIOGOMA-SOCIEDADE RECICLAGEM DE PNEUS, Lda., With a density between 0.35 to 0.40 Kg / Dm³, with physical form of powder and nominal particle size between 0 to 0.6mm. The granulometric analysis of this material is shown in Table 1.

Table 1: Particle size analysis of recycled rubber. Adapted from Barros (2017).

<table>
<thead>
<tr>
<th>Sieve (mm)</th>
<th>Minimum portion of retained material (%)</th>
<th>Maximum portion of retained material (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>0.5</td>
<td>30</td>
<td>50</td>
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<tr>
<td>0.3</td>
<td>30</td>
<td>50</td>
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<td>Bottom</td>
<td>10</td>
<td>47</td>
</tr>
</tbody>
</table>

Initially, solid ingredients were inserted and mixed in the Hobart mixer and then water was added gradually. After placing all the components (Figure 2), the mixture was homogenized at rotation speed 1 for about 2 minutes.

In order to perform the curing process of the mixtures destined for the Uniaxial Compressive and Tensile Strength tests, the mixtures were introduced in PVC cylindrical molds, with a diameter of 46 mm and a height of 125 mm.

Finally, the test pieces were placed in a humid chamber at 28 °C in order to reproduce the conditions of the underground stopes, for 7 or 28 days (Figure 3).

2.2. Test Methods and Procedures

2.1.1. Uniaxial Compressive Strength and deformability parameters determination

To carry out these tests, the methodology recommended by the International Society for Rock Mechanics was followed (ISRM, 1979).

In order to read the extensions caused by the increase in compressive loads, strain gages were introduced, connected to copper conducting wires.

After the installation of the test pieces in the axial bearing system in the FORM + TEST press (Figure 4), three loading and unloading cycles were performed, registering the extensions caused with the load increase, in order to allow obtaining the Young's modulus and Poisson’s ratio, at the minimum possible speed. In the loading and unloading cycles, extensions were registered from each 0.05 to
0.05 kN with a maximum limit of 0.4 kN, in order to ensure that the material is in an elastic regime, and subsequently, they were taken to rupture, the extensions being registered for the same load intervals until the end of the test.

With these tests it was also possible to calculate the Strain Energy Storage and the Strain Energy Storage Index, to check the potential effect of rubber on risk mitigation for rockbursts:

- The Strain Energy Storage \( u \) (kJ m³) was calculated the area delimited by the curve of the tension-extension graph to the maximum point registered, according to ISRM (1979), in the cycles that were until rupture (Figure 5).

And yet, the Strain Energy Storage Index (Wet) (dimensionless), was calculated according to Zhou et al. (2018), using the second loading and unloading cycles of the uniaxial compression tests performed. Explained in the Figure 6, where \( W_{tot} \) represents the total elastic deformation energy observed area in the stress-extension graphs, \( W_{st} \) the accumulated elastic deformation energy calculated from the observed maximum stress point and \( W_{sp} \) the dissipated elastic deformation energy by the sample.

### 2.2.2. Test of Tensile Strength

To carry out these tests following the methodology recommended by the International Society for Rock Mechanics (ISRM, 1979) (Figure 7).

### 2.2.3. Fall Cone Test

To determine the yield stress of the material, with the objective of verifying the influence of the increase of rubber in the flow of the produced material, the Fall Cone Test was used according to the procedure used in Silva (2017), choosing by using a 30° flat cone with 12.21 g of resin (Figure 8).
3. Results and Data Analysis

At the end of Uniaxial Compressive Strength tests, Tensile Strength tests, Fall Cone Test tests, and also the determination of elasticity constants, Young's modulus and Poisson's ratio, and deformation quantifying parameters, such as Strain Energy Storage and the Strain Energy Storage Index, the results obtained were analyzed.

Throughout this chapter, the acquired laboratory results during the experimental campaign with the tailings used in the paste fill in the Neves-Corvo mine, in the Zinkgruvan mine, CIMPOR cement and Biogama rubber will be exposed.

In parallel, a comparative analysis is performed through the arithmetic means of the data obtained, in order to correlate the mechanical performance that the two types of paste fill present with the addition of rubber powder, at 7 and 28 days of curing.

3.1. Uniaxial Compressive Strength

The Figure's 9 graph shows the obtained values averages of the Uniaxial Compressive Strength tests, for the different contents of recycled rubber (0%, 5% and 10% solids by weight), with the tailings of the Neves-Corvo mine, at 7 (7 days_N) and 28 days (28 days_N), and the tailings of the Zinkgruvan mine, at 7 (7 days_Z) and 28 days (28 days_Z). Trend lines were inserted in order to facilitate the interpretation of the performance of the specimens taking into account the origin of the tailings and the curing time.

Regarding the variation of the Uniaxial Compressive Strength with the curing time, all the samples (Neves-Corvo and Zinkgruvan) without rubber showed a greater Uniaxial Compressive Strength at 28 days. This fact can be explained by the decrease in the liquid phase and cement hydration (setting), which promotes the occupation of empty spaces by expansive minerals, which increase the strength of the sample (MEND, 2006; Helsinki et al., 2011).

Through the trend lines shown in Figure's 9 graph, it is possible to observe, globally, a clear decrease in Uniaxial Compressive Strength with the rubber percentage increase.

The loss of strength with the rubber content increase, may be the result of several factors, such as the non-polar and hydrophobic nature of rubber (Topçu, 1995; Huang et al., 2004; Huang et al., 2013), the creation of a “free” water film that provides greater water evaporation and consequent retraction of the material in the curing process. Together, the hydrophilic nature of the paste also hinders the development of an internal bond between the materials and the ability of interfacial adhesion and the traction between the cement matrix are weakened (Huang et al., 2013). This leads to the formation of microstructural heterogeneities, mainly in the transition zone of the cement / rubber interface, since there is a complete adhesion between the siliceous aggregates and the cement matrix, instead of with rubber.
It is also important to consider that the rubber particles, due to their low density, easily rise to the surface of the test pieces, causing a heterogeneous stress distribution (Lijuan et al., 2014).

3.2. Tensile Strength

The Figure’s 10 graph shows the arithmetic mean of the test results, with the increment of recycled rubber particles (0%, 5% and 10% solids by weight), with the tailings of the Neves-Corvo mine and the mine of Zinkgruvan, 7 and 28 days of healing. Trend lines were also inserted in order to facilitate the behaviour interpretation of the test pieces.

However, by analysing the trend lines of the Tensile Strength results, it is possible to verify greater strength in the curing time of 28 days, both for the different materials and for the different percentages of rubber studied. This difference can also be explained by increasing the strength of the materials with the curing time.

As expected, Young’s modulus of the specimens increases the setting time of the paste fill. At 28 days there is an increase in the binding effect of cement and a reduction in the existing liquid phase, the test pieces have a more rigid behaviour, decreasing thus the ability to accommodate energy in the form of deformation before breaking.

As with Uniaxial Compressive Strength, in Zinkgruvan materials, the strength to 28 days is less than 7 days with the increase in the rubber content, which may be due to the granulometry and / or mineralogy of the material.

As shown in Figure 11, Young’s modulus decreases as the rubber percentage increases. This means that the material acquires a more flexible behaviour, with a greater capacity to accommodate and dissipate energy before the occurrence of permanent deformations (Eldin & Senouci, 1994; Khatib & Bayomy, 1999, Topçu, 1997).

The decrease in Young’s modulus can be easily explained by the fact that the rubber has a stiffness clearly lower than the portion of the paste fill material it replaces, and it is foreseeable that the modulus of elasticity will suffer an even greater reduction the greater the content of added rubber (Valadares, 2009).
3.3.2. Poisson's ratio

The Figure 12 graph shows the averages of the calculated Poisson's ratios, with the increment of recycled rubber particles (0%, 5% and 10%), for the tailings of both mines and for 7 and 28 curing days. Trend lines have been added.

As can be seen in Figure 12, at 28 days the samples have smaller Poisson's ratios, that is, they have less lateral deformation with uniaxial carriage, as observed through Young's modulus in 3.3.1.

However, with the Zinkgruvan material this parameter does not show a significant difference.

The Poisson's ratio increases with the increase in the percentage of rubber. The rubber has Poisson's ratio values close to 0.5 (Khaloo et al., 2008; Platzer et al., 2018). This scenario can be explained again based on the materials used in the mixture, since the rubber has higher Poisson's ratios than the paste fill. Since rubber replaces part of the rocky aggregates that make up these mixtures, it would be expected that this ratio would increase.

3.4. Strain Energy Storage

The Figure 13 shows the averages of the calculated Strain Energy Storage, with an increase in the rubber content (0%, 5% and 10% solids by weight), with the tailings of the Neves-Corvo mine and the mine. Zinkgruvan, at 7 and 28 days of healing. Trend lines were also inserted in order to facilitate the performance interpretation.

This parameter refers only to pre-peak energy, since the used equipment only allowed a maximum pre-tension analysis, so only the variation trends were commented.

However, there is also a noticeable increase in deformation energies for specimens with 28 days of curing, which means that there is an increase in the capacity of the paste fill to absorb energy, thus decreasing rockbursts.

3.5. Strain Energy Storage Index (Wet)

The Table 2 shows the average, maximum and minimum values and standard deviations of these indices for each rubber content in the studied curing time intervals.

Table 2: Average, maximum and minimum values of the Strain Energy Storage Index with the variation of the percentage of rubber in solids weight, in the different curing days, and their respective predisposition for the development of rockbursts.
This table also indicates the appetite for mixtures to undergo rockbursts according to the classifications of Neyman et al. (1972), Wang et al. (1998), Zhang & Fu (2008) and Zhou et al. (2017) that are based on the Strain Energy Storage Index.

Tailings from Neves-Corvo, with 0% rubber, show strong to medium appetite according to the classification considered. This appetite decreases with a rubber content increase. For tailings from Zinkgruvan with 0% rubber, no significant changes in the appetite of rockbursts are observed for the 7 days of cure, although a decrease for the 28 days of cure is observed.

In the Figure’s 14 graph, the calculated Strain Energy Storage Index arithmetic averages were represented, with the increment of recycled rubber particles (0%, 5% and 10%), with the tailings of both mines, 7 and 28 days. Trend lines were also inserted in order to facilitate the interpretation of the performance of the test pieces.

There is an increase in the Strain Energy Storage Index with the curing time, that is, the material has a greater appetite for rockbursts, which is in agreement with the parameters previously analysed.

Observing the variation of this parameter with the amount of rubber (Figure 14), it can be said that the Strain Energy Storage Index decreases, undoubtedly, with the increase in percentage of rubber. Thus, the material decreases its tendency to develop rockbursts.

This inference can be related to the deformability characteristics already mentioned in 3.3.1 and 3.3.2 Since rubber is an elastic material, samples with higher levels of rubber have a greater capacity to withstand deformations and to absorb and dissipate energy (Eldin & Senouci, 1994; Khatib & Bayomy, 1999; Khaloo et al., 2008), which will mean a decrease in the appetite for rockbursts. Thus, mixtures with a higher rubber content are good energy absorbers, consuming the increases in stored elastic energy resulting from the increase in excavations generated by mining activity.

3.6. Fall Cone Test

Approximately 24 fall cone tests (30 ° cone) are carried out for the material of both mines, in order to assess the influence of rubber addition on the paste fill flow through the pipes that lead to the interior of the excavation.

The Figure 15 (a) shows the mean cone penetration values and the Figure 15 (b) shows the variation in yield stress.

![Figure 14: Graph of the correlation between the values of the Strain Energy Storage Index in the different days, with the different contents of rubber studied.](image)

![Figure 15: Graph of the correlation between the cone's penetration depth (a) and the calculated yield stresses with the different contents of rubber studied.](image)

By observing Figure 15, it can be concluded that the greater the replacement of tailings by rubber, the greater the yield stress. The test pieces produced with the material from Zinkgruvan have higher yield stress.
4. Conclusion

This dissertation had, as main objective, the study of the paste fill's strength behaviour and deformability when with recycled rubber powder addition, aiming to contribute to the knowledge of the paste fill performance with the addition of these particles.

From the bibliographic research carried out, it can be concluded that there are no works developed on this topic, so this work is considered a relevant contribution.

The laboratory work concluded that the paste fill with the addition of rubber presents a lower performance regarding to its strength characteristics. The Uniaxial Compressive and Tensile Strength, globally, has a clear tendency to decrease with the increase in the rubber content, in accordance with other investigations carried out with concrete, mortar and other cement composites intended for the use of Civil Engineering works. This fact can be attributed to the heterogeneity caused by the non-polar and hydrophobic nature of rubber and hydrophilic paste. However, for 28 days of healing the Uniaxial Compressive and Tensile Strength increase, due to the occupation of the existing empty spaces by the minerals formed by the hydration of the cement.

Young's modulus decreases with the rubber content, while the Poisson's ratio shows an increase with the increase of the rubber percentage, showing values close to those presented by rubber, which is in line with other studies carried out on mixtures with rubber particles with concrete, mortar and other cement composites. These results show an increase in the deformability of the material.

The analysis of the Strain Energy Storage Index carried out using the pre-peak tension-extension curves, so the results obtained must meet this constraint. However, it was concluded that Strain Energy Storage is longer for the cure time of 28 days and for all rubber contents. The Strain Energy Storage Index, which shows a clear decrease with the increase of the rubber content, indicates that the mixtures have a greater capacity to withstand deformation and dissipate energy, therefore the appetite for the development of rockbursts decreases.

With regard to yield stress, there was an increase with the rubber content in the mixture, that is, the mixture offers more resistance to flow, impairing thus the distribution of the paste fill to the stopes.

As this is an innovative investigation, it is essential to continue this work, in order to obtain a further deepening of this data, allowing the study of these new materials and concluding on the practical feasibility of this type of solutions. Given that, in addition to rubber, add new characteristics to the filling and contribute to the circular economy of the mining industry, this proposal also presents itself as a possible solution for the use of these solid wastes that cause a profound environmental impact, thus reducing the global ecological footprint.

The study of tailings mixtures performance with the incorporation of different types of rubber, taking into account both size and granulometric distribution seems essential.

The behaviour observation of these mixtures with changes in the cement content and the amount of water seems equally important.

It is also evident the need for a study on the microstructure of paste fill with the addition of rubber, in order to know the rubber-matrix interaction.

Further research is recommended regarding the workability of these mixtures, in order to avoid any constraint in transportation through the distribution network from the plant to the stope.

And finally, to conclude on the feasibility of applying paste fill with recycled rubber, a cost analysis is essential, since there is a need to acquire the rubber and adapt the paste fill plants.

References
Barros, P. (2017). Ficha Técnica: Pó de Borracha Reciclada 0.0-0.6 mm. BIOGOMA-Sociedade Reciclagem de Pneus, Lda.;


European Tyre & Rubber Manufacturers’ Association (2009): Tyre Generic Exposure Scenario End of Life Tyre Guidance. Version 1.0;


derivation and experimental probing of a physical model. Granular Matter 20, pp. 81;