DUST PRODUCTION IN MINING. SUPPRESSION MEASURES IN QUARRY BLASTING
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Firma del Prof. Tutor: .........................................................

Fecha
Acknowledgements

I thank my Master’s Thesis Tutors. Ph.D Pablo Segarra, for having offered me the possibility to work with him on this project and to take part in all the aspects of it, and for all the knowledge that he transmitted to me; and Ph.D Patricia Pérez for her involvement and commitment, and for being not only a great teacher, but also a great companion.

I also want to convey my gratitude to the other components of the explosives department: José Ángel, Lina, Ricardo and Juan, who have always provided me with all the help I have requested, and to the laboratory staff: Emilio and Héctor, with whom I have shared many enriching moments during this project.

I am grateful to my friends from E.T.S.I de Minas y Energía, for their friendship, for the support we have supposed for each other, and for the good and bad moments we have spent here together.

And, of course, I sincerely thank my family, for all their support and affection. Especially my parents, Javier and Pilar, for providing me with the stability that I needed to develop myself as a person and as a professional, showing me always the values of humility, effort and responsibility.
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ABSTRACT

This work investigates the emission of dust in quarries within the project of "SLIM - Sustainable Low Impact Mining: solution for exploitation of small mineral deposits based on advanced rock blasting and environmental technologies” financed by the European Commission within the Horizon 2020 program. A bibliographic analysis of the specialized literature describes and analyses the state of the art in the production of dust in the different phases of the operation, as well as the existing methods for its mitigation. Then, the measurements taken in a previous project related to the measurement of dust generated in quarries are taken as a baseline. Furthermore, new solutions are proposed and analysed to reduce the emission of dust in the blasting using laboratory tests and in situ tests in two open-pit quarries. The efficiency of these solutions will be tested in a new campaign and compared with dust measurements made during a first campaign of blasts. These include occupational and non-occupational dust measurements.

RESUMEN

Este trabajo investiga la emisión de polvo en canteras dentro del proyecto de “SLIM- Sustainable Low Impact Mining: solution for exploitation of small mineral deposits based on advanced rock blasting and environmental technologies financiado por la Comisión Europea dentro del programa Horizonte 2020. A partir de un análisis bibliográfico de la literatura especializada se describe y analiza el estado del arte en la producción de polvo en las distintas fases de la operación, así como de los métodos existentes para su mitigación. A continuación, se toman como base las mediciones realizadas en un proyecto anterior relacionado con la medición de polvo generado en canteras. Además, se proponen y analizan nuevas soluciones para reducir la emisión de polvo en la voladura a partir de ensayos en laboratorio y de pruebas in situ en dos canteras a cielo abierto. La eficacia de estas soluciones se probará en una nueva campaña y se comparará con las mediciones de polvo realizadas durante la primera campaña de explosiones, las cuales incluyen mediciones de polvo ocupacional y no ocupacional.
MEMORY
1 OBJECTIVE AND SCOPE

The objective of this Master's Thesis is to find, design, test and evaluate effective solutions that involve a significant change in the production of dust in the blasting phase.

The first stage of this project has consisted of an intensive search of the existing bibliography about the problem of quarry dust. This has resulted in the specific delimitation of the concept of dust in this sector, the analysis of its properties and its effects on the human health and the environment. The most appropriate mathematical models to calculate the emission and transport of dust have been also chosen, and the existing control methods in the mining industry have been classified. The sources of dust generation have been analysed from a general view, and then a detailed dissection of each of the unit operations existing in the exploitation process has been made.

Next, baseline measurements of emission of dust obtained in a recent previous measurement campaign that aimed to evaluate the emission generated during the operation phase is presented. In this work, the techniques followed to measure the amount (mass and concentration) and type of occupational and non-occupational dust (TSP, PM10, and respirable crystalline silicon dioxide) suspended in the air by drilling, blasting and mucking activities in El Aljibe quarry are described. Additional data that affect dust emission and dispersion, such as weather, is also provided. From said report, the measuring devices that can be used for this purpose are extracted. In addition, this data will serve as a starting point to evaluate the effectiveness of future solutions presented in this aspect.

This work is a research project that focuses on the search for solutions for the mitigation of dust in the blasting phase. Although this operation is punctual throughout the exploitation of a quarry, with a shorter activity time than other operations, it generates a large amount of dust. To do this, different approaches have been followed throughout the investigation according to the new knowledge that was acquired. In each of the possible dust mitigation measures that have been developed, a selection process has been carried out from the technical and implementation point of view. The guidelines that mark this decision range from the characteristics of each of them to their behaviour during their application, and have been established in order to obtain the highest possible efficiency. These products have been initially tested and studied in laboratory, and later they have been tested qualitatively in the field.
All the tests carried out have focused on the evaluation of technical feasibility to implement the developed measures in the field. It was planned to include in this Master’s Thesis the quantitative field tests to evaluate the efficiency of the solutions but unforeseen delays make this no possible.

It should be noted that the qualitative tests represent a first phase of the investigation. In the following phase, the dust mitigation will be evaluated quantitatively with equipment similar to those used in the previous campaign contained in section 3 of this project.
2 STATE OF THE ART

2.1 Basic concepts

2.1.1 Context

The success and continuity of the mining activity is dictated not only by the economic benefits that drive the business, but also by its relationship with communities, operational safety and the efficient use of resources as scarce as water and energy. In this sense, future targets shall focus on finding and improving a sustainable and environmentally friendly mining. To achieve this, it is necessary to analyse all the stages of mines and quarries operations, in order to reduce the source of contamination, which can cause irreversible damage to the health of workers, equipment and the environment (Rappen, 1994).

The generation of dust is one of the environmental problems caused by the mining industry, and it is a current problem in mining operations and in almost all forms of mining. Mineral dust is generated through a range of processes starting from blasting through transportation, sample preparation, processing and handling. It puts at risk the health of workers and community, and at the same time, the performance and efficiency of mining operations are affected, generating losses in the material processed and in the consumed energy.

Clean air is essential to our health and to the environment. But since the Industrial Revolution, the quality of the air we breathe has deteriorated considerably, mainly as a result of human activities. Rising industrial and energy production, the burning of fossil fuels and biomass, as well as the dramatic rise in traffic on our roads all contribute to air pollution in our towns and cities. All this can lead to serious problems for both health and the environment.

Poor air quality continues to cause serious and avoidable problems. To counter this, the European Union has set itself the goal to achieve levels of air quality that do not give rise to significant negative impacts on, and risks to, human health and the environment. As a next step towards improving air quality, the European Commission adopted in 2013 a Clean Air Policy Package (EC, 2018), including a Clean Air Programme for Europe setting objectives for 2020 and 2030, and accompanying legislative measures.
2.1.2 Definition of dust

There are different definitions for the concept of ‘dust’ depending on the intended approach. Dust is a generic term used to describe fine particles that are suspended in the atmosphere. The Spanish Royal Academy defines an aerosol as a suspension of tiny particles of solids or liquids in the air or another gas (RAE, 2014). The term aerosol refers to both, the particles and the gas, in which the particles are suspended. When the RAE defines dust as solid particles that float in the air we speak of an aerosol, nevertheless the dust also rests on the objects and we continue speaking of dust and not of aerosols. Therefore, it may be suspended in a gas or perched on objects. A generic classification of solid aerosols is shown in Figure 1.

![Figure 1: Classification of solid aerosols.](image)

From a different perspective, the International Standardisation Organisation (ISO, 1995) and British Standard Institute (BSI, 1994), define an aerosol as small solid particles, conventionally below 75 µm in diameter, which settle out under their own weight but which may remain suspended in the air for some time. However, the definition that best fits the requirement of this report is those established in ‘Dust Control Handbook’, which defines dust as tiny solid particles created by disintegration and fracture of larger particles by crushing, grinding or impact; these small particles are dragged by air currents and, depending on their size, can be dangerous to the health of people (Cecala et al., 2012). The smaller particles of airborne dust can remain suspended in the air for hours and pose a greater risk to the respiratory system when inhaled. In general, the smaller the aerodynamic diameter of the inhaled dust particle, the more likely it is to deposit deeper in the respiratory tract. Particulate Matter (PM) is a complex mixture of, in some cases, extremely small solid particles mixed with liquid droplets that get into the air. This mixture is also known as particulate pollution.
2.1.3 Properties of dust

Particles associated with mining activities normally occur as a result of the alteration of fine particles derived from soil or rock. The dust can be mainly classified according to two properties: particle size and composition of the particles (Petavratzi et al. 2005). The behaviour and the particular characteristics of the rock, as well as the industrial processes that take place, are also of great importance.

- Particle size: The size of dust particles is a very important parameter since depends on the energy that supports them. For example, a strong wind, rock blasting, or the air induced by falling material, keep the dust in suspension and the resident time will be greater or less depending on the particle size. Smaller particles have more residence time in the atmosphere and tend to settle when the lift energy decreases or ceases. Particle size is generally described by the diameter of the particle (Figure 2). This is generally defined as the diameter of a sphere of density 1 g/cm³ that has the same terminal velocity in calm air than the particle in question regardless of other properties like shape or true density.

According to its aerodynamic diameter, PM can be divided into:

- Total Suspended Particle (TSP): Generated dust that it is entrained in the air. The maximum size depends on sampling and wind condition, and it is accepted that comprises particles smaller than 100 µm. Other sources establish the maximum size at smaller values of 50–75 µm (Petavratzi et al., 2005).
- PM10: Small solid particles of respirable dust whose aerodynamic diameter is equal to or smaller than 10 µm, formed mainly by inorganic compounds such as silicates and aluminates.
- PM2.5: Particles in suspension with an aerodynamic diameter less than 2.5 µm, called fine particles or fine fraction.

The smaller the size, in resume, the less external energy the particles will need to move, so they can remain suspended longer and can travel longer distances.
Composition: Differentiation can be made between the origins that will determine its final composition:

- Primary particles: discharged directly into the atmosphere from the source of emission. Within the primary particles, the mineral fraction stands out, originating in the natural emissions of the soils. The chemical and mineralogical composition of these particles varies from one region to another depending on the characteristics and composition of the soils. Generally, they are mainly constituted by calcite, quartz, dolomite, clays (especially kaolinite and illite), feldspar and lower amounts of sulphate calcium and iron oxides, among others. Mining activities such as drilling, blasting and hauling among other, where material is further fragmented are a primary source of this material.

- Secondary particles: they are originated from the emissions of their gaseous precursors. The transformation of gas into a particle can take place directly (homogeneous nucleation) or through the intervention of gas and/or liquid and/or solid phases (heterogeneous nucleation). In the secondary fraction the most relevant compounds are sulphates, nitrates and aerosols. Sulphates are formed through the oxidation processes of different natural sulphur gases, while natural secondary nitrates are formed as a consequence of the oxidation of nitrogen oxides (NOx).

Table 1 shows the properties of the coarse and the fine fractions. Mineral dust is typically less complex in its composition, consisting mainly of exposed soil or rock particles.
Smaller particles are composed of elements which are more toxic (such as heavy metals and organic compounds) than those that make up, in general, larger particles. Also, their size makes them lighter and therefore usually lingers longer in the air. This do not only prolongs its effects, but it facilitates their transport by the wind over long distances.

Table 1: Comparison of the basic properties of fine vs course PM.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Fine fraction (PM2.5)</th>
<th>Coarse fraction (PM10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Sulphate SO$_2$-$4$, nitrate NO$_3$, ammonium NH$_4$, hydrogen ion H+, elemental carbon C, organic compounds, PAH metals Pb, Cd, V, Ni, Cu, Zn, particle-bound water, biogenic organics.</td>
<td>Resuspended dust, soil and street dust, coal and oil fly ash, metal oxides of Si, Al, Mg, Ti, Fe, CaCO$_3$, NaCl, sea salt, pollen, mold spores, plant parts.</td>
</tr>
<tr>
<td>Sources</td>
<td>Combustion of coal, oil, gasoline, transformation products of NOx, SO$_2$, and organic including biogenic organics, high temperature processes, smelters, and steel mills.</td>
<td>Resuspension of soil tracked onto roads and streets, suspension from disturbed soils, resuspension of industrial dust, construction, coal and oil combustion, and ocean spray.</td>
</tr>
<tr>
<td>Lifetimes</td>
<td>Days to weeks</td>
<td>Minutes to hours</td>
</tr>
<tr>
<td>Travel distance (km)</td>
<td>100 to 1000</td>
<td>1 to 10</td>
</tr>
</tbody>
</table>

2.1.4 Impact of PM on health

Control of dust in spite of being necessary is almost uncontrollable in most of the processes, causing a number of problems for people, the work area and the environment where it is located (NIOSH, 2003). The particles can produce greater harmful effects depending on their composition, as the main diseases are related to asbestos and silica, in other cases the dust contains heavy metals susceptible to produce specific diseases such as lead (Figure 3). This happens especially when it is made up of dioxide of crystalline silica in the form of alpha-quart, cristobalite and tridymite, due to its carcinogenic nature. Particles less than 10 µm in diameter pose the greatest problems, because they are not retained by barriers in the nose, such as cilia and mucus, and they penetrate through the respiratory tract; the coarse fraction tends to lodge in the tracheobronchial tree, while the fine particles are settled in the bronchioles and the alveoli (Kim et al. 2015) and some may even get into the bloodstream.
Figure 3: Penetration of particles in the respiratory system.

Exposure of dust-related diseases depends on the composition and size of dust particles. The effects can be classified into respiratory and general (Petavratzi et al., 2005).

Respiratory effects:

- Pneumoconiosis: silicosis, asbestosis, pneumoconiosis of the miners of coal, siderosis, aluminosis, berylliosis, etc.
- Lung cancer: dust containing arsenic, chromate, nickel, asbestos, radioactive particles, etc.
- Nasal cancer: wood dust in furniture manufacturing and industries of footwear leather powder.
- Respiratory irritation: tracheitis, bronchitis, pneumonitis, emphysema and pulmonary oedema.
- Allergy: occupational asthma and allergic alveolitis, extrinsic (vegetable powders and certain metals).
- Byssinosis: lung disease by dust from cotton, flax or hemp.
- Respiratory infection: dusts containing fungi, viruses or bacteria.

General effects:

- Intoxication: manganese, lead, or cadmium can pass to blood once inhaled particles.
- Skin lesions: skin irritation and dermatosis (beryllium, arsenic, chromic acid, plastics, etc.)
- Conjunctivitis: contact with certain dusts.
Particulate pollution has health impacts even at very low concentrations. Indeed no threshold has been identified below which no damage to health is observed. Therefore, the objective in this field would be to achieve the lowest concentrations of PM possible. The effects of PM on health occur at levels of exposure currently being experienced by many people both in urban and rural areas and in developed and developing countries. Nevertheless exposures in many fast-developing cities today are often far higher than in developed cities of comparable size. In some cases, the quality of air is worst in the cities than in the surroundings of mines (Alappat et al., 2012).

Reducing average particulate matter concentrations could reduce air pollution-related deaths an important percentage. In the European Union, where PM concentrations in many cities do comply with legal guideline levels, it is estimated that average life expectancy is 8.6 months lower than it would otherwise be (WHO, 2016).

Currently, in the European Union the Directive 2008/50/EC is in force and, specifically, it has been transposed to the Spanish legislation by the Royal Decree 102/2011, of January 28, relative to the air quality improvement. The Standards UNE-EN 12341:2014 set the reference methods to the sampling and analysis of PM. The threshold values of the fractions PM10 and PM2.5 are shown in Table 2 and Table 3 respectively.

*Table 2: Threshold value of PM10 particles in environmental conditions for the protection of health (EC, 2008).*

<table>
<thead>
<tr>
<th>Averaging period</th>
<th>Limit value</th>
<th>Margin of tolerance</th>
<th>Date by which limit value is to be met</th>
</tr>
</thead>
<tbody>
<tr>
<td>One day</td>
<td>50 µg/m³, not to be exceeded more than 35 times a calendar year</td>
<td>50%</td>
<td>Already in force since 1 January 2005</td>
</tr>
<tr>
<td>Calendar year</td>
<td>40 µg/m³</td>
<td>20%</td>
<td>Already in force since 1 January 2005</td>
</tr>
</tbody>
</table>

*Table 3: Threshold value of PM2.5 particles in environmental conditions for the protection of health (EC, 2008).*

<table>
<thead>
<tr>
<th>Averaging period</th>
<th>Limit value</th>
<th>Margin of tolerance</th>
<th>Date by which limit value is to be met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calendar year</td>
<td>20 µg/m³</td>
<td>0%</td>
<td>1 January 2020</td>
</tr>
<tr>
<td>STAGE 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In Table 3, the threshold refers to Stage 2, which set the indicative limit value reviewed by the Commission in 2013 in the light of further information on health and environmental effects, technical feasibility and experience of the target value in Member States. Stage 1 had a limit value of 25 µg/m³ to be met on 1 January 2015 and a margin of tolerance of 20% on 11 June 2008, decreasing on the next January 1 and every 12 months thereafter by equal annual percentages to reach 0% by January 2015.

Numerous scientific studies have linked particle pollution exposure to a variety of problems that indirectly affect health. Some of these detected problems can be:

**Operational:**
- Reduction in the useful life of equipment.
- Risk of corrosion of equipment.
- Rapid wear of pulleys and bearings that generate an increase in repairs and maintenance.
- Decreased visibility.

**Others:**
- Contamination of watercourses or damage of flora and fauna in adjacent areas.
- Negatively affects the image in the local community.
- Modification of natural albedo, which promotes global warming.

**2.2 Prediction models**

The calculation models are scientific models that use some mathematical formula and allow studying the behaviour of complex systems, which are difficult to observe in reality.

The main forces influencing emitted dust particles are gravitational settlement, Brownian motion, eddy diffusion and agglomeration. Other mechanisms are also important, like the impaction, the re-entrainment, and the deposition (Petavrazti et al., 2005). However, because of the characteristics of the material, the calculation models that better conform to the purpose of this study are Law of Stokes and the induced airflow.

**2.2.1 Stokes´s law**

Stokes’s Law is a mathematical equation that expresses the settling velocities of small spherical particles in a fluid medium. The law, first set forth by the British scientist Sir George G. Stokes in
1851, is derived by consideration of the forces acting on a particular particle as it sinks through a liquid column under the influence of gravity (Figure 4).

This law finds application in several areas, and it is particularly important in this study with regard to the settling of sediment. It allows the sedimentation rate of the particles to be predicted, which will depend mainly on the speed of the ventilation air. For example, in underground mining the residence time of the particles in the environment is an indication of the time of exposure to dust to which the workers are located within a specific operation in a confined space. Besides, it is also useful for the design of dust settlers.

![Figure 4: Force balance on a single particle (Native Dynamics, 2013).](image)

The force acting in resistance to the fall is equal to

\[ F = 6 \cdot \pi \cdot r \cdot \mu_F \cdot v \]  

(1)

where: \( r \) is the radius of the sphere; \( \mu_F \) is the viscosity of the liquid and \( v \) is the velocity of fall.
The force acting downwards is equal to

\[ F = \frac{4}{3} \pi \cdot r^3 \cdot (\rho_f - \rho_s) \cdot g \]  \hspace{1cm} (2)

where: \( \rho_f \) is the density of the sphere; \( \rho_s \) is the density of the liquid and \( g \) is the gravitational constant.

It has been shown that particles that fall freely in a fluid medium reach a constant speed called the terminal velocity, for which the resistance offered by the fluid on the particle is balanced by the gravitational attraction exerted on it. The movement of spherical particles in a viscous medium such as air is governed by the Stokes’s Law (Batchelor, 1967). In this way, at a constant velocity of fall the upwards and downwards forces are in balance.

Equating the two expressions Equation (1) and Equation (2) and solving for \( v \) the terminal velocity \( (v_t) \) can be obtained as:

\[ v_t = \frac{2}{9} \cdot \left( \rho_f - \rho_s \right) \cdot g \cdot \frac{r^2}{\mu_f} \]  \hspace{1cm} (3)

\( v_t \) gives the relationship between retarding force and velocity. When viscous force plus buoyant force becomes equal to force due to gravity, the net force becomes zero. If \( \rho_f > \rho_s \), the body falls downwards, while if \( \rho_f < \rho_s \), the body moves upwards with the constant velocity.

The limit velocity of the particle is related to the force of friction experienced by spherical objects moving inside a viscous fluid in a laminar regime of low Reynolds number. This is why the model is valid for the movement of small spherical particles moving at low speeds, so no turbulent wake in its passage through the fluid is formed.

Figure 5 shows a velocity-time graph for an object falling through a fluid (e.g. air, water, oil), where different behaviours can be observed as a function of time. In particular:

- Between points A and B

The object accelerates at first because of the force of gravity. Its speed increases. The resultant force acts downwards because frictional force acting against it is less than the weight of the object.
Between points B and C

The object is still accelerating but its acceleration decreases as time goes by. Its speed still increases but by a smaller amount as time goes by. The resultant force still acts downwards but is decreasing. This is because frictional force acting against it is increasing as the speed increases, but is still less than the weight of the object.

Between points C and D

The object is not accelerating any more. It has reached its terminal velocity and is falling at a steady speed. The resultant force is zero because the frictional force acting against it is now the same as the weight of the object. This means that the object does not stop falling (unless it has hit the ground).

Figure 5: Velocity-time graph for an object falling through a fluid (BBC Science, 2014).

As an example, the time of falling of particles for different diameters has been calculated (Table 4). Equation 3 has been used, and the following data have been taken:

Height of fall: 1 m; Dust density: 1,300 kg/m³; Fluid viscosity (air): 1.71×10⁻⁵ kg/(m s) and Fluid density (air): 1.3 kg/m³.
Table 4: Fall time of the particles.

<table>
<thead>
<tr>
<th>Diameter of the particle (µm)</th>
<th>Fall time</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.4 seconds</td>
</tr>
<tr>
<td>10</td>
<td>4 minutes</td>
</tr>
<tr>
<td>1</td>
<td>6.7 hours</td>
</tr>
</tbody>
</table>

When the particles are less than 0.1 µm, they adopt the Brownian motion, which relates the movement of the dust particles with the gas particles with which they interact. The movement occurs because the dispersed particles continuously collide with the dispersion medium. Due to this collision, the molecules move randomly, so the movement will not be in a straight line. This phenomenon was discovered for the first time by the botanist Robert Brown in 1827.

![Figure 6: Brownian motion of particles in a gas.](image)

Figure 6 is a simulation of the Brownian motion of four big particles (dust particles) that collide with a large set of smaller particles of a gas (molecules of air) which move with different velocities in different random directions.

The mixture of the movement of gases and particles is called Diffusion, in which the gravitational effects no longer matter.

### 2.2.2 Induced airflow

The induction of air is based on the concept that the fine material that falls through the air imparts an impulse to the surrounding air. Due to this energy transfer, a stream of air always travels with the falling material (Figure 7). A good example of the application is in the design of dust collection hoods: a crushed material that falls from a conveyor belt to another will drag air which will fill the
plant with dust emissions. This is the reason for assessing the induced airflow to be withdrawn through an extraction hood. The following air induction equation can be used to estimate exhaust volumes for hoods (Cecala et al., 2012):

\[ Q = 10 \times A_u \sqrt[3]{\frac{R S^2}{D}} \]  

(4)

where: \( Q \) is the flow of induced air (cubic feet per minute); \( A_u \) is the dumping surface area of the material (square feet); \( R \) is the flow of material (ton per hour); \( S \) is the height of the fall of the material (feet) and \( D \) is the average size of material (feet).

The most important parameter in Equation 4 is the material dumping surface area, the opening through which the induction of air occurs. The more adjusted feed is, the smaller the opening area is, and the smaller is the flow of induced air. Also a low height of fall is decisive in the estimation of induced air. When designing a material circuit it is important to keep the surface area values (\( A_u \)) and height (\( S \)) as low as possible to avoid the generation of dust and to reduce the amount of ventilation air.

The material flow (\( R \)) and material size (\( D \)) parameters also affect the induced air flow rate, but these parameters are a constant in the extraction or processing operation and cannot be altered (Cecala et al., 2012).

Figure 7: Induction of air produced by the fall of material from the conveyor belt (NIOSH, 2012).
2.3 Sources of dust generation and control methods in the mining industry

2.3.1 Origin and generation of dust

In mining industry, dust is generated in different areas and due to different causes. It is produced when a bulk solid material is separated and a certain amount of the fine material is transported by air while the rest is deposited in another part. It may also be produced through mechanical breakdown processes or by wind erosion on roads or materials stored in air.

The atmospheric environment in the mining industry is subject to a heavy load of pollution produced by the release or exposure of fine particles in the different stages of the mining and processing cycle. There is not an exact method to determine the amount of dust generated in the different unit processes, since this is site dependent. There are many external and non-controllable factors, including for example the following:

- The dustiness of the material or facility of a material to emit dust during handling, transporting and processing. To evaluate the dustiness of a material, dustiness indices are determined. They are calculated as the mass of the sampled dust divided by the total mass of the tested material (Schneider & Hjemsted, 1996). The dustiness tests are of three main categories (BOHS, 1985): single drop tests, where material is falling through the air into an enclosed chamber; fluidisation tests, where air is passing through the material in a vertical tube; rotating drum tests, where the material is falling through the air several times in a horizontal drum.

- The physical-geographical and climatic conditions are decisive to generate some model of dust control. For example, areas of humid environments and greater water supply are favourable as it decreases the generation of dust. On the other hand, dry areas with high wind regimes need greater control of the roads by high generation of dust.

- Wind regime existing in the area, which will depend on the topography of the place. It is necessary to know the wind direction in the location of the facility and plant.

Table 5 shows the sources of mineral dust in mines and quarries. It also ranks them as primary and secondary source. Finally, the overall contributions to total site dust are also shown.
Table 5: Dust sources in mineral sites (Petavratzi et al., 2005).

<table>
<thead>
<tr>
<th>Operation and equipment</th>
<th>Emission mechanism</th>
<th>Primary source</th>
<th>Secondary source</th>
<th>Relative potential contribution to total site dust levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling and blasting</td>
<td>Air flush from drilling and from force of blast</td>
<td>+</td>
<td>-</td>
<td>Small</td>
</tr>
<tr>
<td>Loading and dumping</td>
<td>Dropping material from height</td>
<td>-</td>
<td>+</td>
<td>Moderate</td>
</tr>
<tr>
<td>Draglines</td>
<td>Dropping material from heights</td>
<td>-</td>
<td>+</td>
<td>Large</td>
</tr>
<tr>
<td>Crushing and preparation</td>
<td>Impact, abrasion and dropping from heights</td>
<td>+</td>
<td>-</td>
<td>Large</td>
</tr>
<tr>
<td>Conveyors</td>
<td>Dropping from heights</td>
<td>0</td>
<td>-</td>
<td>Small</td>
</tr>
<tr>
<td>Haulage roads</td>
<td>Raised by tyres, exhaust and cooling fans</td>
<td>0</td>
<td>+</td>
<td>Large</td>
</tr>
<tr>
<td>Storage piles</td>
<td>Wind blow, high wind speeds</td>
<td>0</td>
<td>-</td>
<td>Small</td>
</tr>
</tbody>
</table>

(+) Signifies a major source, (-) signifies a minor source, (0) signifies a negligible source.

The composition, toxicity level and typical size of the emitted dust have a strong correlation with the source of emission. In this sense, the particulate material of the mining works can be divided into three groups (Higueras & Oyarzun, 2003).
- Mineral dust. Coming from mining operations as a result of abrasion or rock crushing of mining processes. Activities such as drilling, blasting, handling, hauling and crushing are some of the emission sources. Its composition depends on the properties of the rock that are mined. They usually make up the coarse particulate matter called PM10.

- Rolling dust. The sources are in the mining roads, affected by the rolling of vehicles of high tonnage and the action of the wind. They contribute mainly to emissions of PM10, as well as coarser fractions of dust. One of its main components is silica, due to its abundance on earth. Clays such as kaolinite and feldspar are common too, due to their fine size. Rolling dust is one of the components of fugitive dust, or dust derived from not easily defined sources.

- Ashes. Coming from pyro metallurgical and combustion processes used in mining that give rise to ashes. These represent the main source of PM2.5 within the mining activities. The chemical components found in this group vary and may have high levels of toxicity. Some of the components in this group are sulphate, metalloids (As and Sb), acids and volatile organic compounds. Then, many of these components can participate in chemical reactions with the environment and produce new pollutants known as secondary species.

### 2.3.2 Sources of PM10

The main sources of pollutants can be classified, according to the type of source, as fixed, mobile and fugitives. Fixed sources correspond to industrial processes such as copper smelters, which is an important source of material PM2.5 and other pollutants such as NOx and SO\textsubscript{2}. Mobile sources correspond to different types of transport. Finally, fugitive sources consist of emissions not released through a vent or stack. They are produced by not easily defined sources or from more than one source, mainly material stockpiles, unpaved roads and base ground, and their emission rate depends strongly on meteorological parameters such as wind speed, humidity and rainfall. To analyse the dust emissions in the environment of the mine, a physical and chemical estimation of dust is necessary. The most important data are the concentration of dust in the environment, the size distribution and the chemical composition.

The sources of emission of particulate material in the mining activity are multiple. In several mining projects, five main groups are recognised (referred to PM10): mineral exploitation, transport, unloading, processing plant and wind erosion. Exploitation includes blasting, drilling and mucking. The transport of ore considers the transport of material, supplies and people, and it is represented by the lift of dust from the surface and its suspension in the air. For the processing plant, the generation of suspension dust is primarily associated with the primary crushing stage, although the sieving
stages, secondary or even the tertiary crushing are also other sources. Wind erosion considers dust emissions produced by wind action, on dumps, tailings deposits, stockpiles, leach pads and conveyor belts.

Among the mentioned sources of emission, those that produce a greater total amount of dust are the production and the transport activities. This is because they are continuous activities, which are carried out during the entire life of the mine. On the other hand, although the generation of total dust is lower than in the others activities because it is a specific one with a short period of activity, the blasting phase represents a very important emission source, which produces very high amounts of dust in very short times. That is, it has a high emission rate.

The existing methods of dust control in all mining operations are presented below.

2.4 Control methods

The most common procedures for obtaining dust samples are: filtration, sedimentation, centrifugation, electrostatic precipitation, bubbling, impact, light scattering (direct reading) and beta-ray attenuation. The sampling instruments can be classified into two main groups:

- Collecting instruments: They collect a volume of air where the dust particles are presented. Dust concentration is determined by particles counting methods or by gravimetric method.
- Direct reading instruments: When the dust sample arrives to the instrument, they use beta-ray attenuation, electrostatic precipitation or light scattering to assess the dust concentration.

2.4.1 Emission estimation methods

The concept of atmospheric emission is defined as the direct or indirect discharge to the atmosphere of gases or particles through a chimney, duct or point of discharge. Meanwhile, an emission source is any activity, process and operation, mobile or stationary element that, independent of its field of application, produces or may produce emissions. The methods of control are not always effective and there may be problems of propagation in the air of particulate material to sectors of the population or high traffic of people. Accordingly, it is very important for the mining industry to have tools to carry out emission inventories and carry out transport modelling to identify pollution levels by PM10 in the air. An inventory is a set of data on emissions of air pollutants according to the source, type and amount of pollutants emitted in a geographical area and in a certain time interval. The inventories of emissions are the starting point for the implementation, evaluation and
adjustment of programs and strategies for prevention, minimisation and control to improve air quality.

For the construction of the emissions inventory there are different methodologies depending on the cost that is willing to incur and the reliability of the results that it requires. Figure 8 shows the different methodologies for estimating emissions.

![Figure 8: Methodologies for estimating emissions according to the level of reliability and cost (INECC-SEMARNAT, 2005).](image)

The most reliable, but most costly, estimation is the direct measurement in field of the emissions from each polluting source (direct measurement). The next option, following a decreasing order of cost and reliability is to use an emission model. This corresponds to calculation systems developed to estimate the pollutants emitted into the atmosphere by the various sources for a given period and geographic area. The models vary in base of their complexity and the resources used. If there is sufficient information about the relationship between the emission level and environmental variables for the sources analysed, the use of an emission model may be recommended. However, the reliability of the model is subject to the quality of the input data, so even though the necessary resources are present to make the model, this may not be the best option. The mass balance technique is used to estimate emissions considering that the mass of the pollutant is equal to the difference between the inputs and outputs of the process.
The most used method to estimate total emissions corresponds to the emission factors (indirect method), which consists of calculating the emission according to the activity levels of each source and its associated emission factor (mainly expressed in weight per unit of activity). The emission factor is a simplification for a complex problem, estimating emissions easily and fairly accurately.

- **Emission factors**

An emission factor \((EF)\) is a representative value that relates the amount of pollutant emitted to the atmosphere with the activity generated by this pollutant. These factors are expressed as the weight of the pollutant divided by a unit of weight, volume, distance, or the duration of the pollutant emission activity.

- **Activity Level**

The activity level \((AL)\) represents the degree of use of the source within the analysis period. The important thing is that the expression is in accordance with the emission factor that is used to obtain the amount of pollutant emitted by the source within the period. Like the emission factors, the level of activity of a source varies over time.

- **Efficiency of reduction of emissions**

The efficiency of abatement or control \((EA)\) represents the reduction of emissions before releasing it to the atmosphere, which can be achieved through a team or some process or activity that seeks to reduce emissions.

- **Calculation of emissions**

The general methodology used to estimate atmospheric emissions is as follows AP-42 (EPA, 1998; EPA, 2006):

\[
E = EF \cdot AN \cdot \left(1 - \frac{EA}{100}\right) \tag{5}
\]

where: \(E\) is the total emission of the source of a certain period; \(EF\) is the emission factor; \(AL\) is the activity level and \(EA\) is the abatement efficiency or emission reduction.
Mining emission factors

The mining activities and processes contemplated for the emissions inventory are those found in open pit mining, which generate fugitive emissions to the atmosphere. The emission factors are based mainly on the AP-42.

- **Drilling**

  The drilling emission factor is based on Chapter 11.9 (Mineral Products Industry) of the AP-42 and the Australian Emissions Manual for the Mining Industry (Version 3.1, Annex A, Chapter 1.1.8), which is shown below:

  \[
  EF = 0.31 \left(\frac{kg \ PM_{10}}{Drilling}\right)
  \]

  The factor 0.31 corresponds with a drilling hole with a length of 15 m (production drilling). It should be noted that this value does not depend on other operational parameters.

- **Blasting**

  The emission factor associated with the blasting process comes from chapter 11.9 of the AP-42 (Mineral Products Industry) based on tests conducted in coal mining (EPA, 1998) which is shown below:

  \[
  EF = k \cdot 0.00022 \cdot A^{1.5} \left(\frac{kg \ PM_{10}}{Blasting}\right)
  \]

  The factor depends on the area visualised in the plan that includes the blast carried out in the open air in square meters \(A\) and the aerodynamic coefficient \(k\) for PM10 with value \(k\) equal to 0.52 for this emission factor. It should be noted here that the U.S. EPA determined that this estimator should only be used for one direction. The most reliable emission factors for particulate emissions should be based on specific sites, field tests to determine the amount of particulate material generated from blasting (EPA, 1998).

- **Dumping of material**

  The emission factor for the dumping of material, either when loading equipment loads the truck and unloading when the truck lifts its hopper and drops the material in some sector destined for said
activity, is based on chapter 13.2.4 of AP-42 (Miscellaneous sources), which has the following expression:

\[ EF = k \cdot 0.0016 \cdot \left( \frac{U}{72} \right)^{1.3} \left( \frac{m}{7} \right)^{1.4} \left( \frac{kg\ PM10}{Loaded\ tons} \right) \]  

(8)

This expression is based on the wind speed \((U)\) at the place of loading or unloading of material in m/s, on the percentage of moisture of the material \((m)\) and the aerodynamic coefficient \((k)\) for PM10 with value of \(k = 0.35\). This factor is a function of the tonnage loaded in the hopper or unloaded from the high-tonnage truck in different destinations.

- **Transportation of material (truck transit)**

For unpaved roads, emissions of Total Suspended Particulate (TSP), PM10 and PM2.5 can be estimated from an emission factor \((EF)\) through Equation 9 (EPA, 2006). The inputs needed to determine the emission factor are the silt content on the surface \((s)\) in \(%\), the weight of the vehicle \((w)\) in tons, the days of the year with rainfall > 0.25 mm \((P)\) and the efficiency of the dust suppression programme \((C)\) in \(%\).

\[ EF = k \times \left( \frac{s}{12} \right)^{a} \times \left( \frac{w}{2.72} \right)^{b} \times \left( \frac{365-P}{365} \right) \times \left( \frac{100-C}{100} \right) \left[ \frac{Kg}{Km} \right] \]  

(9)

The constants \(k, a\) and \(b\) are different for the cases PM2.5, PM10 and Total Suspended Particulate (TSP). In the case of PM10 the constants are \(k = 0.42, a = 0.9\) and \(b = 0.45\) (EPA, 2006).

On the other hand, the parameters \(S\) and \(P\) have a default value when there is no information about it and they are 8.3 and 105 respectively (EPA, 2006).

- **Trituration**

Different mineral processing equipment generates different amounts of dust emissions. The emission factor extracted from chapter 11 of AP-42 (Processing of metallic minerals) which has the following expression:

\[ EF = 0.02 \left( \frac{kg\ PM10}{Processed\ ton\ in\ crushing} \right) \]  

(10)
This factor does not depend on other operational parameters and corresponds to primary crushers. Relative dust emission ratio rates (the baseline is the emission rate of the primary crusher) for the common ore processing equipment are presented in Table 6.

Table 6: Relative emission ratio of crushers (NIOSH, 2012).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Relative emission ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Crusher</td>
<td>1</td>
</tr>
<tr>
<td>Secondary Crusher</td>
<td>Without data, the tertiary crushing rate would be an upper limit</td>
</tr>
<tr>
<td>Tertiary Crusher (Dry)</td>
<td>51</td>
</tr>
<tr>
<td>Tertiary Crusher (Wet)</td>
<td>2</td>
</tr>
<tr>
<td>Screening (Dry)</td>
<td>214</td>
</tr>
<tr>
<td>Screening (Wet)</td>
<td>12</td>
</tr>
</tbody>
</table>

Wind erosion

Emissions of dust in stockpiles will depend exclusively on characteristics and properties of the material and external conditions such as humidity percentage, mass flow and material segregation. They are considered fugitive sources and are affected by wind action.

To calculate the emission factor for wind erosion, a methodology proposed by the U.S. EPA is used. It requires the area exposed in square meters (A), the friction threshold speed in m/s (\(u_f\)) and the fastest mile of anemometer in m/s (\(u_z\)) that is obtained from meteorological records, of which they must also be corrected to the height of 10 meters by means of the following expression:

\[
u_{10} = u_z \cdot \frac{\ln(\frac{10}{0.005})}{\ln(\frac{z}{0.005})}
\]  

(11)

Where \(z\) is the height of the anemometer of the real measurement. In addition, the type of surface must be taken into account to determine the friction velocity of said surface. Once the fastest miles
have been obtained, they should be transformed into equivalent friction speeds using the following formula:

\[ u^* = 0.053 \cdot u_{10} \]  

(12)

With the above values, the erosion potential \( (Pi) \) or the emission factor in the same words is estimated as expressed in grams of PM10 emitted per square metre for each disturbance period using the following equation:

\[ Pi = \left( 58 \cdot (u^* - u_t)^2 + 25 \cdot (u^* - u_t) \right) \]  

(13)

When \( u^* > u_t \). For the annual calculation of emission by wind erosion measured day by day, it is calculated by means of the following equation:

\[ EF = k \cdot A \cdot \sum_{i=1}^{N} Pi \left( \frac{k g \text{PM10}}{day} \right) \]  

(14)

2.4.2 Classification of control methods

The strategies and methods of dust control can be summarised in Table 7. The strategies are listed from the most desirable (Prevention) to the least desirable (Dilution). The cost and efficiency of these methods are also assessed.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Methods</th>
<th>Cost</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention</td>
<td>Addition of water</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Modify the operation or practices improving</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal</td>
<td>Dust collectors</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Suppression</td>
<td>Wet sprays</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deliquescent chemical products</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water curtains</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>Closed cabins</td>
<td>Medium</td>
<td>Medium – High</td>
</tr>
<tr>
<td></td>
<td>Air curtains</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Ventilation by local extraction</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Blasting out of shift</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Control of personnel location</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Dilution</td>
<td>Main ventilation streams</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local ventilation dilution</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>
For control and dust mitigation, the suppression of matter particulate in wet and dry conditions is differentiated. The decision on the technique to be used depends on the specifications of the problem, the subsequent stages and the conditions of the source of the emission (Cecala et al., 2012). In terms of costs and performance, each system has its advantages as Table 8 shows.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Dry systems</th>
<th>Wet systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of installation and use</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Probability of Failure</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

When addressing the problem, it must take into account the proximity to personnel circulation; wind weather conditions (magnitude and direction) and humidity; nearby communities; mineralogy and mining methods.

2.4.2.1 Dry systems

Dry dust collection systems are designed within a control volume, confining the point of emission of particulate material. Dust is deposited at the points of the operation and then separated from the column of air from which it comes, by electrostatic precipitation or using filters. Due to their structure, they are large and must adapt to the system or operation. They are used mainly in transfer points, crushing zones and earth moving areas where manipulation conditions and the subsequent stages of the material make wet control difficult. It can have a high cost of installation, but it turns out to be effective. Similarly, there are other applications to control pollution, such as placing covers and hermetic closures in the emission centres. In the machines, dust extractors capable of reducing the exposure of personnel are also a solution.

Local extraction system

Local exhaust ventilation systems operate on the principle of capturing a pollutant near its source. The current emphasis on the control of air pollution emphasises the need for efficient air cleaning devices in industrial ventilation systems, the lowest flow rates of the local exhaust system result in lower costs for air cleaning devices. The local exhaust systems are composed of up to four basic elements: the exhaust hood, the duct system (including the extraction pipe and the recirculation
duct), the air cleaning device and the exhaust fan. The purpose of the hood is to collect the pollutant generated in a stream of air directed towards the hood. A duct system must then transport the contaminated air to the cleaning device. In the filter, the contaminant is removed from the air stream and the fan must overcome all losses due to friction, bell inlets and accessories (Figure 9).

The ventilation system by extraction is a concept applied not only locally but more broadly in larger sectors depending on the source of pollution. The configuration of the hood, the ducts and the cleaning systems are varied, it is important to differentiate between the dust capture methods (extraction hood) and the air filtering methods, such as sedimentation and shock chambers.

![Diagram of a local ventilation system](image)

**Figure 9: Graphic description of the basic elements of a local ventilation system. (NIOSH, 2012).**

2.4.2.1 Wet systems

In humid conditions the particulate material can be addressed when it is not yet suspended in the air, or when it is already dispersed. In the first case of a preventive nature, water sprinklers are used often combined with chemical reagents called ‘dust suppressors’ to agglomerate the particles and stabilise the conditions of the solid material prior to the particle suspension. On the other hand, when the particles have already been suspended in the air, sprinklers can be used, capable of colliding dust particles with water droplets, so they have greater weight and they settling more easily. The sprinklers are usually installed in transfer points, emptying hoppers and belt travel. Obstruction of sprinkler nozzles or their detachment may occur, losing control of the dust dispersion. The key
points for an effective dust control by spraying a wet agent are the correct selection and application of moisture, choosing the spray model, the location and type of nozzle, and the control of the size of the drops. Besides, optimal operations require of maintenance and periodic cleaning. Many times, the location of the sprinklers and the need to stop their operation become into a problem.

*Forms of application humid methods*

- **Prevention**: The material is wetted with direct pulverisation of the mineral to prevent that dust reaches the air.
- **Dust suppressant**: It consists of precipitating the dust presented in the environment by spraying the dust cloud and causing the particles to agglomerate and fall from the air.

*Principles of humid spray systems*

To use wet sprays effectively, it must be remembered that each type of mineral and point of application is a unique situation and should be evaluated separately to achieve an optimal design. For example, wet sprays cannot be used with all minerals, especially those that have higher concentrations of clay or slate. These minerals tend to block the screens, even at low percentages of humidity. In addition, water cannot be used at any time throughout the year in climates with low temperatures that will cause freeze water.

- **Water application**

  When water is used to control dust, it only has a limited residual effect due to evaporation, and must be reapplied at several points throughout the process to remain effective. Excessive application of the amount of moisture can be a problem in all operations and can affect the equipment, as well as the overall process and transportability of the final product if it is shipped in bulk. In most cases, an appropriately designed spray system using finely atomised water atomisers will not exceed the moisture application at the 0.1% (USBM, 1987). However, systems that address prevention in larger areas with aerosols of larger drops can add to the process up to 1.5% moisture.

- **Chemical additives**

  In dust control systems with sprinklers the use of binder substances involves an increase in the effectiveness of the method. This solution decreases the surface tension of the water, moistening a larger contact surface. It allows agglomerating a greater percentage of PM10 in suspension which
adheres to the solution particles settling them on the ore. The solution is applied in the form of foam under pressure doubling the volume of water. On the other hand, the use of surfactants increases the rate at which droplets can wet or coat powder particles; therefore, less moisture is used to produce the same effects as typical water applications (Swinerman et al., 2002). The effectiveness of chemical additives depends on the type of wetting agent: hydrophobic nature of the mineral particles, particle size of dust, concentration of dust, pH of water and minerals present in the water used (Rocha, 2005).

- Atomisation methods

The atomisation is the process of generation of drops by forcing the liquid through a nozzle that is achieved by hydraulic atomisation or with compressed air (Cecala et al., 2012). There are two main types:

  - Hydraulic or airless atomisation

  It controls the size of the drop by forcing the liquid through a known orifice diameter at a specific pressure. This method uses highly liquid pressures and produces drops of relatively small to medium size in hollow cone spray patterns, full cones or evenly distributed cones. Hydraulic fine spray nozzles are preferred in most areas because operating costs are lower since no compressed air is required.

  - Atomisation with compressed air

  It controls the size of the drop by forcing the liquid through a hole at lower pressures than the hydraulic atomisation method, using compressed air to break the liquid into small drops. This method produces very small drops and uniform distribution in a variety of spray patterns. However, it is more complex and expensive because it requires compressed air. In most cases, air atomisation nozzles are effective in places where dust particles are extremely small and nozzles can be located very close to the source of dust, although some applications will require large capacity air atomisation nozzles to reach long distances. Again, there are two main types:

    - Nozzle types and spray patterns

Spray nozzles are classified by the atomisation method, and by the spray patterns that they produce. The most commonly used spray nozzle produces a complete cone, hollow cone or flat fan patterns.
- Air atomisation nozzles

They inject compressed air into the liquid stream to achieve the high pressure spray of the mixture. Figure 10 shows the two ways of mixing, internal and external:

- With an internal mixing nozzle, the atomising air pressure acts against the pressure of the liquid to provide additional control of the liquid flow rate, producing round spray patterns.

- With an external mixing nozzle, the atomising air pressure does not affect the liquid pressure and produces flat jet patterns (Figure 11).

![Figure 10: Typical internal (top) and external (bottom) mixture of the nozzle (NIOSH, 2012).](image)

![Figure 11: Circular patterns and flat jet (NIOSH, 2012).](image)
Hydraulic nozzles

They produce a spray pattern in the form of a solid cone, a hollow cone or a flat fan. The full Cone nozzle (Figure 12) provides a high velocity impact area and is used when the nozzles have to be located away from the source of dust, since they allow covering more area (Bartell et al., 2005). The hollow cone hydraulic nozzles produce a circular ring pattern spray (Figure 13). They generally produce smaller drops than the other types of hydraulic spray at the same flow rate, and also have larger holes, which cause less obstruction of the nozzle. They are usually useful when the dust in the air is very dispersed. The flat fan nozzles (Figure 14) produce relatively large droplets through a wide range of flow rates and spray angles, these nozzles are useful in dust prevention (Bartell et al., 2005).

Figure 12: Hydraulic nozzle with full-cone spray pattern (NIOSH, 2012).

Figure 13: Hydraulic nozzle with hollow cone spray pattern (NIOSH, 2012).

Figure 14: Hydraulic nozzle with a flat fan spray pattern and different patterns (NIOSH, 2012).
From trial and error, together with the collection of historical data, it is possible to establish a correlation of effectiveness with respect to a certain type of spray patterns in the different sectors of a mining task. Table 9 shows the pressure performance conditions of the air and liquid in different nozzle types. It also gives the performance of these methods in different mining and processing activities. These have been classified in suppression and prevention activities.

**Table 9: Typical application of atomisers in the mining process (NIOSH, 2012).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Compressed air (Hydraulics)</th>
<th>Fine spray (Hydraulics)</th>
<th>Full cone (Hydraulics)</th>
<th>Hollow cone (Hydraulics)</th>
<th>Flat fan (Hydraulics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard pressure (liquid)</td>
<td>10 - 60 psi</td>
<td>30 – 1,000 psi</td>
<td>10 – 300 psi</td>
<td>5 – 100 psi</td>
<td>10 – 500 psi</td>
</tr>
<tr>
<td>Standard pressure (air)</td>
<td>10 – 70 psi</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>Does not apply</td>
<td>Does not apply</td>
</tr>
<tr>
<td>Dust suppression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaw crusher</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Loading points</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge in primary crusher</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer points</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust prevention</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stockpile</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td>×</td>
</tr>
<tr>
<td>Transfer points</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Paths</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2.5 Emission and control of dust in unitary operations**

In open-pit and underground mining operations there are different activities in which the generation of dust is presented in a clearly visible manner and with clear harmful effects.
2.5.1 Drilling

The drilling operation is a source of respirable dust, which can cause high levels of exposure to the drill operator, the drilling aide, and all personnel in the vicinity during the operation. The National Institute for Occupational Safety and Health determined that drilling dust can be reduced by using wet or dry technical controls for dust reduction, closed cabinets and the implementation of a dust-control programme.

Superficial drill dust control

Dust surface control methods use wet or dry drilling with dust collection systems.

- Wet drilling

Wet drilling injects water together with air to eliminate detritus. Tests have shown that this technique can provide dust control efficiency up to 96% (USBM, 1987). Wet systems are efficient, but they can freeze in the winter. Caution is advised if wet systems are used when there are sources of electrical energy nearby. When water flow rates are high, there are operational problems such as plugging the bit and jamming the rotation because the water causes detritus too heavy to be eliminated by the compressed air. On the other hand, very little water reduces the efficiency of dust control, in such a way that the amount of water needed would depend on the type of surface drilling and the material being drilled. The operator must slowly increase the amount of water to the point where visible dust emissions decrease. The disadvantages of wet methods can cause premature wear of tricone-type drills and shorten their useful life by 50% or more (Page & Organiscak, 1999). There is a solution to the disadvantage of short lives when drilling wet. To obtain an acceptable service life of the bit, the water must not reach the bit. This can be achieved through effective water optimisation and water separation.

- Dry Drilling

Dry dust control is achieved with a dust collection and filtering system mounted on the drilling machine. This system has the advantage of operating in several climates and can be efficient up to 99% (USBM, 1987). Figure 15 shows a basic configuration of a dry polka collection system.
The dust collectors basically consist of:

- Suction hood, which is placed on the surface at the point of the hole and where the dust that is sent through a hose to the separation and filtering unit is sucked.

- Separation and filtering system. It is carried out in two stages: in the first stage, a cycloning is carried out separating most of the coarse dust and in the second stage the filtering is carried out, retaining the rest of the powder.

- System of depression or partial vacuum of the set, with fans placed in the final stage after the filtering unit.

The dust is collected in bags or deposited directly on the surface of the bench. For the system to be efficient, it is necessary to establish and document a maintenance programme for dust control systems. Dry systems require meticulous maintenance of the drilling platform cover.

### 2.5.2 Blasting

Blasting is the common method of rock excavation in quarries, surface and underground mines. While blasting apparently generates large amounts of dust, the operation occurs with sufficient frequency that it is not considered a significant contributor to particulate material of fewer than 10 μm (EPA, 1991; Richards and Brozell, 2001). Blasting is generally done once a day, so the level of
activity \((AL: \text{time relationship between the duration of blasting and the duration of the working day})\) is a reduction factor in the estimates of PM10.

If it comes from underground mining, it will be emitted to the atmosphere from one or several defined points: the ventilation chimneys and the air circulation wells. If it comes from open-pit operations, the origin will be in the entire front of exploitation. Powder composition will be the same as that of the blasted rock, which will often be composed by ‘problematic’ mineral components, containing oxidative minerals, heavy metals, etc.

2.5.2.1 Control methods

As a result of blasting being considered a negligible source of dust, there is very little documentation for dust control of blasting operations. There are five methods of dust control that can be used to control dust during blasting, several of which are only effective for underground mining (Cummins & Given, 1973).

- **Wet methods**

  A common method of dust control for blasting operations is to wet the entire area before starting blasting. This procedure minimises dust that enters the air from blasting and allows it to adhere to wet surfaces (Cummins & Given, 1973). It has been shown that the method is effective in controlling dust during blasting in underground mines. This can also be effective for surface mining depending on the time interval between irrigation and the blasting time causing that moisture evaporates quickly making irrigation ineffective.

- **Water cartridges**

  Cartridges that are inserted into the borehole with the explosive have been used successfully to reduce dust in blasting operations of underground coal mines (ILO, 1965). Water cartridges consist of a properly sized plastic bag that is filled with water or can be filled into the hole. The cartridges can be placed in front of, next to or behind the explosive without causing any adverse effect on the fragmentation. Figure 16 shows a typical blast hole containing an explosive charge with a water cartridge to suppress dust generated during blasting. This cartridge uses a PVC bag that is inserted into the hole after the explosive and then filled with water to maintain a tight seal with the plug. In coal mining operations, it is stated that the use of these cartridges has reduced the dust by 40–60%.
Figure 16: Basic scheme of a dust control system in blasting holes with water cartridges (NIOSH, 2012).

- Fogger sprays

In the past, many underground operations used a fogger type nebuliser in the header where the blasting takes place. Figure 17 shows this configuration, which uses compressed air and water forced through a nozzle to create a fogged area. The nozzle, located at a distance of approximately 30 m from the face, is switched on before the start of blasting and remains in operations 20 to 30 minutes after the explosion (ILO, 1965). This method of dust control is highly used in pit mining, where the position of the fogger sprays depends on the wind conditions in order to control the exit and expansion of dust. Another way to use water sprinklers is to form water and air curtains, causing the isolation of the sector, not letting dust particles escape to the rest of the environment. This system must be complemented by some method of dust capture.
Figure 17: Spraying system with blasting water (NIOSH, 2012).

- Air filtration systems

Another method of dust control that has been used in underground mining operations is to filter the return air from the ventilation air in the blasting area. This method consists of placing filters inside the exhaust ventilation duct with water sprayers, which spray the filters and are oriented in the same direction as the airflow. The filters are only used during blasting and the duct containing the filters is approximately twice the diameter of the ventilation pipe (ILO, 1965). Dry filters have been used successfully in the past for the same purpose.

- Ventilation design

The most common method for controlling dust is to allow dust and blast gases to be dispersed and removed through the ventilation system in the case of underground operations, or by atmospheric dispersion in the case of surface operations. Underground operations usually schedule blasting during off-shift times to allow sufficient time for the area to be ventilated, dispersed and dust and blast fumes removed (Cummins & Given, 1973). The time needed for the dispersion of dust depends
on the location within the mine and the efficiency of the ventilation system. It is thus important that the ventilation system of the mine is maintained in good operating conditions to optimise the removal of dust and gases in order to minimise the removal time. In surface operations, the area is free of personnel just before blasting, the blasting schedule must consider weather conditions, that is, low wind speed and low investment potential can be used to minimise impacts of generating blasting dust. In general, dust and gas dispersion occurs rapidly after the blast, depending on wind speed and direction, and work is not allowed in the affected area until dispersion is complete. It has been observed that the use of multiple delay detonators to initiate individual explosive charges in millisecond time intervals can reduce the generation of blasting dust, but this has not been verified (Miller et al., 1985).

2.5.3 Material hauling

The circulation of high tonnage trucks in mining roads generally unpaved is one of the practices that has proved to be challenging in environmental terms. They represent the main source of fugitive emissions of particulate matter, making up from 78% to 97% of the total emissions (Organiscak & Reed, 2006). This phenomenon puts at risk the health of the operators (silicosis), the visibility of mine operators and the role hauling equipment. As a result, the performance and efficiency of mucking and hauling operations deteriorate.

To suspend a particle from the surface and make it airborne is necessary an aerodynamic drag force capable of overcoming the gravitational force and inter-particle cohesive forces present in the soil (Liu & Sun, 2002). In particular, due to the transit of vehicles on non-paved roads, the generation of dust can be explained using two factors: the mechanical action of the vehicle and the wind speed or turbulence in the nearby region (Nicholson et al., 1989). When a vehicle travels along an unpaved road, the forces associated with the movement crush and disintegrate the road components, and then many of the aggregates and particles are further fragmented, reducing their size and being more easily airborne. Sliding and friction between the wheels and the road causes cutting forces on the surface that promotes the suspension of the finest fraction of surface material. Finally, the particles are ejected as a result of a centrifugal force generated by the wheel (Tong et al., 2011). The speed of the vehicle contributes to the speed that the particles acquire when they are ejected from the ground (Chen et al., 1999). For mining roads, particulate emissions occur under the interaction of air with particles (wind transport) in combination with the movement of truck wheels (mechanical action). Without the existence of fluid the dispersion of particulate material does not occur outside the domains of a wheel. It is the turbulence just behind and at the sides of the trucks, the main driver of
particulate matter (Chen et al., 1999; Nicholson et al., 1989). The transport of soil particles by the wind can be under different regimes, depending on the particle size and wind speed (Figure 18) (Neuman & Nickling, 2009). In the case of smaller particles (<20 μm) the inter particle forces are greater than aerodynamic forces. For this reason, these particles are supplied with a hopping motion (named saltation) that allows suspending the smallest ones or raise dust when they return to the road surface. When fine particles are already suspended, they are exposed to turbulent air fluctuations.

![Figure 18: Diagram of the different transport modes of soil particles due to the wind (Neuman & Nickling, 2009).](image)

Currently, the most frequent and direct solution, in the case of the mining roads, has been through the irrigation of water by water trucks. However, the extreme conditions of typical arid and high mountain areas conceive the use of water as a costly and ineffective solution. With efficiency no higher than 40% and evaporation rates close to 30 minutes, its daily practice means excessive water consumption and a partial solution.

Therefore, it is necessary to see the mining roads as an asset of the mine, as they have a direct relationship with productivity. For roads in better conditions the cycle of loading-unloading takes less time involving therefore a lower cost per tonne transported. Other advantages of having mining roads in better condition and quality are:
• Lower emissions of fine material involve less road wear or deterioration of the road base. Road life is lengthened and fewer resources are required in maintaining the road base.
• Less pollution allows greater visibility of drivers, safer driving conditions and environmental friendliness.
• Greater regularity of the road offers less resistance to rolling. Then, there is less fuel consumption, less wear on the power train, tyres and of the suspension of trucks and vehicles.

2.5.3.1 Control methods

The first step to avoid dust emissions in mining roads is to pay attention in their design. Hence, it is proposed that the area in direct contact with wheels should be designed, built and maintained with materials of mineral associations of low susceptibility to abrasion with each other (low relative difference in its hardness). An economic alternative would be to extend a single layer of quartz particles, and avoid materials of inferior hardness. This measure controls part of the fines originated by fragmentation, not that produced by the disaggregation of the granular medium. The use of a wide distribution of sizes can achieve a greater densification of the soil and consequently, a soil more resistant to deform. Moreover, with a ‘well-graded’ soil (i.e. it contains particles of a wide range of sizes), the contact forces between the particles are reduced (number of contact coordination between particles increases) and the probability of rupture of the parent particles decreases from 5–6 times (Shi et al., 2015).

• Wet method

Water acts as the main agent by surrounding the particles and generating a suction matrix in the skeleton of the soil. Its presence between the pores of the soil allows the cohesion of particles under the appearance of the capillary force and the superficial tension of the water. On the other hand, water can be used as a solvent for dust suppressants such as salts or chemical reagents. The presence of water can contribute to the formation of solid bridges between particles (crystallisation of dissolved substances or hardening of binders present in water). Thus, its presence to a greater or lesser extent is fundamental for the control of dust emissions from the ground and, therefore, from the mining roads.
- Others dust suppressors

In many places where constant removal of particulate matter is pursuit, dust suppressants and/or chemical soil stabilisers are used. In general, they are applied to mining roads reducing the suspension of soil dust in several ways (Vorobieff, 2004). Different sources and brands are used and they can be classified according to their composition and its working mechanism. Some of the most commonly used suppressors on mining roads are listed in Table 10, as well as their main disadvantages and efficiency. The performance of water is also given for comparison.

Table 10: Dust suppressors’ performance.

<table>
<thead>
<tr>
<th>Suppressor</th>
<th>Efficiency (%)</th>
<th>Soil leaching</th>
<th>Ph and salinity modification</th>
<th>Fauna affection (negative effects)</th>
<th>Mud generation</th>
<th>Material corrosion</th>
<th>Hygroscopic (Slippery surface)</th>
<th>High cost</th>
<th>Not allowing immediate circulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>50</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium Chloride</td>
<td>55</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Magnesium Chloride</td>
<td>77</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Lignosulphonates</td>
<td>&lt;63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetable oils and molasses</td>
<td>&lt;84</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Asphalt emulsion</td>
<td>&gt;95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic polymers</td>
<td>40 - 50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
o **Hygroscopic salts**

They absorb the humidity of the environment, increasing the surface tension and overcoming the evaporation of water as a mechanism to suppress dust. Additionally they have an electrochemical effect that reduces the thickness of the double layer and, therefore, improves the mechanical strength between particles. They also reduce the deformability and permeability of the soil. Some hygroscopic salts used as dust suppressors are magnesium chloride (MgCl$_2$), sodium chloride (NaCl) and calcium chloride (CaCl$_2$). Its efficiency is based on the relative humidity and the temperature of the environment. In mining operations, a well-known agent is Bischofita (Valenzuela et al., 2014).

o **Lignosulphonates**

They are organic products capable of forming a new surface in the soil by acting as electrochemical cementing agents like sulphonated oils, enzymes and ammonium chloride. Lignosulphonates increase the electrical conductivity of the capillary water and indirectly modify the exchange capacity of the cation. As a consequence, the excess water is released and the water affinity of clay decreases. They are mainly used in soils with a high content of clays. However, in very rainy conditions they easily disintegrate and disappear due to their solubility in water.

o **Asphalt and asphalt emulsions**

They work by agglomerating and encapsulating the soil particles. They form a thin film resistant to rolling. Additionally they can increase the breaking point of the soil, which can rise up to 3 orders of magnitude, in relation to soils without any treatment (Zimon, 1982). The great advantage over other suppressors is that they are hydro repellent and do not have restrictions with the weather. By contrast, they do not work in all types of soil.

o **Polymers**

Polymers are used as adhesives and binders, preferably for compaction, by over-suppression of dust. The molecules react with free ions in the soil and form a very stable and strong reticular structure. They are mainly used for soils with low clay content. As a disadvantage they crack easily and they have a low in the presence of water.
Electrochemical products

They act as clay dispersers and achieve a more plastic response of the material. Products of this type are enzymes and sulphonated oils.

Biotechnology

The mixture between a chemical solution and a reagent produces the biochemical reaction of bacteria, which agglomerates and encapsulates the particulate matter. Bacteria take about 24 hours to reach their optimum concentration. These bacteria can be found in the environment in various types of soil. Certified by the ISP as harmless to humans, they are 95% effective after treatment. Its commercial name is Bioseal® (Chavez, 2017) and it is an innocuous product, both for human beings and for the environment. Its implementation, operation and maintenance costs are competitive with the current market.

2.5.4 Crushing, grinding and scrapping

Mineral crushing, grinding and screening operations can be the main sources of dust in the air due to the nature of the processes of size reduction and segregation. The amounts emitted will depend on the type of material (composition, hardness and abrasiveness) and the requirements of the final product. The crushing and impact during grinding involves dust generation. Screening involves that the product is vibrating on the meshes decks and falling to another deck or to a belt conveyor. The control of the dust generated by these operations can be achieved with an adequate analysis of the sources and the identification of the appropriate control technologies. The exposure of the worker to dust can be handled through engineering controls to suppress or enclose sources of dust. Additionally, the worker can be isolated from the source using operator cabins, control rooms and closed cabins. Administrative controls, such as operating procedures, work practices, and worker training, are also commonly applied to supplement engineering controls. The performance of installed dust control systems, which often represent large capital investments, should be periodically evaluated, maintained and, when necessary, modified to maximise performance. For example, the effectiveness of dust control systems installed to protect workers’ health only can be demonstrated by collecting personal air samples for comparison with the occupational exposure limit for the substances in question.
2.5.4.1 Dust emission

Different mineral processing equipment generates different amounts of dust emissions. Table 6 shows emission rate ratios for each equipment, taking the emission of primary crusher as a baseline. It shows that the emissions are larger in dry conditions. Emissions also increase as the size of material processed decrease (Table 6).

2.5.4.2 Control methods

- Wet control methods

In general, the use of wet control method is made through humid sprays systems. Control methods in grinding operations are more efficient when the material is moistened before grinding (Figure 19) (i.e. prevention measures are more suitable than suppression ones).

![Diagram of dust suppression system](image)

*Figure 19: System of suppression of dust before the crushed (NIOSH, 2012).*

When the wet material is subject to further fragmentation such as in crushing operations, effective prevention requires the application of further amount of water on the wet greater surface area of material produced by the decrease of fragment size. The suppression of respirable dust in the air by the use of water, usually through aerosols directed to the dust cloud, is not always highly efficient. It
is difficult that hydraulic atomising nozzles produce water droplets small enough to suppress respirable particles effectively. Water droplets of appropriate size can be produced with air atomising nozzles, but this method requires a source of compressed air to atomise water, and very small orifices in the nozzle that are subject to clogging, which requires greater maintenance attention. In addition, the use of air atomisation spray, due to the volume of the air/water mixture released, generally requires a closed area to prevent the dispersion of the dust to the surrounding areas. All these factors increase operating costs.

- **Dry control methods**

The control of generated dust is achieved through containment, exhaust and cleaning of dusty air. The installation and operation cost of this approach, called dry control, may be more expensive, but it can be very effective. In addition, control of dry dust may be necessary when the product is adversely affected by the addition of water, for example, clay materials. The control of dry dust must create conditions that prevent the escape of dusty air from the controlled space in the areas occupied by the workers. This control is achieved by using exhaust ventilation in order to create a negative air pressure within the controlled space in relation to the exterior of the controlled space (Figure 20). The amount of ventilation necessary to achieve this control is affected by:

- The degree of the enclosure of the controlled space, with required exhaust volume increasing as the area of unsealed openings in the enclosure increases.
- The airflow created by the motion and processing of the mineral, including the air that is dragged inside moving material and the airflow induced by moving material and equipment.
- The air displaced by the material that flows inside or outside an enclosure.
- The effect of ambient wind conditions (speed and direction) that can overcome the differential pressure between the interior and exterior of the controlled space.

In general, the top part of the crusher should be as close as possible from the feeding (feed side) (USBM, 1974) (i.e. reducing the parameter \( S \) in Figure 20). The enclosures should be constructed of physically resistant materials appropriate for the operating environment and climatic conditions.

For the design of the extraction hood in crushers it is necessary to consider that the mechanical action of the crushers can generate air movement; that is, jaw crushers can have a bellows effect, and cone or rotary crushers can act as fans, despite the fact that they do none of these kinds of crushers operate at high speeds. A method to estimate the maximum air flow generated from
hummer crusher is obtained in Equation 15 (Bruton, 1999), assuming that the maximum volume (cubic feet) of air generated per revolution of the shaft can be estimated by modelling the set the hammer/shaft as a fan.

\[ A_{GEN\,REV} = \frac{\pi}{4D^2W} \]  

where: \( D \) is the diameter of the hammer assembly (feet); \( W \) is the width of the hammer (feet).

![Image: Dry powder control with extraction (NIOSH, 2012).](image)

**Figure 20: Dry powder control with extraction (NIOSH, 2012).**

### 2.5.5 Dumping of material

It refers to the discharge of ore from trucks, front loader or conveyor belts to bins or material feeders, where the dust generated is the product of the fall because of gravity. The dust control system consists of partial closure with hanging curtains and the use of wet methods for water spraying (Figure 21). The local ventilation system with extractor hoods is an efficient solution, and the enclosure of the volume to control must be maximised. In other words, the number and area of openings should be minimised as much as possible. Initial exhaust rates can be estimated by Equation 16, which accounts for air displaced by a dumping operation.

\[ Q_E = 33.3 \times \left( \frac{600T}{G} \right) \]  

where: \( T \) is weight of material dumped (t/min) and \( G \) is bulk density of material (lb/ft\(^3\)).
Dumping operation is not continuous. The use of detection control sensor with a timed duration to activate the exhaust system fan and water sprays is a good practice. Whenever local exhaust ventilation is selected as a means of dust control, the maintenance and cleaning openings should be designed in the enclosure and should be equipped with airtight seals (Figure 22). It is recommended maintaining a minimum air capture speed of 200 fpm (feet per minute) in all openings of the enclosures (USBM, 1971). When the feed or discharge belt openings penetrate into the dust control boxes, it is recommended adding the belt speed in feet per minute at the design speed of 200 fpm to take into account the volumetric flow of the process material and the movement of air induced by the belt (Yourt, 1969).
2.5.6 Wind erosion

The effect of wind erosion is predominant on materials stored in open air. This occurs as stockpiles where 5,000 t up to values 100,000 t are stored.

2.5.6.1 Control methods

- Coal storage areas

A common practice in coal fields that are exposed to marine air currents consists on covering the stockpiles with a thin layer of calcium oxide. This acts as a protective cover on the coal penetrating under normal conditions up to 3 cm on the outer layer of the stockpile. The application of this coating increases also the electrical resistance of the material, which reduces the risk of possible fires, in turn, as a thick material is applied, it prevents the generation of excess dust due to the existing natural sources.

- Addition of water

The methods in which the humidity is added can vary regarding the way of application. Already described methods such as sprinklers, fog, curtains of water and direct flow are common. The effectiveness of these systems depends on the amount of water applied, technique used and the properties of the material to be stored. Thus, for example, coal reduces the amount of dust when it is moistened, but if it is used as fuel to generate electricity, it must be dried. This implies additional energy expenditure to the system, as well as decreases the efficiency of the generation cycle. If moisture is applied to a material that will later be transported on conveyor belts, problems such as slippage of the belt, accumulation of fines in the scrapers and problems of saturation or blockages in transfer chutes can be caused.

- Lateral walls and skirts

Currently some stockpiles or storage piles in mining operations use the technique of closing or partially encapsulating part of the stockpile, thereby protecting the material on the side faces of the stockpile from being separated and generating dust. This provides space to heavy equipment in case of needing maintenance or any change. This system is accompanied in some areas by rubber skirts that seek flexibility in maintenance and reduce the amount of dust. This equipment helps to considerably reduce the amount of dust generated, but it also makes the project more expensive and
it can present a bigger problem when carrying out maintenance inside the feeders or the same stockpile. At the same time, if they are not properly sized and installed, it tends to generate vertical air currents inside the stockpile which cause upwards air flows to the interior, causing again dust.

- Stockpiles of negative pressure

Following the previous principle and its relative effectiveness, in situations where the material to be stored is very fine or harmful to the environment and the community, it has been decided to close the stockpiles completely. This is usually used in areas with environmental factors that would generate dust. In operations where this type of dome is used on the stockpile, it is usually combined with a pressure difference system. If there is a leak, this system allows, by means of extractors connected to the interior, the air flow from the outside flow towards the interior of the stockpile itself. Its greatest use to prevent pollution of the coastal and sea lands is in port sectors where the ore is stocked prior being shipped. It is usually used in copper or iron concentrate loading sectors, where the moisture percentage of the ore is of vital importance and must be controlled continuously.
3 BASELINE MEASUREMENTS

The aim of the tests performed in this work was to assess dust emission in mining activities, such as drilling, blasting and mucking. Then, the qualitative data obtained will serve as baseline to assess the efficiency of control emission techniques proposed in this Master’s Thesis. The measurements were carried out during the first campaign of large-scale blasts held in El Aljibe quarry (Almonacid de Toledo, Spain) (Figure 23).

![El Aljibe open-pit quarry.](image)

The quarry mines mylonite to produce track ballast for high-speed and conventional trains (32/56 mm fraction), for high-strength concrete and asphalt mixtures (6/12 mm fraction) and for sub-base and base courses (<25 mm fraction) in road and rail track construction. The mylonites are formed by 40-60 % of porphyroblasts included in a very fine matrix (35-45 %); there are also small quantities of opaque minerals and alteration minerals, such as chlorite (5 %, Arnó and Fueyo Consultores, 2016). The porphyroblasts are mainly feldspar and plagioclase (40-60 %) while the matrix is made up by biotite (15-20 %) and quartz (20-25 %). This quartz can be classified as α-quartz because mylonites were formed at temperatures up to 450°C regarding their petrographical study (Fueyo and de la Cuadras, 2016). Thus, it can be the source of the crystalline silicon dioxide in the respirable fraction of PM.

The mylonite is a fine-grained metamorphic rock formed by milonitization, a type of dynamic metamorphism in which the grain size of a rock is diminished by ductile shearing. Milonitization occurs at depths of more than 10 km underground where minerals recrystallise in fine sizes. The
most resistant minerals, such as potassium feldspar, can be recrystallized as porphyroblasts. New minerals are usually formed in mylonites. Depending on the matrix percentage, protomilonites (<50%), mesomilonites (50 to 90%) and ultramilonites (> 90%) are distinguished. In the proper mylonites the matrix grains are less than 0.05 mm and in the ultramilonites less than 0.01 mm. This rock has fine grain and foliated structure with porphyroblasts. All these are not characteristics that benefit the tests in situ, since it would present elevated filtration in case of a leak in the liners.

PM was monitored from the end of May to the end of September 2017 during the first campaign of large scale tests. This consisted of six blasts located one behind each other in the Southwest part of the main pit in the deepest level. All the blasts have seven blastholes along one row parallel to the free vertical face of the bench. The blastholes were charged with emulsion explosive and plugged with drilling chips. This material type leads to a poor performance to contain the explosive gasses in the rock mass and may be also a source of PM emissions due to its fine size; the use of other material such as angular crushed rock with sizes about 1/12\textsuperscript{th} of the hole diameter (about 7 mm) will contribute better to PM suppression (AECI, 1987). The stemming length is nearly constant in all blasts, about 1.8 m. A summary of the main blasts characteristics is shown in Table 11; it shows the mean of the parameters measured for each hole. Two rock volumes obtained both with CloudCompare (2017) are also given; they are the actual volume of broken rock between post and pre-blast faces $V_a$ and the volume of broken rock in front of the blastholes $V_b$. From them and the mean of the bench heights, the respective ground surface areas $A_a$ and $A_b$ are calculated. This is the only blasting characteristics considered in the calculation of the emission factors from blasting, and it is qualitatively ranked as small with mean and standard deviation for the six blasts shown in Table 11.

The material from each blast was mucked and hauled to a mobile screen Kleemann MS 19D placed in the bottom level of the pit nearby to the resulting muckpile. This operation generally took two days per blast and was made as follows. A backhoe loader of 5 m\textsuperscript{3} of bucket capacity was used to muck the material in two stockpiles, and a frontal shovel with a bucket capacity of 2.25 m\textsuperscript{3} was employed to feed the mobile screen with feed capacity up to 500 t/h and a screening area of the top deck of 9.3 m\textsuperscript{2}. After sieving and weighting, the resulting material was dumped on an adjacent pile from an un-mucked blast. During the testing period, no additional activities than this occurred in the pit; the processing plant (and the primary crusher) was stopped, while traffic of trucks and hauling activities occurred in the surroundings of the stockpile area; this can be qualitatively ranked as low.
Although European legislation on air quality, Directives 1999/30EC (EC, 1999) and 2008/50/EC (EC, 2008), and US standard (US EPA 1997) considered PM10 and PM2.5 as pollutants, TSP has been typically considered to assess PM emission from mining and it is monitored in this work together with PM10. They both are the parameters generally considered when mineral PM emissions in mines or quarries are studied (Roy et al., 2011; Sairanen et al., 2017). Since mechanical breakdown processes of rock, material handling or stocking in piles are a limited source of fine PM, PM2.5 has not been monitored. Filter paper based instruments are used to measure the amount (mass and concentration) and type of occupational and non-occupational dust (TSP, PM10, and respirable crystalline silicon dioxide) suspended in the air. These instruments draw a volume of air for a certain time through a pre-weighted filter in which particulates are trapped; Echo PM10 and APEX standard apparatus have a 10 μm size-selective inlet to prevent that larger particles are collected on the filter, whereas CAV-A/mb not.

Table 11: Main blast characteristics.

<table>
<thead>
<tr>
<th>Blast</th>
<th>$B \times S$</th>
<th>$H$</th>
<th>$Aa$</th>
<th>$Ab$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>m</td>
<td>m²</td>
<td>m²</td>
<td>kg</td>
</tr>
<tr>
<td>1</td>
<td>2.0 × 3.2</td>
<td>11.4</td>
<td>59.5</td>
<td>44.9</td>
<td>540.6</td>
</tr>
<tr>
<td>2A</td>
<td>2.6 × 3.2</td>
<td>11.1</td>
<td>68.7</td>
<td>56.9</td>
<td>510.5</td>
</tr>
<tr>
<td>3</td>
<td>2.4 × 3.0</td>
<td>11.7</td>
<td>68.5</td>
<td>50.1</td>
<td>567.1</td>
</tr>
<tr>
<td>4</td>
<td>2.4 × 3.1</td>
<td>11.6</td>
<td>73.4</td>
<td>49.3</td>
<td>600.6</td>
</tr>
<tr>
<td>5</td>
<td>2.4 × 3.2</td>
<td>11.7</td>
<td>60.4</td>
<td>49.8</td>
<td>599.7</td>
</tr>
<tr>
<td>6</td>
<td>2.2 × 3.1</td>
<td>11.5</td>
<td>70.5</td>
<td>46.6</td>
<td>565.9</td>
</tr>
<tr>
<td>Mean</td>
<td>2.3 × 0.2</td>
<td>11.5</td>
<td>66.8</td>
<td>49.6</td>
<td>564.1</td>
</tr>
<tr>
<td>Sd.</td>
<td>0.2 × 0.1</td>
<td>0.23</td>
<td>5.62</td>
<td>4.12</td>
<td>34.8</td>
</tr>
</tbody>
</table>

Figure 24 shows a photograph of each equipment used and Table 12 summaries their main characteristics. It also shows the analysis techniques followed and the laboratories where the samples were analyzed; they all are accredited according to Spanish National accreditation agency-AENAC. The results obtained are given in the form of concentration expressed in μg/m³; these are obtained from the ratio of the mass of particulates trapped in the filter (TSP, PM10 or crystalline silicon dioxide) divided by the air sampled volume.
Figure 24: Dust samplers used: CAV-A/mb for TSP (left), Echo PM for PM10 (center) and APEX Standard for occupational respirable PM (right).

Table 12: Instruments and analysis techniques used to monitor air quality.

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Non Occupational</th>
<th>Occupational</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TSP</td>
<td>PM10</td>
</tr>
<tr>
<td>Model</td>
<td>CAV-A/mb</td>
<td>Echo PM</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>MCV S.A</td>
<td>Tecora</td>
</tr>
<tr>
<td>Equipment</td>
<td>High-vol. sampler</td>
<td>Low-vol. sampler</td>
</tr>
<tr>
<td>Flow rate, m&lt;sup&gt;3&lt;/sup&gt;/h</td>
<td>20</td>
<td>2.3</td>
</tr>
<tr>
<td>Filter/membrane material&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Glass fiber- F&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Quartz fiber- F</td>
</tr>
<tr>
<td>Filter diameter, mm</td>
<td>150 mm</td>
<td>47</td>
</tr>
<tr>
<td>Measuring method</td>
<td>Gravimetric&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Gravimetric&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Laboratory</td>
<td>LABAQUA</td>
<td>LABAQUA</td>
</tr>
<tr>
<td>Quantification limit&lt;sup&gt;c&lt;/sup&gt;, mg/filter</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Precision, %</td>
<td>13 %</td>
<td>14.6%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Respirable fraction with median size of 4 μm and maximum size close to 10 μm (NIOSH, 1994), that it is considered equivalent to the PM10; <sup>b</sup>F: filter; M: membrane; <sup>c</sup> It is 10 times the standard deviation of blank or limit at which the difference between two distinct values can be assessed; The measurement standard followed is: <sup>d</sup>Ministerio Gobernación (1976), <sup>e</sup>AENOR (2015) and <sup>f</sup>Fernandez et al. (2013).
Concentration of PM generally decreases when the increasing distance to the source and concentrations of larger-size fractions decrease faster compared to the smaller ones. PM retention is higher within few tens of meters from the source (10–25 m), and also when the samplers are placed at higher elevations due the barrier effect of the pit walls on PM propagation. The effect of distance on PM concentrations is not apparent when local PM sources, such as traffic, are considered; or when PM is sampled at far distances because of the effect that other PM sources have on the original emission along the propagation path. Considering this, non-occupational PM monitoring stations, identified as S1 and S2, were placed in the upper level of the pit (see Figure 25). In this area, the largest concentrations of dust are expected, before being dispersed outside of the quarry. Station S1 is close to the quarry offices near the entrance to the operation, while S2 is downwind near to the stockpile area. The dust samplers CAV-A/mb and Echo PM require 220 V power supply to maintain the desired flow rate. On the locations used, it was possible to plug the samplers to the electrical network of the quarry.

Figure 25: Ortophoto of the quarry area from drone flights. Quarry facilities, emission sources (blasts, mucking and sieving area- point H) and non-occupational samplers.
Table 13 shows the UTM coordinates in the ETRS 89 system of the monitoring stations; it also gives the location of the gravity centre of the blasthole’s collars of each blast and the point $H$ around, where mUCKing and sieving activities of all six blasts occurred. This position is also plotted in Figure 25. The topography between dust sources and the monitoring stations is complicated with high walls formed by several benches and a difference of height about 70 m.

Table 13: Coordinates of monitoring stations and PM sources.

<table>
<thead>
<tr>
<th>Point</th>
<th>E (m)</th>
<th>N (m)</th>
<th>Z (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station-S1</td>
<td>428,148</td>
<td>4,400,353</td>
<td>728</td>
</tr>
<tr>
<td>Station-S2</td>
<td>428,395</td>
<td>4,400,158</td>
<td>721</td>
</tr>
<tr>
<td>GC$^a$-Blast 1</td>
<td>428,163.9</td>
<td>4,400,175.7</td>
<td>654.6</td>
</tr>
<tr>
<td>GC-Blast 2</td>
<td>428,162.0</td>
<td>4,400,173.9</td>
<td>654.6</td>
</tr>
<tr>
<td>GC-Blast 3</td>
<td>428,159.5</td>
<td>4,400,171.9</td>
<td>654.6</td>
</tr>
<tr>
<td>GC-Blast 4</td>
<td>428,156.5</td>
<td>4,400,170.4</td>
<td>654.6</td>
</tr>
<tr>
<td>GC-Blast 5</td>
<td>428,154.3</td>
<td>4,400,168.2</td>
<td>654.6</td>
</tr>
<tr>
<td>GC-Blast 6</td>
<td>428,151.5</td>
<td>4,400,167.5</td>
<td>654.6</td>
</tr>
<tr>
<td>Hauling-H</td>
<td>428,211.39</td>
<td>4,400,185.2</td>
<td>645.0</td>
</tr>
</tbody>
</table>

$^a$GC: gravity center.

A total of fifty five measurements were made. Among them, 18 and 25 measurements correspond to non-occupational TSP and PM10 data, respectively. The rest (twelve records) are measurements of occupational respirable matter (ORM), where concentration of crystalline silicon dioxide was obtained. Table 14 summarises the measurements made during drilling, blasting and mucking activities in each blast. The activities with larger number of measurements were blasting and mucking, while data from drilling was limited. For non-occupational measurements (TSP and PM10) the position of the monitoring station (S1 and S2) is given in subscripts. Initially, it was planned to monitor TSP and PM10 in both stations but availability of dust samplers during the monitoring campaign prevent this. If an activity was monitored more than once in the same blast, a number is given in Table 14 as a superscript near to the parameter in question; this is the case of hauling in blast 2A that was monitored twice.
In order to assess the background concentration of non-occupational TSP and PM10 in the quarry due to non-well defined dust sources, such as trucks running from the quarry entrance to the stockpile area across unpaved areas, and wind erosion on final products stored in stockpiles and on unpaved facilities outside and inside the pit, additional measurements were carried out. These measurements were always made before the blast was shot. In blasts No. 3, 4 and 5, they were also carried out after the blast, during non-mucking periods.

ORM measurements were made with a personal sampling device carried by the operator (see Table 14). This means that air quality was monitored most of the time inside the cabin of the drill rig or loader during drilling and mucking, while the contrary occurs when the sampling device is carried by the blaster to assess dust during the preparation and shot of the blast.

Table 14: Summary of dust measurements per blast as function of the activity.

<table>
<thead>
<tr>
<th>Blast</th>
<th>Drilling</th>
<th>Blasting</th>
<th>Mucking</th>
<th>Background before blast</th>
<th>Background after blast</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;</td>
<td>-</td>
<td>TSP&lt;sub&gt;S1,S2&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PM10&lt;sub&gt;S1,S2&lt;/sub&gt; ORM</td>
<td>-</td>
<td>PM10&lt;sub&gt;S1,S2&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2A</td>
<td>- ORM</td>
<td>PM10&lt;sub&gt;S1&lt;/sub&gt; ORM</td>
<td>PM10&lt;sub&gt;S1&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt; ORM&lt;sup&gt;2&lt;/sup&gt;</td>
<td>PM10&lt;sub&gt;S1&lt;/sub&gt;</td>
<td>-</td>
</tr>
<tr>
<td>B3</td>
<td>- ORM</td>
<td>- ORM</td>
<td>-</td>
<td>-</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;</td>
</tr>
<tr>
<td>B4</td>
<td>- ORM</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;&lt;sup&gt;3&lt;/sup&gt; PM10&lt;sub&gt;S2&lt;/sub&gt;&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>B5</td>
<td>- ORM</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt;</td>
<td>TSP&lt;sub&gt;S2&lt;/sub&gt; PM10&lt;sub&gt;S2&lt;/sub&gt;</td>
</tr>
<tr>
<td>B6</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>TSP&lt;sub&gt;S1&lt;/sub&gt;, PM10&lt;sub&gt;S2&lt;/sub&gt; ORM</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup>One of the measurements was made while the material was sieved in the mobile screen
Additional critical parameters in dust measurements are the sampling time and weather factors, like wind speed and direction and temperature (Petavratzi et al., 2005). When dust measurements are generally carried out for regulatory purposes, measuring standards suggest a sampling period of 24 h. But to assess dust concentration from mining activities, in which dust is dispersed quickly in the atmosphere as occurs for instance in blasting, shorter sampling times adapted to the duration of these activities should be used. Table 15 shows the main statistics (number of measurements, mean, standard deviation and range), of the sampling time. For non-occupational TSP and PM10 measurements, the smaller times of about 1 h correspond to blasting; Roy et al. (2011) sample dust from blasts in large surface coal mine during a shorter time of 20 min. The longer times correspond to mucking and background after blasting in which dust was also sampled at night, involving for mucking, for instance, that fugitive dust is also collected. Occupational dust measurements were generally carried out were in average 4.5 h for drilling, 5.8 h for blasting and 8.5 for mucking (see Table 15); in blast no. 3, the monitoring device was not stopped after mucking was finished, making up a total of 16 h from which 8 h correspond to mucking and the other 8 h to non-working period in the quarry.

Table 15: Statistics of the sampling time.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Non-occupational</th>
<th>Occupational</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>Mean</td>
</tr>
<tr>
<td>Drilling</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Blasting</td>
<td>10</td>
<td>1.3</td>
</tr>
<tr>
<td>Mucking</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Background before blast</td>
<td>10</td>
<td>2.1</td>
</tr>
<tr>
<td>Background after blast</td>
<td>9</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Climate data from the National Weather Station of Mora (8.4 km SouthEast from the quarry of UTM coordinates 433,068.4 m and 4,393,303.2 m) were downloaded every day when dust was monitored (AEMET, 2017). For each of non-occupational dust measurements, the mean of the data recorded during the sampling time was calculated. For the wind direction, directional statistics have been considered and the mean wind direction $W_{DIR}$ is obtained as follows:

$$W_{DIR} = \tan^{-1}\left(\frac{W_E}{W_N}\right)$$  \hspace{1cm} (17)

where

$$W_E = \text{mean} \left(\sin(W_{DIR,i})\right); \quad W_N = \text{mean} \left(\cos(W_{DIR,i})\right)$$  \hspace{1cm} (18)

A summary of the climate data during the monitoring period is shown in Table 16. These are typical of the summer season of a continental Mediterranean climate with low humidity and winds qualitatively described as calm to light breeze. The predominant wind direction is NorthWest, so station 2 is at downwind and station 1 upwind.

Table 16: Climate statistics at National weather Station of Mora (AEMET, 2017).

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std.</th>
<th>Min</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature T, °C</td>
<td>28.96</td>
<td>6.2</td>
<td>14.8</td>
<td>38.6</td>
</tr>
<tr>
<td>Wind velocity $W_v$, m/s</td>
<td>2.51</td>
<td>0.7</td>
<td>0.89</td>
<td>4.2</td>
</tr>
<tr>
<td>Wind direction $W_{DIR}$, °</td>
<td>292.3</td>
<td>-</td>
<td>0</td>
<td>323.9</td>
</tr>
<tr>
<td>Humidity H, %</td>
<td>29.95</td>
<td>12</td>
<td>15</td>
<td>55</td>
</tr>
</tbody>
</table>

Figure 26 shows concentration values of TSP (left graph) and PM10 (right graph) as function of the activities monitored; the symbol type indicates the monitoring station and, its colour, the blast number. TSP concentration from drilling in blast No. 2, 1217 μg/m³, has been discarded, as the flow rate for this measurement was atypically high, 27 m³/h. By contrast, in the rest of the measurements
it is around the nominal flow rate in Table 12. Measurements with a sampling time larger than 8 h that lump dust from more than one activity, mainly from fugitive sources, are marked in Figure 26 with a line. These values are not higher than the others, which in the case of mucking indicates that dust from this source is predominant.

Figure 26: Non-occupational dust concentrations TSP (left graph) and PM10 (right graph) as function of the activity.

In Figure 26: drilling (D), blasting (B), mucking (M), background before and after the blast (BB and BA, respectively). The symbol shows the monitoring station (circles for S1 and triangles for S2) and the colour of the blast in which data was gathered (black for B1, red for B2, green for B3, blue for B4, magenta for B5, and yellow for B6). Measurements with a mass of particulates trapped in the filter below the quantification limit of the laboratory are shown with an unfilled marker and the resulting concentrations are an upper bound (the higher PM10 from mucking in blast No. 2 corresponds to sieving).

Figure 26 shows that mining activities monitored do not produce significantly different concentration of TSP than the background levels in the quarry, 187.9 sd. 90.1 versus 154.2 sd. 56.3 μg/m³, respectively (mean and standard deviation values).
The mass of PM10 retained in the filter is in general below the quantification limit of the laboratory (0.3 mg, Table 12) and the resulting concentration values are an upper bound; these data are shown with non-coloured markers, while solid markers indicates that particulate mass in the filter could be determined. This occurs at least in one measurement from drilling, blasting and mucking. To assess these values, PM10 concentrations measured every hour in the city of Toledo (24 km NorthWest from the quarry is the closest one in which data are available) on the same dates when the first campaign of blasts was held, were downloaded from the web page of the Viceconsejería de Medio Ambiente CM (2018). The 25 and 75 percentiles that show the bounds of PM10 expected, 50 % of the times, are shown in Figure 26 (right graph) as grey solid lines; these are below the threshold value of 50 μg/m³ for a period of 24 h (EC, 2008). The maximum value monitored in Toledo, that corresponds to a day in which Saharan dust intrusions were detected is also plotted (grey dashed lines). Only one of the solid markers (the black triangle from blast No. 1) exceeds this value.

The concentrations of these fractions are plotted in Figure 27 as function of the activities monitored; the colour of the symbol shows the blast number. Non-filled markers indicates that the mass of the material in the filter cannot be determined as it is below the quantification limit of the laboratory (0.2 mg for PM10 and 3μg for crystalline silica, Table 11); the respective concentrations are unknown, but smaller than the plotted values in Figure 27. This occurs in five and one measurements of respirable PM and crystalline silica, respectively. Measurements with a sampling time larger than 8 h are marked with a line, which occurs only for one measurement from mucking. Although there is not a significant difference in occupational dust measurements between mining activities, the largest mean concentrations values for respirable PM and free silica are obtained in drilling, while the smaller values correspond to mucking in which the operator is generally inside the loaders. Mean concentrations of dust inhaled by the blaster are in the middle.

All occupational concentrations are below the threshold values of 3 mg/m³ for respirable matter and 0.1 mg/m³ for crystalline silica (Ministerio de Industria, Turismo y Comercio, 2007). This suggests a good performance of the mitigation measurements installed in the drilling rig, backhoe and frontal shovel loader. In addition, data monitored during the execution of the blast suggest that respirable PM due to traffic of vehicles and fugitive sources is low. Similarly occurs with the dust produced by the blast, where the initiation point of the emission is always upwind the blast and thus, the blaster does not come back to the block until the dust plume has been dispersed.
Figure 27: Occupational dust concentrations of respirable PM-PM10 (left graph) and crystalline silicon dioxide (right graph) as function of the activity.

In Figure 27: drilling (D), blasting (B) and mucking (M). Black markers shows measurements in blast B1, red ones in B2, green in B3, blue in B4, magenta in B5, and yellow in B6. Unfilled markers show measurements with a mass below the quantification limit of the laboratory given in Table 12, where resulting concentrations are an upper bound.

Although the potential dustiness of the rock is generally determined through single drop test, fluidisation test and rotating drum tests (AENOR 2010), other properties such as the uniaxial compressive strength (UCS; AENOR 1990) and resistance to impact (Los Angeles abrasion value, LAAV; AENOR 2010) may give some hints on the production of dust. Los Angeles test produce an abrasive action on the studied rock by mixing standard steel balls with the rock and rotating in a drum; the result is expressed as the mass of material below 1.7 mm expressed as a percentage of the test sample and it is used to assess the resistance of aggregates to fragmentation and dust generation (Tervahattu et al., 2006). The UCS and LAAV (mean and standard deviation) of mylonite are 182sd.66 MPa (Castedo et al., 2018) and 12.3 sd. 0.6 % (Fueyo and de la Cuadra, 2016). These high strengths values and low LAAV’s indicate that the mylonite breaks difficult into fine particles; the petrographic characteristics of the rock with a matrix formed by fine grains resulting from a high recrystallization typical of metamorphic rocks formed at high pressures are behind these results and support that in 19 out of 26 measurements of non-occupational PM10 concentrations, the dust trapped in the filter cannot be determined as it is below the quantification limit of the laboratory.
4 SOLUTIONS TO MITIGATE DUST EMISSION IN BLASTING

In this Master's Thesis, the research work focuses on the search of solutions to reduce the emission of dust in the quarry blasting process. Blasting is an important source of dust, although it is a one-off and non-continuous process that is carried out less frequently than other mine operations. In addition, there are currently no effective solutions implemented in the sector.

Open blasting generates a very visible plume, which, in addition to the aforementioned problems for human health, can cause problems with social concerns in nearby communities, as well as problems of image and awareness. In the case of indoor blasting, it can be possible to reduce waiting times from when the blasting is triggered until the tunnel can be accessible again due to problems of emission of dust and toxic products. Thus, it is possible to improve the productivity of the mine and the safety of workers.

4.1 Polyacrylamide

The starting point of the research was to establish materials that could be used to reduce dust emissions during blasting processes. Firstly, some companies related to dust control were searched. Although none of them were specifically focused on the aspect of blasting, as this is an issue that is not yet applied, contacts were established with some companies that developed dust mitigation works in other aspects, such as roads or industrial factories. Finally, a meeting was arranged at the E.T.S.I. de Minas y Energía with the company Optimasoil, dedicated to the development of nanotechnology for a wide spectrum of applications. The result of this meeting was the collaboration between both parties, providing Optimasoil the materials considered appropriate for this study. In this way, Optimasoil was in charge of supplying a nanometric polymer which when mixed with water, was sought to create a hydrogel. This hydrogel will be introduced in the boreholes in order to spread and trap the dust wetting the dust particles and avoiding their dispersion.

The desired product is one that could enhance the water's mitigating effect, having a high reactivity with it. In this sense, it was thought that a gelled product would tend to reduce the specific surface of the water, helping the action of water.

The meeting also analysed and devised different solutions for its application in the field. As seen above, water is a good agent for dust mitigation. In fact, it is the most efficient one, because no product has been found yet that potentiates its effect in a significant way. Therefore, it is assumed
that water must be present in this application. In addition, water is available, easy to use, and safe for human beings and the environment. As possible solutions, several possibilities were discussed:

- Irrigation of the surface. This technique is already used on roads, and rural and industrial areas, even accompanied by film-action additives that create a durable layer that prevents dust from moving away from the ground. However, in this case, it is not considered as a good option, since the explosion would cancel the effect of superficial irrigation, and in addition, it would add a greater number of resources to the area of the blasting bench and would interfere in the rest of the works that must be done there.

- The drilling of extra holes between the first line of blastholes and the face of the bench. These holes would not be charged with an explosive charge but they would be completely filled with water. In this way, the water would wet the area when it shot out and the drill lines were fragmented. However, this option has an impact on the total cost of drilling and it would imply more works and time dedication.

- The introduction of a dust mitigation product into the borehole, as a stack, between the lower and upper gravel pile. This product will be scattered in the hole area. It seems to be the most appropriate option considering the interference with other activities in the pit, the need for resources for its application, and the efficiency, so this will be the work line.

It was valued to extend the research to the reduction of dust emission also during the drilling process. However, this idea was discarded because blasting and drilling processes are very different, and the last one would require a parallel investigation of the same size, although in this case it would not start from zero since there are already cooling and water injection techniques applied in drilling process.

### 4.1.1 Properties of polyacrylamide

The used nanometric polymer is composed entirely of sodium polyacrylate in powdered form (Figure 28). The particle size varies from 1.27 cm to 45 μm in diameter. It has a grayish-white physical appearance. As indicated in the technical data sheet of the product (Annex A), sodium polyacrylate is classified as a super absorbent, and in aqueous solution, it goes from a liquid to a semi-solid state or gel. This product can absorb large amounts of water or aqueous solutions while retaining the liquid under pressure. Once it is saturated, the hydrophobic nature of the product does not allow it to be solubilised in an aqueous medium. The gelation is produced from multiple
hydration of the reticular structure of the molecule, that is, water becomes part of the polymer molecule, instead of the molecule becoming part of water.

The apparent density is 0.5 g / cc. It expands approximately 1% when hydrated, and is able to absorb more than 250 times its weight in water. It can also solidify most aqueous solutions in less than two minutes, and does not require mixing.

The product is not toxic to human health, although contact with eyes may cause irritation. The hydrogel produced mixing the product with a liquid does not present a danger either. However, the toxicity of the hydrogel depends on the chemistry of the liquid that the polymer absorbs.

Technical and security data sheets of this product are available in Annex A and Annex B respectively.

Figure 28: Sodium polyacrylate supplied by Optimasoil.
4.1.2 Laboratory tests with polyacrylamide

The aim of the laboratory work was to observe and analyse the properties and the behaviour of the product, to establish the most efficient form of application in the field, as well as to find the appropriate dosage to achieve a greater performance of the hydrogel.

The work procedure in the laboratory was to test different dosages guided by the results of the tests carried out at the base dosage recommended by the manufacturer.

The laboratory tests are carried out with tap water, since its composition and its density are the most similar to that which can be supplied in the field. The same guidelines are followed for each test in each mixture, reducing the error as much as possible.

The photographic report of all the tests is included in Annex D.

In a first laboratory session, the aim is to specify, qualitatively, the range of concentrations most suitable for the desired purpose. Then, the value that appears in the technical data sheet (Annex A) is taken as a base, and an upper threshold (375 mL: 1 g) and a lower one (125 mL: 1 g) will be tested too. In addition, the mixtures will be made twice: firstly, the process will be helped by agitation, but not secondly.

The used instruments are:

- Beakers (where the mixture is made).
- Pipette.
- Test tube.
- Agitator.
- Clock glass (for weighing polyacrylamide).
- Scale (mg precision ± 0.002g).
- Teaspoon.
- Stopwatch.

The procedure consists of pouring the product over the water that is in the beaker. The behavior of the hydrogel is evaluated qualitatively from the visual analysis and the use of the agitator (resistance to be agitated).
Firstly, as said before, the process is assisted by agitation:

1) 375 mL water : 1 g sodium polyacrylate (Figure 29).

Very dilute gelatin accumulates at the bottom of the glass. Water remaining. Slight resistance to agitation after two minutes.

2) 250 mL water: 1 g sodium polyacrylate (Figure 30).

Gelatin is accumulated up to a height of 200 mL in the glass. Resistance to agitation after two minutes.

3) 125 mL water: 1 g sodium polyacrylate (Figure 31).

Gelatinous aspect and behaviour. The product absorbs all the water. Greater resistance is appreciated, until practically not being able to continue agitating after a minute and a half.

Although the manufacturer mentions that two minutes are required to obtain the final state of the mixture, it is appreciated that after this time it becomes more consistent. Therefore, after observing the evolution of the state of the mixture over time, it is recommended to wait 5 minutes for the mixture to acquire a more suitable gelatinous behavior.

The process is repeated without agitation:

In these cases, when turbulences are not created by agitation, it is possible to appreciate visually how the polyacrylamide is deposited in the bottom of the beaker and absorbs the water, so the gelatin is formed upwards.

The result of the mixtures presents the same state as in the agitated case, and consequently, agitation will not be necessary in the field. In this way, the procedure is simpler and more efficient.
Figure 29: Polyacrylamide sample 375:1. No agitated (left) and agitated (right).

Figure 30: Polyacrylamide sample 250:1. No agitated (left) and agitated (right).

Figure 31: Polyacrylamide sample 125:1. No agitated (left) and agitated (right).
The selection of the range of dosages to be tested is based on the following thinking:

The most diluted mixture (375 : 1) is discarded because it is too liquid, since the product is not able to absorb all the water. This would make the mixture be more likely to seep into the cracks in the borehole produced by drilling and the characteristics of the soil, disappearing and thus, losing the desired effect. The range of 250: 1 - 125: 1 is selected, since it is considered to be a gelatinous state that would make the mixture less prone to filter in the field. This range will be divided into dosages with a difference of 15 mL of water, resulting in a total of nine samples (Table 17).

Table 17: Range of tested hydrogel samples.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Water (mL)</th>
<th>Sodium polyacrylate (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>235</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>205</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>190</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>175</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>145</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>130</td>
<td>1</td>
</tr>
</tbody>
</table>
For each of them, the following tests will be carried out:

- **Tilt**: beaker tilt 45°. In order to analyse the behaviour of excess water, if any, like adherence to vessel walls and stabilisation time.

- **Vibration**: repeated beating on the walls of the beaker. In order to analyse movement, vibration, etc. of the mixture.

- **Wettability**: by using common paper squares of 2 cm x 2 cm (Figure 32) that are marked every 0.5 cm. Vertical insertion of the paper by using pliers on the surface of the mixture for 30 seconds, as shown in Figure 33 (left). In order to analyse the paper after its extraction, such as moisture level and adhesion of the mixture. Next, another paper is placed horizontally on the surface (Figure 33 right). The results are compared with that obtained in water.

- **Cut**: making marks using a spatula on the surface of the mixture. In order to analyse the resistance to marking, consistency, plasticity or shape recovery.

- **Dump**: dumping the mixture from a height of 1.9 m to imitate the behaviour of the mixture before a shock (as in the field is the explosion). In order to analyse the adhesion, the resistance to overturning, the time required for dumping, the compactness, the radius of spreading, the permanence of the form after the overturning, and any other related behaviour (Figure 34).

![Figure 32: Paper square prepared for wettability test.](image-url)
Figure 33: Wettability test.

Figure 34: Result of the dump test of the sample #5.
The results of the tests are summarized schematically in the following tables (Table 18 to 22):

**Table 18: Tilt test.**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water-hydrogel separation. Liquid-gelatinous state.</td>
</tr>
<tr>
<td>2</td>
<td>Water-hydrogel separation.</td>
</tr>
<tr>
<td>3</td>
<td>Gelatinous behaviour.</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogel responds slowly to inclination. No traces of water on side walls.</td>
</tr>
<tr>
<td>5</td>
<td>Slow inclination. No traces of water on side walls.</td>
</tr>
<tr>
<td>6</td>
<td>No reaction to the inclination. No traces of water on side walls.</td>
</tr>
<tr>
<td>7</td>
<td>No response to the inclination. No traces of water on side walls.</td>
</tr>
<tr>
<td>8</td>
<td>No response to inclination. No traces of water on side walls.</td>
</tr>
<tr>
<td>9</td>
<td>No response to inclination. No traces of water on side walls.</td>
</tr>
</tbody>
</table>

**Table 19: Vibration test.**

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slightly vibration of small but appreciable amplitude.</td>
</tr>
<tr>
<td>2</td>
<td>Slightly vibration of small but appreciable amplitude.</td>
</tr>
<tr>
<td>3</td>
<td>Non-appreciable vibration. Compact state.</td>
</tr>
<tr>
<td>4</td>
<td>No.</td>
</tr>
<tr>
<td>5</td>
<td>No.</td>
</tr>
<tr>
<td>6</td>
<td>No.</td>
</tr>
<tr>
<td>7</td>
<td>No.</td>
</tr>
<tr>
<td>8</td>
<td>No.</td>
</tr>
<tr>
<td>9</td>
<td>No.</td>
</tr>
</tbody>
</table>
Table 20: Wettability test.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wettability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vertical: paper does not remain vertically, similar to water case. Small granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: small spheres of hydrogel remain adhered to the paper. Wet paper surface uniformly, pierced by water, but without getting rid of.</td>
</tr>
<tr>
<td>2</td>
<td>Vertical: paper does not remain vertically, similar to water case. Small granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: small spheres of hydrogel remain adhered to the paper. Wet paper surface uniformly, pierced by water, but without getting rid of.</td>
</tr>
<tr>
<td>3</td>
<td>Vertical: paper holds vertically. Small granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: small spheres of hydrogel remain adhered to the paper. Paper surface not wetted uniformly.</td>
</tr>
<tr>
<td>4</td>
<td>Vertical: paper holds vertically. No film of liquid. Small granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: small spheres of hydrogel remain adhered to the paper. Paper surface is not wet.</td>
</tr>
<tr>
<td>5</td>
<td>Vertical: paper holds vertically. No film of liquid. Small granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: small spheres of hydrogel remain adhered to the paper. Paper surface is not wet.</td>
</tr>
<tr>
<td>6</td>
<td>Vertical: paper holds vertically. No film of liquid. Granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: spheres of hydrogel remain adhered to the paper. Paper surface is not wet.</td>
</tr>
<tr>
<td></td>
<td>Granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: spheres of hydrogel remain adhered to the paper. Paper surface not wet.</td>
</tr>
<tr>
<td></td>
<td>Granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: spheres of hydrogel remain adhered to the paper. Paper surface not wet.</td>
</tr>
<tr>
<td></td>
<td>Granular remnants of mixture remain adhered to the paper.</td>
</tr>
<tr>
<td></td>
<td>Horizontal: spheres of hydrogel remain adhered to the paper. Paper surface not wet.</td>
</tr>
<tr>
<td>Sample #</td>
<td>Cut</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>No resistance to cutting. The cut disappears.</td>
</tr>
<tr>
<td>2</td>
<td>No resistance to cutting. The cut disappears.</td>
</tr>
<tr>
<td>3</td>
<td>No resistance to cutting. The shape of the cut remains.</td>
</tr>
<tr>
<td>4</td>
<td>Mild resistance to cut. The shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
<tr>
<td>5</td>
<td>Resistance to cut. Shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
<tr>
<td>6</td>
<td>High-cut resistance. Shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
<tr>
<td>7</td>
<td>High-cut resistance. Shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
<tr>
<td>8</td>
<td>High-cut resistance. Shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
<tr>
<td>9</td>
<td>High-cut resistance. Shape of the cut remains. Granular particles adhere to the spatula.</td>
</tr>
</tbody>
</table>
Table 22: Dump test.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dump</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogel turn over immediately. Non-compact mixture. Splatter. Flattening of dump surface. Remains of water move towards the outside.</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogel does not overturn completely, 10% remains stuck in the glass. No splash. No flattening on dump surface, mound shape. No traces of water in displacement. Spherical shape.</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogel does not overturn. Compact mixture.</td>
</tr>
<tr>
<td>7</td>
<td>Hydrogel does not overturn. Compact mixture.</td>
</tr>
<tr>
<td>8</td>
<td>Hydrogel does not overturn. Compact mixture.</td>
</tr>
<tr>
<td>9</td>
<td>Hydrogel does not overturn. Compact mixture.</td>
</tr>
</tbody>
</table>
As it can be seen, the difference between some sections is not really visible. However, in #3, #5 and #9 there are appreciable changes.

In all tests, samples #1 and #2 have a too-liquid state. That is, there is too much water in relation to the product, which means that not all water is absorbed. This aspect is negative since in the field there are more possibilities of leaking through the cracks in the ground or those created by the drilling of the hole.

Also in all cases, it is appreciated that sample #3 marks a turning point in the behavior of the mixtures. In the inclination test, it is the first dosage that is capable of absorbing all the water, thereby creating a homogeneous hydrogel; in vibration, it is the first one that does not vibrate after the disturbance; in the wettability test, it is the first one that holds the paper vertical; in the cut, it is the first one that conserves the form; and in the dump test, it is the first one that does not show traces of water in displacement after the collision with the ground. All these characteristics prove that this is the first dosage that presents a gelatinous state instead of a liquid state.

Sample #5 has some characteristics that differentiate it from #3 and #4, which are very similar. For example, it is the last sample that can be inclined, since the following ones (#6 to #9) will not respond to this stimulus; it is the first one that presents a high resistance to the cut; and it is the first one that does not overturn completely, keeping 10% of its total adhered in the beaker. These characteristics are taken into account to find a not too gelatinous mix and for a correct application in the field, and the overturning of the mixture in the hole to its expansion in it and after the explosion.

Finally, between samples #6 and #9 there are no significant differences in their behavior. They are mixtures with a high gelatinous and thus, “a priori”, no interesting for this project. Then, they are discarded, with the exception of sample #9, which will be tested in the field as a higher threshold concentration value to evaluate if it gives new information to the investigation or if it represents an advantage in dust mitigation after the explosion.

4.1.2.1 Sample preparation for field actions

The preparation for the test consisted of preparing the amount of sodium polyacrylate that would be used in each hole. Each dosage was transported in hermetic common zip bags (Figure 35). In order to facilitate the use of water in the field, an empty water bottle was also prepared, which was marked up to certain capacities so that the exact amount of water could be calculated (Figure 36).
The necessary quantity of mixture was calculated from the dimensions of the hole according to the Table 23. The useful height of the hole destined for the mixture was one metre, which goes from the lower gravel pile, placed above the explosive charge, until reaching the level of the upper gravel pile. The perforation diameter was 0.089 m. In addition, extra bags were prepared in case any unforeseen event had arisen.

*Figure 35: Bags with dosages prepared in the laboratory.*

*Figure 36: Water bottle with intermediate capacities marked.*
Table 23: Calculation of the quantity of mixture needed in blasting (used water density during the tests is marked in red).

<table>
<thead>
<tr>
<th>Type of water</th>
<th>Salinity (g/L)</th>
<th>Water density (g/cm(^3))</th>
<th>Water density (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled</td>
<td>0</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>Tap</td>
<td>3</td>
<td>1.003</td>
<td>1003</td>
</tr>
<tr>
<td>Ocean</td>
<td>33-37</td>
<td>1.033-1.037</td>
<td>1033-1037</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blasthole</th>
<th>Useful length (m)</th>
<th>Diameter (m)</th>
<th>Volume (m(^3))</th>
<th>kg water</th>
<th>L water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.089</td>
<td>0.0062</td>
<td>6,2398</td>
<td>6,2398</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.089</td>
<td>0.0062</td>
<td>6,2398</td>
<td>6,2398</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.089</td>
<td>0.0062</td>
<td>6,2398</td>
<td>6,2398</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dosage: L (for 1g of product)</th>
<th>Dosage (g product) for 1L</th>
<th>Dosage (g product) for 6L</th>
<th>Dosage (g product) for last incomplete L</th>
<th>Total dosage (g product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.22</td>
<td>4.55</td>
<td>27.3</td>
<td>1.1</td>
<td>28.4</td>
</tr>
<tr>
<td>5</td>
<td>0.19</td>
<td>5.27</td>
<td>31.62</td>
<td>1.27</td>
<td>32.89</td>
</tr>
<tr>
<td>9</td>
<td>0.13</td>
<td>7.7</td>
<td>46.2</td>
<td>1.85</td>
<td>48.05</td>
</tr>
</tbody>
</table>

109.34 total polyacrylamide

4.1.3 Dosage

From the tests carried out, a selection of the samples most appropriate to test in the field should be made. To optimise the time and resources, the selection should be limited to three, and this number is also sufficient to make a representation of the entire tested range, since it is not necessary to test a larger number in the field because the difference in the behaviour is not always great.
To choose the correct dosages, we must take into account the characteristics that have been mentioned above, which are summarised below:

- Fluency: important for the moment of making the mixture in situ and its subsequent overturning in the hole (the mixture will be made outside and not inside).
- Filtration: it is important to avoid residual water or a liquid state that causes a leakage to possible cracks in the hole, resulting in an unwanted concentration or an insufficient effect.
- Spreading: appreciable when dropping the mixture from a certain height and observing the result after the collision with the ground (since it will receive the shock caused by the explosion). A mixture that is spread over a larger radius is thought to be more convenient.
- Agglomeration: so that the granules that are formed after the shock are smaller, helping the recreation.

Based on these criteria, samples #1 and #2 are disregarded because they are susceptible to filtration. Mixtures #4, #6, #7 and #8 are also disregarded for not showing appreciable differences with the immediately superior ones. In this way, the selected dosages are #3 and #5. Sample #9 will also be tested in order to test the lower limit in case its application in the field indicates that a lower dilution is better for future blasting.

In order to characterise the selected samples quantitatively and to obtain numerical values to establish a relationship with other products, the calculation of their densities and their viscosity indexes in the laboratory was carried out. For this, the densities were measured first by the use of a pycnometer, and then the Stokes law was applied in order to obtain the viscosity indexes by using the standardised norm (UNE-EN ISO 12092) and useful bibliography (Shearer and Hudson, 2002) for its application in the laboratory.

The calculation of the densities, and the necessary measures for this, are only carried out for the samples selected as more convenient. To carry out these measurements, the procedure of the standard UNE-EN ISO 12092 has been followed, but some modifications have been applied due to the available material in the laboratory and to the test conditions, and in order to adapt it to the specific nature of the material.

The used instruments were:
- Glass pycnometer.
- Thermometer (incorporated in pycnometer).
- Filter paper.
- Syringe.
- Acetone.
- Desiccator.
- Test tubes.
- Double rinse pipette.
- Pear for pipette.
- Weighing machine.

The measurement procedure using a pycnometer followed these steps:

1) Weighing of empty pycnometer.
2) Filling of the pycnometer with the required dosage.
3) Weighing of the pycnometer and mixture.

Controlling the temperature of the tests and the liquid (both at room temperature), and knowing that the used pycnometer has a capacity of 50 mL, density can be calculated using the general density formula:

\[ \text{Density} = \frac{(\text{filled pycnometer mass} - \text{empty pycnometer mass})(g)}{\text{pycnometer volumen (cm}^3\text{)}} \] (21)

Applying the values in the Table 24:

**Table 24: Measurements with pycnometer.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dosage</th>
<th>Pycnometer</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Product g</td>
<td>Water mL</td>
<td>Product g</td>
</tr>
<tr>
<td>#3</td>
<td>1</td>
<td>220</td>
<td>0,32</td>
</tr>
<tr>
<td>#5</td>
<td>1</td>
<td>190</td>
<td>0,37</td>
</tr>
<tr>
<td>#9</td>
<td>1</td>
<td>130</td>
<td>0,54</td>
</tr>
</tbody>
</table>
The pycnometer used (Figure 37) was calibrated before carrying out the tests by calculating the density of distilled water, which is known. The process has been repeated three times, cleaning the pycnometers with acetone to eliminate any remaining liquid, and drying the instruments in a desiccator instead of electric ones, to avoid the expansion of the glass because of the heat.

![Figure 37: Pycnometer with thermometer used for the test.](image)

For the procedure of measurement by the Law of Stokes the test is prepared according to the standard UNE 1067. Some modifications have been applied due to the available material in the laboratory and to the test conditions, and in order to adapt it to the specific nature of the material. The following elements were used:

- Test tubes.
- Corks.
- Graph paper.
- Digital gauge.
- Metal balls.
And the working procedure was as follows:

1) Each mixture was prepared in a test tube, in which a strip of graph paper was placed outside.
2) A metal ball was introduced into every test tube. These balls were previously cleaned to prevent any dirt embedded in its surface which could influence the result. They were measured with the digital caliber (Figure 38) and weighed on a precision scale (Figure 39). The results can be seen in Table 25.
3) The test piece is closed with a cork, and the system is left to rest until the ball reaches the bottom of the test tube or stops falling through the mixture (Figure 40).
4) Subsequently, the system is turned 180º, and the distance travelled by the ball, appreciable with accuracy thanks to the built-in strip of graph paper, is calculated in a fixed time (Figure 41).
5) The Law of Stokes is applied (see section 2.2.1).

<table>
<thead>
<tr>
<th>Metal ball</th>
<th>Measure</th>
<th>Diameter (cm)</th>
<th>Volume (cm³)</th>
<th>Mass (g)</th>
<th>Density (g/cm³)</th>
<th>Average (g/cm³)</th>
<th>Final (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1,265</td>
<td>1,059</td>
<td>8,338</td>
<td>7,866</td>
<td>7,866</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,265</td>
<td>1,059</td>
<td>8,338</td>
<td>7,866</td>
<td>7,866</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,265</td>
<td>1,059</td>
<td>8,338</td>
<td>7,866</td>
<td>7,866</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1,265</td>
<td>1,059</td>
<td>8,339</td>
<td>7,867</td>
<td>7,867</td>
<td>7,868</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,265</td>
<td>1,059</td>
<td>8,339</td>
<td>7,867</td>
<td>7,867</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,265</td>
<td>1,059</td>
<td>8,339</td>
<td>7,867</td>
<td>7,867</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1,265</td>
<td>1,059</td>
<td>8,342</td>
<td>7,871</td>
<td>7,871</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1,265</td>
<td>1,059</td>
<td>8,342</td>
<td>7,871</td>
<td>7,871</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,265</td>
<td>1,059</td>
<td>8,342</td>
<td>7,870</td>
<td>7,870</td>
<td></td>
</tr>
</tbody>
</table>

Table 25: Stokes’ Law measurements.
Figure 38: Measurement with digital caliber.

Figure 39: Precision scale four decimals.

Figure 40: Law of Stokes’ test.
Figure 38 shows the moment, for the three samples, in which the metal balls, after being introduced into the test tube, stop in their descent, since the viscosity of the mixtures does not allow them to continue descending. The elapsed time was 20 minutes.

The results obtained with both procedures are consistent.

Selected dosages are resumed in Table 26.

Table 26: Field dosages for polyacrylamide.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dosage</th>
<th>Polyacrylamide</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>130</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>190</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>220</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
As it is have been mentioned in section 4.1.2, although it is considered that the time necessary for the mixture to be completed is two minutes according to the manufacturer, it has been observed that the real time is higher, of approximately 5 minutes. Therefore, in the field, it will be considered that mixtures have been correctly made after 5 minutes.

4.1.4 Field test with polyacrylamide

The mixture of sodium polyacrylate and water could be tested in one of the bench blastings programmed in Monte Espartinas quarry owned by Sain Gobain Placo Iberica located in San Martin de la Vega, near Madrid. Figure 42 is a view of the open-pit and the blasting bench.

![Open-pit and blasting bench](image)

Figure 42: Open-pit and blasting bench.

The holes reserved for the use of the investigation were located as shown in Figure 43. This figure represents only a section of the first row of holes. The blast began in the left profile, being the blasthole number 1 (B1) the fifth in the row from the beginning. Between the used holes, a space of two intermediate holes was left, in order to improve the visualisation of the result and to be able to distinguish the effect of the different mixtures. All the boreholes were initially dry.
Saint Gobain Placo Iberica took care of providing the necessary water and containers to prepare the mixture.

It was decided to make the mixtures on the outside of the hole for a better control of them and to avoid leaks. The filtration can be produced by two factors: the characteristics of the terrain, which is, a priori, the case of greater severity, or by cracks or fissures that may have occurred in the walls of the hole during drilling. In addition, from the laboratory tests it is known that the dump inside the hole is feasible thanks to the gelatinous states of the selected sample.

The terrain in this case is constituted by marls (Mapa Geológico de España, IGME). The marl is a type of sedimentary rock mainly composed by calcite and clays, with predominance, generally, of calcite, which gives it a whitish colour with shades that can vary quite according to the different proportions and compositions of the main minerals.

The concentrations in the blastholes were ordered as follows:

- Borehole 1: Sample #9. The most concentrated one.
- Borehole 2: Sample #5. The intermediate one.
- Borehole 3: Sample #3. The less concentrated one.

Once the explosive charge is introduced into the bottom of the blasthole, and is covered with 20 cm of gravel, the procedure for the mixture was as follows:
1) The vessel is filled with the amount of water needed for 1 m of the hole (Figure 44 left). To obtain the exact measurement, water is first introduced per entire litres and then, for the fractions of incomplete litres, the marked bottle is used (Figure 44 right).

2) The polyacrylamide is added. The marked bags are used to add the corresponding dose (Figure 45 left).

3) It takes five minutes to form the hydrogel (Figure 45 right). While this is happening, a measuring tape with a plumb is introduced to measure the exact free depth, for later checks.

4) Pouring of the mixture from the vessel, introducing the hydrogel (Figure 46 right) into the charged blasthole (Figure 46 left).

5) The depth is measured again with the metre with a plumb line, to check whether there has been any leakage.

Here the existing problem could already be appreciated. In the minutes after the dump, when measuring the depth using a metre with plumb, it was observed that the hydrogel has "disappeared". That is to say, despite the gelatinous state of the mixture, filtration through the ground had not been avoided. This effect was enhanced by the type of terrain.

6) Blasthole is covered with gravel (Figure 47 left).

7) The used blastholes are marked. On the one hand, they are marked on the ground by a green spray (Figure 47 right). On the other hand, empty sandbags are placed on the face of the bench to identify the location of the holes from the distance at the time of the explosion (Figure 48).

Figure 44: Preparation of the water (left) and auxiliary bottle for water measurement (right).
Figure 45: Product addition (left) and hydrogel formation (right).

Figure 46: Charged blasthole (left) and dump of the hydrogel (right).
Figure 47: Used gravel (2.4 cm) (left) and marking of blasthole with spray (right).

Figure 48: Marking of the blastholes in the face of the bench.
4.1.5 Conclusions of field test with polyacrylamide

From the on-site tests, interesting conclusions that will mark the future of the investigation are obtained.

On the one hand, it is extracted that the calculation of the mixture is simple, consisting of only two compounds. The polyacrylamide is easy to prepare and transport, and very large or heavy amounts of it are not required for the usual volumes of a bench blasting. As for water, it is a part of easy supply, available in any operation, and of which very high volumes are not needed either. In addition, the mixture is safe for human beings and the environment. It does not require special security measures, and neither its preparation nor its discharge requires more than five minutes or more than two people (with one would be sufficient). Also, it does not interfere in the rest of the works that are being carried out in the bench.

On the other hand, no significant results could be obtained as the mixture dispersed in the field. An effect could not be seen during the blasting, nor at a later time when returned to the blasting area. Nevertheless, it is extracted that the use of this mixture cannot be used without a container medium, as it is very sensitive to filtration through the ground. Therefore, it is thought to use liners in the future, similar to those used for ANFO in wet holes. It seems appropriate to use liners that are first introduced empty in the hole, with a bottom load, and then to fill them by dumping from the surface. This would be the way to avoid another problem that could arise in case of introducing the liners already filled from the surface, since tears could occur by friction with the walls of the hole or with some irregularity or roughness existing in them.

From now on, the decision is made to look for new solutions and not to continue focusing on the use of polyacrylamides. The reason is that it is considered that the search for the reduction of the superficial tension of the water by means of the use of surfactants could be more interesting, instead of an increase of it. In addition, the polyacrylamide does not seem to show the desired effect of engulfing the powder particles with the hydrogel granules. This is probably due to the gelatinous state of the mixture, too thick to trap the particles inside. Therefore, it is considered that it would be more efficient to focus on a mixture with a more liquid behavior that contains another product that enhances the water-mitigating effect.
4.2 Surfactant

After studying a hydrogel-type compound, the possibility of having been looking in the opposite direction arises. That is, rather than gelling, which would tend to reduce the surface area of water, the surface area should be increased by some type of foaming additive to reduce the surface tension of water. In order to dust particles raise the rate of water absorption, this new option is valued and investigated, which will result in better soil wetting.

Surface tension is the phenomenon by which the surface of a liquid tends to behave as if it were a thin elastic film (Zoilo, 2008). It is a manifestation of intermolecular forces in liquids, and together with the forces that occur between liquids and solid surfaces that come into contact with them, it gives rise, for example, to capillarity.

The conclusion of following this line comes after seeing applicable solutions offered by certain companies in the agricultural sector who avoid the formation of puddles after watering. These are formed because of the surface tension of the liquid drop. The degradation of the surface tension results in the collapse of the drop, which spreads and wets the entire surface without dripping. This raises the rate of absorption, increasing soil moisture.

The phenomenon by which a substance reduces surface tension by dissolving in water or another aqueous solution is termed surface activity.

When talking about surface activity, we must also talk about the surfactant agents, which are substances that influence by means of surface tension the contact surface between two phases (Zoido, 2008). The market for surfactants is currently distributed as follows (Sanz, 2010):

- 33% Soaps, carboxylates, lignosulphonates, where:
  - 50% household soaps,
  - 35% industrial use soaps.
- 22% Synthetic detergents of the sulphonate or sulphate type, where:
  - 50% domestic use (powders, liquids),
  - 17% oil industry,
  - 7% cement additives,
  - 4% agro-food,
  - 3% cosmetics, pharmaceutical products.
- 40% Non-ionic ethoxylates, where:
  - 40% alcohol ethoxylates,
  - 20% alkyl phenol ethoxylates,
  - 15% fatty acid ether,
  - 10% amine or amide derivatives.
- 4% Cationic, especially quaternary ammonium.
- 1% Amphoters, especially betaines and amino acid derivatives.

4.2.1 Properties of surfactants

The properties of surfactants are obtained through their molecular structure. They are composed of a hydrophobic part and a hydrophilic, or water soluble moiety. According to their molecular structure they can be classified as (Figure 49):

- Anionic surfactants: They are the most produced on an industrial scale in terms of volume and are the most used at the domestic level. In terms of effectiveness / price ratios, they are the best in general. Natural soap is an anionic surfactant.
- Cationic surfactants: They have bactericidal properties and can kill different microorganisms or at least delay their growth.
- Non-ionic surfactants: Frequently used for tableware, they do not form much foam.
- Amphoteric surfactants: Used in shampoos and creams to be used on the skin.

![Figure 49: Classification of surfactants.](image-url)
Surfactants are one of the best ways to reduce the surface tension and, therefore, can be applied to formulations to raise the rate of water absorption. Surfactants can also be used to improve the penetration of agrochemicals and control soil-borne diseases, such as nematodes and fungi. Among the surfactants are synthetic substances that are regularly used in washing, including products such as laundry detergents, dishwashers, products to remove dust from surfaces, and also shampoos.

The interest of surfactant compounds lies in their amphiphilic character. A molecule is amphiphilic when it has a polar-nonpolar double affinity (Sanz, 2010). That is, the presence of the same molecule of two or more groups with antagonistic properties with respect to the same solvent. All amphiphilic substances have a common molecular structure that has two parts: a polar group containing heteroatoms such as O, S, P or N that are in alcohol, acid, sulphate, sulphonate, phosphate, amine, amide, etc.; and an apolar or less polar group which is in general a hydrocarbon group of the alkyl or alkyl benzene type, and which may optionally contain halogen or oxygen atoms. The polar part has affinity for polar solvents, in particular for water, and is commonly referred as hydrophilic part. By contrast, the apolar group is called the hydrophobic or hydrophobic part, or lipophilic (from the Greek "phobos", fear, and "lipos", fat).

Thus, the surfactant molecules, owing to their amphiphilic character, possess the property of solubilising polar and nonpolar molecules. The following formulas show two common amphiphilic molecules used as cleaning agents (Figure 50).

\[ \text{CH}_3(\text{CH}_2)_{15}\text{CH}_2\cdot\text{COO}^-\text{Na}^+ \]
\[ \text{CH}_3(\text{CH}_2)_{10}\cdot\text{CH}_2\cdot\text{SO}_3^-\text{Na}^+ \]

*Figure 50: Amphiphilic molecules of cleaning agents.*

In the presence of water or other polar or apolar solvent, the amphiphilic molecules self-aggregate spontaneously adopting diverse morphologies (spherical, laminar, cylindrical, spiral...) with different degrees of curvature and characteristic dimensions. These associations are due to weak intermolecular interactions (Van der Waals, hydrogen bridges, etc.). Therefore, the enthalpy of the formation of these aggregates is small and, therefore, its shape and size can be controlled by modifying parameters such as amphiphilic concentration, temperature, pH, etc.
Amphiphiles have many properties and are classified according to their applications: soaps, detergents, dispersants, emulsifiers, foaming agents, bactericide, corrosion inhibitors, antistatic, etc. or according to the type of structures they form: membranes, microemulsions, liquid crystals, liposomes or gels.

It should be noted that, for the purposes of this project, two main groups acquire particular importance: detergents, which are used to separate dirt from any type of surface; and emulsifiers, which allow the emulsion of oil in an aqueous solution (emulsifier o / w) or of water in an organic solution (emulsifier w / o). Due to the amphiphilic capacity of these surfactants, they are able to mix two immiscible phases forming stable emulsions.

Because of their double affinity, amphiphilic molecules "do not fit well" in a solvent, apolar or polar, since there will always be an interaction that will not be satisfied. This is why amphiphilic molecules show a strong tendency to migrate to the interfaces, in such a way that their polar group is inside the water and their apolar group is oriented towards an apolar organic solvent or on the aerial surface. The hydrophilic groups are solvated in the aqueous part and the lipophilic ones are arranged in the apolar phase (air or fat).

![Diagram of monomolecular layer](image)

*Figure 51: Monomolecular layer of aqueous solution.*

In aqueous diluted solutions, a monomolecular layer is formed on the surface as shown in Figure 51. As the concentration of the tensioactive substance increases, its molecules are oriented in the water forming micelles constituted by 25 to 200 chains (Figure 52).
Figure 52: Orientation of molecules forming micelles.

Due to this orientation, some amphiphilic molecules have the property of decreasing the surface tension in an air-water or fat-water interface. It is necessary to emphasise that not all amphiphiles possess such activity. Then, it is necessary that the molecule possess relatively balanced properties, that is, it is neither too hydrophilic nor too hydrophobic.

As a consequence of this decrease in surface tension these substances have the following properties:

- Detergent power or ability to remove dirt and grease from a surface (skin, fabric, etc.).
- Emulsifying power or ability to produce colloidal dispersions of fat in aqueous medium or water in fat medium.
- Foaming power that leads to foam formation.
- Wetting activity that makes the water impregnate a surface in a homogeneous way.

The detergent power and the ability to form emulsions have the same principle, the surfactant molecules are adsorbed on the oil or fat particles, eliminating them from the surface in the first case, and forming stable micelles, in the second case, due to the repulsion between particles with a negative charge. The foaming power is due to the fact that an aqueous surface protected by a lipophilic layer envelops air bubbles. The wetting power of surfactant aqueous solutions is due to the "anchoring" of the lipophilic chains on the surface to be wetted; thus, for example, the impregnation of the fabrics in the dyeing or washing operations in the textile industry is facilitated, or the pesticide solutions applied on the leaves of the plants are prevented from forming drops that slip without adhering, which would nullify the effectiveness of the treatment.
Due to these properties the surfactants have very important technical applications. Thus, most of the surfactants manufactured are destined to detergents that are used in compositions with other products. Other applications are the preparation of emulsions (mainly in food, cosmetics, acrylic paints, and insecticide preparations), the separation of minerals by flotation, as bactericides, in the drilling of oil wells and in many other applications.

4.2.2 Laboratory tests with surfactant

As the surfactants are compounds that are incorporated in a large number of products and applications in the day to day, it was decided to select products of easy acquisition. This is also positive thinking about the possible future application.

On the one hand, it was decided to use a regular household detergent for domestic use. This is a concentrated generic detergent available in any supermarket (Figure 53).

![Concentrated dishwashing machine used in tests.](image)

This product is composed of less than 5% amphoteric and non-ionic surfactants, between 5% and 15% anionic surfactant, 2-bromo-2-nitropropane-1,3-diol, Methylchloroisothiazolinone, Methylisothiazolinone, and perfumes.
On the other hand, in order to test another type of surfactant, a sparkling agent was purchased from an event company (Figure 54). It is a liquid specially formulated to use with semi-dry foam cannons with snow effect.

![Foaming liquid carafe.](image)

Figure 54: Foaming liquid carafe.

This product is composed of between 10% and 30% of anionic surfactants, preservatives such as Methylchloroisothiazolinone, Methylisothiazolinone, and sodium C10-16 pareth-2 sulphate.

In the laboratory, the objective is to observe the properties and behaviour of the selected products, to establish the most efficient dosages, and to look for additives that could enhance the effect of the compound. To do this, series of qualitative tests will be carried out, focused on being able to compare and to check the appearance of the desired surface tension. In addition, different ways of applications in the field will be designed and detailed, to avoid problems arising during the first blasting.
For the tests, the following elements will be used:

- Bubble blower (Figure 55).
- Beaker.
- Test tube.
- Bottle of foam concentrate.
- Glycerine.
- Commercial concentrated dishwasher.
- Tap water.
- Funnel.
- Agitator.
- Funnel.
- Gloves.

*Figure 55: Bubble blower.*

The tests will be first carried out on mixtures of one part of foamer (sparkling agent) and other of water, and then on one part of detergent other of water. The objective is to find three dosages, since in the next blasting it will be possible to test three blastholes.
In all cases it is important to add the water first and then the product, since otherwise the foam would be formed immediately and it would not be possible to clearly observe its behaviour. Also for this purpose the dump will be done through a funnel.

The tests to be performed will be the following:

- Formation of bubbles by a bubble blower after the product overturning.
- Formation of bubbles after slight agitation.
- Formation of bubbles after strong agitation with an agitator for one minute.

The formation of bubbles, their consistency, their duration in time and their size are a sample of the surface tension of the liquid, so this is why it is used here as a basis for comparison.

- The samples have been shaken with a sudden movement similar, but with lower energy, to that produced by the impact of the blast.

The aim of the tests is to estimate the formation of foam in the field, and to decide the behaviour that could be more suitable there.

The photographic report of all the essays is in Annex D.

First, the samples of foam are tested. According to the manufacturer's instructions, it is initially tested a dosage of 20% in volume. All the samples will be based on 100 mL.

Then a lower and higher value will be taken, in an equidistant way to the concentration marked by the manufacturer in order to establish a comparison and then to choose the most suitable mixture. In this way, values of 30% and 10% in volume will be taken.

The result of the tests are resumed in Table 27.

After these tests, it is demonstrated that the most concentrated mixtures have, logically, a more foamy behaviour, and therefore have a higher surface tension than the less concentrated ones. Although a decrease in surface tension with respect to the hydrogel is sought, a sufficient foaming state is desired.
Table 27: Result of the laboratory tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dosage (mL product : mL water)</th>
<th>Result of the tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>After product overturning</td>
</tr>
<tr>
<td>1</td>
<td>20 : 80</td>
<td>No bubbles</td>
</tr>
<tr>
<td>2</td>
<td>30 : 70</td>
<td>Bubbles that move</td>
</tr>
<tr>
<td>3</td>
<td>10 : 90</td>
<td>No bubbles</td>
</tr>
</tbody>
</table>

A small amount of glycerine is now added to the samples (Figure 56). The glycerine comes from the distillation of olive oil attacked with methanol, and is usually used as a reaction catalyst such as, for example, caustic soda, and it also has a large number of industrial and civil applications. Glycerine can be easily purchased at a pharmacy. 6 mL of glycerine is added to each of the three samples, and then the whole mixture is stirred.

When compared to the previous tests:

- Sample 1 (20%): larger bubbles are formed and they move. Increased foam formation.
- Simple 2 (30%): larger bubbles are formed, they move, and they even bounce from the ground until they break. Increased foam formation.
- Simple 3 (10%): larger bubbles are formed and they move. Increased foam formation.

Therefore, after the addition of glycerine it is clear that it is positive to give consistency to the foaming state of the mixtures. As it is a non-polluting organic product, its application is possible in the field.
The tests are then carried out on the detergent and water mixture. The detergent is a generic concentrated dishwasher. There is no specified dosage from the manufacturer, but it is considered appropriate to test a dosage of 1/3 of dishwasher and 2/3 of water.

The result of the tests are resumed in Table 28:

*Table 28: Result of the tests after the addition of glycerine.*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dosage (mL product : mL water)</th>
<th>Result of the tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>33.33 : 66.67</td>
<td>Easy formation of bubble that move</td>
</tr>
</tbody>
</table>
After the addition of 6 mL of glycerine larger bubbles are formed, they move and bounce from the ground until they break. Increased foam formation.

The characteristics of the foam formed in each case are summarised in Table 29.

Table 29: Foam generated in tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Foam height (mm)</th>
<th>Foam quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>dense, stable</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>dense, stable, homogeneous</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>dense, stable</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>dense, stable, homogeneous</td>
</tr>
</tbody>
</table>

4.2.2.1 Sample preparation for field actions

On the other hand, it was necessary to devise the way of placing the mixture in the blastholes to avoid filtration on the ground. Being in this case the mixture more liquid than in the case of the hydrogel, with which there were already problems in this regard, it was decided to try the application of liners.

The liners were supplied by MAXAM. The liner roll shown in Figure 57.

The total length supplied is 265 m. The diameter is 13 cm, and the liner has a thickness of 600 gauges. The roll is continuous, so it is possible to cut off the desired length by using scissors.
To test the functionality of the liner in this case, sections of 1.5 m were prepared. The purpose was to have a useful length to be tested of approximately 1.2 m. It was oversized because it must be taken into account the loss of length due to the closure of the liners.

It was decided that in the field, the empty liner would be introduced first, since in case of introducing it after filling, friction with the walls of the holes or with some roughness could occur, which would cause its deterioration or tearing, filtering the liquid to the ground. The bottom load is necessary to introduce the liner within the hole up to its lower limit.

For laboratory tests, a drill core was introduced as a bottom charge (Figure 58), and then, the liner was filled with water. In this way, its resistance to the total weight can be checked.

The problem arises in the way in which the liner can be closed to avoid the liquid coming out. The main problem occurs in the base, since it must withstand the vertical pressure of the bottom load plus the weight of the fluid, and it must prevent its escape. The liner must be inserted closed and hermetic in the base of the blasthole. At the top, the liner must be initially open in order to dump the mixture inside. Here, in the upper part, there is not the same problem of leakage and pressure than at the bottom for closing the liner.

Firstly, the base was closed by using insulating tape, double-sided tape, and folding, as shown in Figure 59 (left and right). Flanges were also used to reinforce the closure. It was observed that, although initially it seems to be an effective solution, after a brief time a constant dripping of liquid begins to be appreciated. It must take into account that in the field, the time elapsed between the preparation of mixture refilling and blasting is usually around two hours, so a constant trickle will make the liquid disappear almost completely during all that time.

This liner was left to rest overnight vertically, in the position that can be seen in Figure 60, and the result was the complete emptying of the interior of the liner. Therefore, this option did not prove to be adequate.

It was decided to perform a simple knot on both the top and bottom of the liner, as shown in Figure 61. This action requires a total length of the liner greater to maintain the complete useful length for the mixture, since to make the knot about 20 cm are required. This technique, although simple, worked correctly, preventing water from leaving the bottom of the liner. To add more security, it is decided to knot the lower part of the liner twice, with only one knot in the upper part once the mixture is poured.
This liner was left to rest overnight in the same position as before, and after that time the liquid level decreased only a few centimetres, as can be seen in Figure 62. This is an acceptable loss considering that the time between the installation of the liner and the blasting is shorter.

Figure 57: Liner supplied by Maxam.

Figure 58: Bottom charge.
Figure 59: Closure with insulating tape (left) and insulating tape, flanges, and bending (right).

Figure 60: Resting position of the liner.
Figure 61: Knot closure.

Figure 62: Decrease in fluid level.
### 4.2.3 Dosage

All samples meet the requirements initially defined as necessary. However, it is preferable to make a selection between the foaming mixtures, since significant results are sought, and, in addition, it will be possible to test only three blastholes in the field.

Therefore, it is decided to select the lower and upper thresholds tested for the foaming. In this way, the most concentrated and the less concentrated behaviours will be seen in the field, in order to appreciate the differences that could occur there, since the intermediate value represents only a medium term but no significant advantage.

In this way, the dosages to be tested are those shown in Table 30:

Table 30: Field dosage for surfactant.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Dosage</th>
<th>Added glycerine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surfactant Water</td>
<td>mL in base 100 mL</td>
</tr>
<tr>
<td>2</td>
<td>Foaming liquid 30%</td>
<td>70%</td>
</tr>
<tr>
<td>3</td>
<td>Foaming liquid 10%</td>
<td>90%</td>
</tr>
<tr>
<td>4</td>
<td>Dishwasher 33.33%</td>
<td>66.67%</td>
</tr>
</tbody>
</table>

### 4.2.4 Field test with surfactant

These mixtures could be tested in one of the production blasts carried out in El Aljibe quarry.

All the field trials that are carried out have as objective the evaluation of the technical feasibility of this solution to be implemented in the normal activity of a mine. The evaluation of the dust suppression has been done, qualitatively, as in the previous blasting, since as has been said, this work includes the first phase of the investigation. In a second phase, the dust reduction will be evaluated quantitatively with equipment similar to those used in section 3.
The necessary preparation for the in-situ test consisted of acquiring all the necessary material and in carrying out the calculations of dosages and quantities.

The material that was brought to El Aljibe was:

- 5 bottles of generic concentrated dishwasher of 1 L, acquired in any supermarket (Figure 63 left).
- 1 bottle of 5 L of glycerine, purchased at a pharmacy.
- Bottle of foaming liquid.
- Bottle with marked measurements to make more accurate measurements.
- 3 liners of 1.7 m (plus several spares in case they are necessary) (Figure 63 right).

![Figure 63: Used dishwasher (left) and prepared liner (right).](image)

The calculations, visible in the Table 31, were made in this case for a useful hole height of 1.2 m, and a drilling diameter of 0.089 m. The added glycerine was 4% by volume in each case.
Table 31: Calculation of the quantities of surfactants.

<table>
<thead>
<tr>
<th>Type of water</th>
<th>Salinity (g/L)</th>
<th>Water density (g/cm³)</th>
<th>Water density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled</td>
<td>0</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>Tap</td>
<td>3</td>
<td>1,003</td>
<td><strong>1003</strong></td>
</tr>
<tr>
<td>Ocean</td>
<td>33-37</td>
<td>1,033-1,037</td>
<td>1033-1037</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Useful blasthole length (m)</th>
<th>Diameter (m)</th>
<th>Volume (m³)</th>
<th>Kg water</th>
<th>L water</th>
<th>Blasthole capacity (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2</td>
<td>0,089</td>
<td>0,007</td>
<td>7,49</td>
<td>7,49</td>
<td>7,49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Blasthole capacity (L)</th>
<th>Water (L)</th>
<th>% water</th>
<th>% foaming liquid</th>
<th>Dishwasher %</th>
<th>% dish-washer</th>
<th>% added glycerine</th>
<th>Added glycerine (L)</th>
<th>Total (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7,19</td>
<td>5,03</td>
<td>70,00</td>
<td>2,16</td>
<td>30,00</td>
<td>+</td>
<td>4,00</td>
<td>0,30</td>
<td>= 7,49</td>
</tr>
<tr>
<td>3</td>
<td>7,19</td>
<td>6,47</td>
<td>90,00</td>
<td>0,72</td>
<td>10,00</td>
<td>+</td>
<td>4,00</td>
<td>0,30</td>
<td>= 7,49</td>
</tr>
<tr>
<td>4</td>
<td>7,19</td>
<td>4,79</td>
<td>66,67</td>
<td>2,40</td>
<td>33,33%</td>
<td>+</td>
<td>4,00</td>
<td>0,30</td>
<td>= 7,49</td>
</tr>
<tr>
<td>Σ</td>
<td>16,29</td>
<td>2,88</td>
<td></td>
<td>2,40</td>
<td></td>
<td></td>
<td></td>
<td>0,90</td>
<td>22,46</td>
</tr>
</tbody>
</table>

Three blastholes were charged in a blast with 159 in total with three different concentrations of surfactant (Figure 64).

Figure 64: Scheme of the location of the boreholes used in El Aljibe quarry.
From the initial point of the blast the concentrations were ordered as follows:

- Blasthole 1: Sample #3. The lowest concentration of foaming liquid.
- Blasthole 2: Sample #2. The higher concentration of foaming liquid.
- Blasthole 3: Sample #4. Dishwashing.

The average depth of the holes was 16 m. The holes presented water inside due to the rainfall that had occurred in the area and that had been drilled for some time. In borehole 1 there was 5 m of water, in borehole 2, 7 m of water and in borehole 3, 6 m of water.

The total useful length of the borehole for the pile-up was two meters. The operators put 40 cm of graded sand (0/6 mm) above the explosive and under the liner. The liner was placed and another 40 cm of sandpaper was placed on top of it.

The procedure for placing the liner in the quarry was as follows:

1. The hole was charged to a length from the collar of 2 m.
2. 2 m of the liner was cut.
3. Two knots were made in one of the ends of the liner. This area constitutes the base of the liner.
4. Insulating tape was used to reinforce the base of the liner and prevent the leakage of liquid.
5. A stone previously wrapped in insulating tape was introduced inside the liner with care not to cause rips.
6. 40 cm of gravel was introduced into the hole.
7. The empty liner was introduced into the hole taking care not to tear it and proceeded to fill it, first with the water and then with the asset being careful not to generate foam inside the liner.
8. The liner is closed, either with a knot, or with a flange, depending on the accessibility to make the knot in the hole.
9. 40 cm of gravel was placed above the liner.
10. The used blastholes were marked with red spray (Figure 65).

Figure 66 shows the blasting bench during the preparation of the blasting.
Figure 65: Used blasthole marked with red spray.

Figure 66: Performing works prior to blasting.
On this occasion it was possible to have a high-speed camera to record the blasting. Specifically, it is the Fastcam SA3 model (Figure 67).

Designed to provide ruggedness and reliability, the Photron Fastcam SA3 offers high performance recording for a broad range of applications in research and development of different sectors. The Fastcam SA3 ensures system stability under High-G conditions and long-term system reliability. Fastcam SA3 system design features a built-in battery for backup of images stored in memory in case of a power loss, optional keypad with integrated viewfinder and it provides exceptional light sensitivity, image quality and colour fidelity.

Some of the features are:

- Suitable for operations in High-G environments. Operation tested to 100 G, 10 msec, 6 axis.
- 17 μm pixel size to ensure high light sensitivity for demanding frame rates or low light applications.
- 2 μs global shutters electable independent of the frame rate.
- Composite video output for real time monitoring during set up, recording and playback.
- Optional remote keypad control with integrated viewfinder.
- 4 GB recording memory options.
- High performance Gigabit Ethernet interface.

Technical data sheet is available in Annex C.

*Figure 67: Fastcam SA3 high-g high-speed video system.*
On this occasion, the video was recorded with a recording speed (frames per seconds) of 1600 and with a resolution of 740x640 pixels. The recording time was 5 seconds.

### 4.2.5 Conclusions of field test with surfactant

Below there is a detailed analysis of the results of each hole, thanks to the images obtained with the high-speed camera (Figure 68).

![Figure 68: Initial situation of blasting.](image)

- **Borehole 1 (Figures 69 to 71):** It can be seen that after the blast, dust is ejected a bit more than in the adjacent ones. Not in the shape of a “pen”, as if it was badly plugged. It could be because the hole with the plugging of mixture is less effective at first than the plugging used in the other holes.

  At the beginning of the explosion, this effect is appreciated: the liner with mixture seems less effective in its function as a pile-up than drilling detritus, which is the material used in the other blastholes (Figure 70). Initially, in the tested blastholes, a "plume" of dust arises, which does not happen in the rest of the blastholes because of the difference in effectiveness of the aforementioned pluggings. Later, however, the dust does not spread in the form of a "pen", but a "mushroom" shape is formed by the effect of the surfactant, which causes the dust not to disperse and become trapped near the ground (Figure 71).
Figure 69: Evolution of blasthole 1 ($1.82625 \times 10^6$ ms).

Figure 70: Evolution of blasthole 1 ($2.09375 \times 10^6$ ms).

Figure 71: Final evolution of blasthole 1 ($2.376875 \times 10^6$ ms).
In borehole 2, nothing seems to be especially appreciated in comparison with the other blastholes in which the normal practices followed by the quarry were used.

Blasthole 3 (Figures 72 to 74): an effect similar to blasthole 1 seems to be appreciated, although to a lesser extent. Not to be confused with the pen produced in the second row of holes.

Figure 72: Evolution of blasthole 3 ($2.4457 \times 10^6$ ms).

Figure 73: Evolution of blasthole 3($2.4475 \times 10^6$ ms).
Figure 74: Final evolution of blasthole 3 (3.248125 x 10⁶ ms).

Once the blasting is finished (Figure 75), it is not possible to appreciate the difference of grey tonalities (humidity) or any other useful characteristic as using only three separated holes, being surrounded each one of them by holes charged normally.

Figure 75: After blasting (3.95125 x 10⁶ ms).
The conclusions can be summarised in the following:

- The liner disintegrates with the explosion: it does not shoot out vertically. This is positive and is one of the main necessary things to test. In a view of the muckpile, no liners cannot be appreciated nor humid fragments (the fact that the blast has several rows may be the reason for such result).
- The field application (dosage and mixture) of this technique is simple.
- The blasthole 2 (it has a higher concentration and, moreover, more water due to rain) is the one that ejects less dust. The blasthole 1 (it has the lowest concentration and, in addition, less water due to rain) is characterised by the "mushroom effect", which has the negative part of expelling dust from the top, and the positive part that this expulsion is not vertical, seeming the mixture can keep the dust close to the ground, not letting it escape higher. The blasthole 3 (it has dishwasher and intermediate quantity of water quantity due to rainfall) has an intermediate behaviour.
5 CONCLUSIONS

This work has been done as a first phase to apply mitigation measures to dust emission in blasting. In a second phase, tests will be carried out in El Aljibe quarry in six different blast in order to obtain quantitative measurements and to evaluate the effectiveness of the solutions devised in this first phase.

This work is the result of an intensive collection and review, and a meticulous study of the state of the art of dust emission in mining. From this, the necessary concepts have been compiled, the origin of the generation of dust in this sector has been understood, the existing mitigating methods have been classified, and the existent knowledge about other phases of production has been extrapolated to the case of blasting. Based on this, solutions consisting of improving the water mitigation effect, which is the most effective agent so far, have been developed.

To obtain quantitative data in the field, it is recommended to make dust measurements with specific instruments destined to this aim similar to those used in the measurement campaign of El Aljibe in 2017, presented in section 3 of the Memory. The data obtained in that campaign will be used in order to be able to make a comparison between the use of the selected technique and the usual operation. The following baseline information, obtained during the usual blasting operation is shown below:

- To evaluate TSP and PM10, instruments based on filters are used in different locations of the quarry pit limits and in different activities: drilling, blasting and cleaning, and fugitive sources. It has been concluded that mining activities do not produce significantly different TSP concentrations than the quarry bottom levels. The high resistance of the rock (high UCS and low LAAV, see section 3) agrees with the low level of rock dust and low production of PM10 extracted in El Aljibe. When PM10 concentrations can be determined, only half of the measurements are above the 50 mg / m³ limit.

Figure 26, which appears in section 3, shows that monitored blasting do not produce significantly different concentration of TSP than the background levels in the quarry, 187.9 sd. 90.1 versus 154.2 sd. 56.3 μg/m³, respectively (mean and standard deviation values). The mass of PM10 retained in the filter is in general below the quantification limit of the laboratory (0.3 mg, Table 12) and the resulting concentration values are an upper bound.
- Occupational breathable particulate matter and respirable crystalline silicon dioxide are evaluated with a personal sampling device during drilling, preparation and execution of the explosion, and cleaning. No significant differences have been detected in the measurements of occupational dust among mining activities, but the highest average values of concentration occur in the perforation, while the smallest values are obtained in the mucking activities. Figure 27, which appears in section 3, shows that the dust produced by the blast is low. The reason for such result is that the initiation point is always upwind the blast and that the blaster does not come back to the block until the dust plume has been dispersed. All occupational concentrations are below the threshold values of 3 mg/m$^3$ for respirable matter and 0.1 mg/m$^3$ for crystalline silica.

In this first phase, the objective has always been to find technically feasible solutions for its implementation in the field. All of them start from the reality that water is the most effective agent for the mitigation of dust, so a product capable of enhancing its effect must be found.

For this reason, in this research, two main lines have been followed: the use of polyacrylamides for the generation of a hydrogel in order to increase the surface tension of water, and the use of surfactants to reduce it. From the qualitative results obtained here, the following conclusions can be drawn:

- Both solutions are easy to prepare, since they consist of mixtures of water with other products in which is only necessary to perform the calculations to generate the proper dosage. The tested dosages in the field fulfilled the expected behavior after the laboratory tests, thus, the tests are considered adequate and reliable. In addition, the application in the field is also simple and allows not interfering in the rest of the works that are carried out during the preparation of the blasting.

- After the first field test, where the polyacrylamide was applied, it was found that a means of containment is necessary for the mixture inside the hole. The hydrogel had a gelatinous behavior and not liquid, but despite that, any mixture with water seems to be very sensitive to seepage through the ground due to cracks of the terrain or to those caused by borehole drilling.

- To avoid the problem of the previous point, the option of the liner looks to be adequate. It is simple, easy to apply, and the design seems the most appropriate. Maybe other resistant materials to avoid breakage could be tested but it must always allow the cartridges to be easily prepared and also it must ensure that it breaks completely after the explosion enabling
the correct dispersion of the liquid. In the case of the liner, when tested in the field in the second blast, the one corresponding to the tests with the surfactant, it was found that it does not shoot out vertically due to the explosion, which was one of the main concerns and would have forced to devise other solution.

- Although, due to filtration problems of polyacrylamide in the field test, specific qualitative results could not be obtained, it was decided to focus the research in another direction. The reason is that it is considered that the search for the reduction of the superficial tension of the water by means of the use of surfactants could be more interesting, instead of an increase of it, with the aim of achieving greater dispersion of the mixture in the area of blasting. In addition, the polyacrylamide does not seem to show the desired effect of engulfing the powder particles with the hydrogel granules. This is probably due to the gelatinous state of the mixture, too thick to trap the particles inside. Therefore, it is considered that it would be more efficient to focus on a mixture with a more liquid behavior that contains another product that enhances the water-mitigating effect.

- When testing surfactants, it seems that this solution is adequate for the purpose of the project. The recording of the blasting with the high-speed camera allowed observing the behavior of these mixtures, and positive conclusions seem to have been obtained. The "mushroom effect" that can be seen in hole 1 of the blasting of El Aljibe shows that the mixture is able to retain dust closer to the ground, avoiding vertical dispersion and subsequent transport due to wind.

- The addition of glycerin in the laboratory proved to be a fundamental step to improve the characteristics of the surfactant, so its use in the field is recommended.

- During the development of the research, possible options have been ruled out from the moment of their idealization. The reason is that it should be taken into account that there are also other considerable features, especially in the case of performing tests or studies on a larger scale, such as attention to any environmental risk that the used product could cause, or the fact that the use of water or liquids may affect the subsequent treatment of the exploited resource.

- The current strategy consists on evaluating the effectiveness of the surfactant in the blasts that will be carried out in phase two of this investigation. The used surfactant will be the dishwashing detergent, since it has been proven in the field that both, this and the foaming liquid, have similar effects. The purchase of detergent is much simpler, since it is possible to buy it in any conventional physical supermarket. In addition, it represents a cheaper option.
6 FUTURE RESEARCH

Future research could start from the obtained conclusions in this work, where two main lines of work have been followed.

As mentioned, these works have been carried out as a first phase of the research, consisting of a literature review and the initial search for suitable products for this purpose and have been based mainly on qualitative analysis.

The second phase will consist in the application of all the techniques and knowledge acquired in the first phase in future blasting that will take place in El Aljibe quarry.

These blasts, similar to the ones where quantitative data measured and obtained, will be made in a similar position as those of the campaign of 2017. Here the use of the liner as means of containment of the mixture will be applied. These mixtures will be those of the surfactants analysed in this project.

As it is planned to use six blasting in that quarry to continue with the field tests of this project, it is considered appropriate to divide this number to test certain characteristics in each fraction. The final objective is to establish the characteristics of the mixture that generate a greater mitigating power.

When checked in the field both the in-situ preparation and the result obtained, it is found that the effect of the foaming liquid and the dishwasher is the same. Thus, the tests will be carried out with the last one. This is because its acquisition is much simpler, since it is possible to buy it in any conventional physical supermarket. In addition, it represents a cheaper option. The foaming liquid is a more specific product, whose acquisition is done over the internet, so it may depend on the delivery times and shipping costs.

First, two blasts with normal pile-up will be used, that is, the blast will be carried out in the usual way, without mixtures. These will serve to perform the reference measurements and to take the baseline values to be able to compare the results with those obtained in the following tests in which the solutions developed in this project will be included.

Then, two blasting will be used to test and to obtain quantitative measurements of the dust with the selected dosages after the tests made in this project. The products to be used are: detergent, water,
and glycerin. The concentrations are the following: 33.33% detergent, 66.67% water (1/3 : 2/3), and addition of 4% by weight of the mixture of glycerin.

And finally, in two other blasting, mixtures with greater dosages will be tested. The products to be used are: detergent, water, and glycerin. The concentrations are the following: 66.67% detergent, 33.33% water (2/3 : 1/3), and addition of 4% by weight of the mixture of glycerin.

In this way, the suitability of the selected dosages will be checked, and it will be analysed if the changes in the concentrations present any advantage in the field.

In order to obtain comparable values in a quantitative way, PM10 and TSP dust measuring equipment will be used, in positions similar to those of the previous campaign. In addition, we will also proceed to record each of the blasting with the high-speed camera that was used in the last blast of this project and that is previously described, in order to be able to analyze in detail the effect of the mixtures at the time of the explosion and post-explosion.

On the other hand, throughout this work have also been valued other lines of research, from all the concepts studied, the meetings that have taken place with different entities, and the search for new possibilities. These options can be taken into account for future investigations that seek a different approach after having tried the solutions already mentioned.

For example, and considering that they could require greater investment in operation time and resources, one possibility would be drilling extra holes, or irrigating the whole blasting bench. In this last case of watering, there are polymeric acrylic additives with a conglomerate base that can reduce the amount of water used, reaching levels of 1 kg of product per 300 L of water. It should be taken into account that water is also a resource.

Another option could be to use starches that foam with heat, as they could foam with detonation. The starch granules are insoluble in cold water, but they can contain water when the temperature increases, that is to say, the granules of starch produce the process called gelatinisation.

In addition, the research could be extended to the generated dust during the drilling of the boreholes. This activity generates dust too, and depending on the terrain, the climate, or the blast dimensions, it can be a considerable source of it. In this sense, the studies could start from the methods of cooling or injection of water in drilling, technique already used in the drilling operations.
7 REFERENCES


Control and Prevention, National Institute for Occupational Safety and Health, NIOSH Information Circular 9.


- [Petavratzi et al., 2005] Petavratzi E., Kingman S., Lowndes I. 2005: Particulates from mining operations: A review of sources, effects and regulations. Nottingham Mining and Minerals Centre, School of Chemical, Environmental and Mining Engineering, University of Nottingham, University Park, Nottingham NG72RD, UK.


ANNEXES
Annex A. Polyacrylamide data sheet
Protecciones de seguridad

Protección respiratoria: Use NIOSH / MSHA aprobado o equivalente con filtro de alta eficiencia para niveles de partículas superiores a 0.05 mg / m3.
Ventilación: según corresponda para controlar los niveles de polvo en el aire por debajo de los límites de exposición aplicables.
Guantes de protección: impermeable / de goma
Protección ocular: Gafas de seguridad
Otra indumentaria o equipo de protección: Ninguna
Prácticas de trabajo / higiene: Buenas prácticas de limpieza
OTRAS NOTAS: Resbaladizo cuando está mojado

Manipulación segura

Evítense el contacto con los ojos y la piel.
El contacto con los ojos, la piel o la ropa puede causar irritación. Se debe tener cuidado para minimizar la exposición y evitar la inhalación de polvo respirable en el lugar de trabajo. Se requiere protección respiratoria para exposiciones superiores al nivel recomendado de polvo respirable.
Lavar exhaustivamente tras la manipulación.

NOTA 1: En caso de contacto por cualquier vía proporcionar atención médica inmediata.
NOTA 2: La información y sugerencias son hechas con base en la experiencia e investigaciones realizadas, esto implica una garantía ya que se recomienda que cada cliente realice pruebas preliminares.
CONTACTE A SU ASesor TÉCNICO COMERCIAL.
CONSULTE LA HOJA DE DATOS DE SEGURIDAD
Annex B. Polyacrylamide security data sheet

HOJA DE DATOS DE SEGURIDAD

SECCIÓN 1. IDENTIFICACIÓN DE LA SUSTANCA O LA MEZCLA Y DE LA SOCIEDAD O LA EMPRESA.

1.1 Identificador del producto
Nombre comercial: OPTIMASORB
Nombre Químico: Poliacrilato de sodio reciclado.
1.2 Datos del proveedor de la ficha de datos de seguridad
Nombre del producto: OPTIMASORB
Compañía: OptimaSoil
C/ Trespaderne, 7 1ºA
28042, Madrid
Tel: 910020204
e-mail: info@optimasoil.com
www.optimasoil.com

SECCIÓN 2. CARACTERÍSTICAS FÍSICAS/ QUÍMICAS

2.1 Clasificación de la sustancia/mezcla y etiquetado:
Aspecto y olor: color blanco grisáceo de aspecto polvo granular
Punto de ebullición inodoro: N/A
Presión de vapor y densidad de vapor: N/A
Densidad aparente: 0.5 g/cc
Punto de fusión: N/A
Velocidad de evaporación: N/A

SECCIÓN 3. INFORMACIÓN PELIGROSOS

Componentes peligrosos: OSHA PEL - ACGIH TLV -
Otros componentes: Partículas respirables (polvo)
Límite de exposición recomendado (polvo) 0.05 mg / m3
NFPA / RMIS: Salud 1 Reactividad 0
Incendio 0 Peligro específico 0
Clase DOT: No regulado
SECCIÓN 4. Datos de peligro de incendio y explosión

Punto de inflamación: No disponible
Límites inflamables: No disponible LEL - - UEL - -
Medios de extinción: Cualquier

Procedimiento especial de lucha contra incendios: Al igual que con cualquier incendio, use un aparato de respiración autónomo de presión positiva en cualquier espacio cerrado cuando combata incendios.

Peligros inusuales de incendio / explosión: Bajo ciertas condiciones confinadas, un polvo fino concentrado de este material en el aire puede causar una explosión de polvo si se lo incluye.

SECCIÓN 5. REACTIVIDAD

Estabilidad de los datos: Estable
Incompatibilidad: Oxidantes fuertes
Descomposición o subproductos peligrosos: Descomposición térmica libera CO, CO₂, hidrocarburos. Polimerización peligrosa: No ocurrirá
Condiciones a evitar: Ninguna conocida

SECCIÓN 6. DATOS DE PELIGRO PARA LA SALUD

Vía (s) de entrada: Inhalación, piel, ojos
Peligros para la salud: El contacto con los ojos, la piel o la ropa puede causar irritación. Se debe tener cuidado para minimizar la exposición y evitar la inhalación de polvo respirable en el lugar de trabajo. Se requiere protección respiratoria para exposiciones superiores al nivel recomendado de polvo respirable.
Carcinogenicidad: Ninguna conocida
Signos / Síntomas de la exposición: Síntomas leves irritantes
Condiciones generalmente agravadas por la exposición: Enfermedades respiratorias

Procedimientos de emergencia y primeros auxilios:
Ojos: enjuague con abundante agua, consulte a un médico.
Piel: Lave con agua y jabón.
Inhalación: llevar al aire libre, consultar al médico

SECCIÓN 7. MEDIDAS DE CONTROL

Protección respiratoria: Use NIOSH / MSHA aprobado o equivalente con filtro de alta eficiencia para niveles de partículas superiores a 0.05 mg / m³.
Ventilación: según corresponda para controlar los niveles de polvo en el aire por debajo de los límites de exposición aplicables.
Guantes de protección: impermeable / de goma
Protección ocular: Gafas de seguridad
Otra inductaria o equipo de protección: Ninguna
Prácticas de trabajo / higiene: Buenas prácticas de limpieza
OTRAS NOTAS: Resbaladizo cuando está mojado.
SECCIÓN 8. PRECAUCIONES PARA UNA MANIPULACIÓN Y USO SEGUROS

Pasos a seguir en caso de que se libere o derrame material: si es posible, utilice un aspirador (utilizando un sistema con filtro HEPA) para evitar la generación de polvo en el aire.
Método de eliminación de desechos: Elimine de acuerdo con las regulaciones de cada país.
Precauciones que deben tomarse durante el manejo y almacenamiento: Almacene en un lugar fresco y seco. Evite respirar en polvo. Evite el contacto con la piel y los ojos.

SECCIÓN 9. INFORMACIÓN COMPLEMENTARIA

DESCARGO DE RESPONSABILIDAD: La información contenida en este documento está disponible únicamente para su consideración, investigación y verificación por parte de los destinatarios originales de este documento.
Los usuarios deben considerar esta información solo como un complemento de otra información recopilada o disponible para ellos. Los usuarios deben realizar determinaciones independientes de la idoneidad e integridad de la información de todas las fuentes para garantizar el uso y la eliminación adecuados de estos materiales para la seguridad y la salud de los empleados, los clientes y el medio ambiente. Esta información de riesgo no es un sustituto de la evaluación de riesgos en las condiciones reales de uso. Los usuarios tienen la responsabilidad de mantenerse informados en la actualidad sobre la información de riesgo químico, para diseñar y actualizar sus propios programas, y para cumplir con todas las leyes y regulaciones nacionales, federales, estatales y locales aplicables con respecto a la seguridad, la salud ocupacional, el derecho a saber y la protección del medio ambiente. OpimaSorb no hace que los materiales peligrosos se vuelvan no peligrosos: los líquidos acuosos se cambian meramente y temporalmente a un estado semisólido gelificado.
Annex C. High speed camera FASTCAM SA3 data sheet

**FASTCAM SA3**

A rugged, megapixel High-Speed imaging system for General Application and Automotive Safety Test recording

2,000fps operation at 1024 x 1024 pixels

Designed to provide ruggedness and reliability, the Photron FASTCAM SA3 offers high performance recording for a broad range of applications in research and development and automotive safety testing.

Like the award winning FASTCAM MH4 multi-head camera system the FASTCAM SA3 ensures system stability under High-G conditions and long term system reliability.

FASTCAM SA3 system design features built-in battery for backup of images stored in memory in case of power loss, optional keypads with integrated viewfinder and Gigabit Ethernet communication.

Utilizing Photron’s Emmy award winning sensor technology, FASTCAM SA3 provides exceptional light sensitivity, image quality and color fidelity.

Two FASTCAM SA3 models are available:

**Model 60K:** 1024 x 1024 pixel resolution at frame rates up to 1,000fps

**Model 120K:** 1024 x 1024 pixel resolution at frame rates up to 2,000fps

Both systems offer higher frame rates at reduced image resolution and two microsecond global shutter.

**FEATURES**

- Performance examples:
  - **FASTCAM SA3 Model 60K**
    - 1,024 x 1,024 pixels @ 1,000fps
    - 768 x 768 pixels @ 1,500fps
    - 512 x 512 pixels @ 3,000fps
    - 256 x 256 pixels @ 7,500fps
    - and at reduced resolution up to 60,000fps
  - **FASTCAM SA3 Model 120K**
    - 1,024 x 1,024 pixels @ 2,000fps
    - 768 x 768 pixels @ 3,000fps
    - 512 x 512 pixels @ 6,000fps
    - 256 x 256 pixels @ 15,000fps
    - and at reduced resolution up to 120,000fps

- Suitable for operation in High-G environments. Operation tested to 100G, 10m/sec, 6 axis.

- 17μm pixel size to ensure high light sensitivity for demanding frame rate or low light applications

- 2us global shutter selectable independent of frame rate.

- Composite video output for real time monitoring during setup, recording and playback

- Optional remote keypad control with integrated viewfinder

- 2GB or 4GB recording memory options

- High performance Gigabit Ethernet interface.
### FASTCAM SA3 Specifications

#### Frame Rate vs Image Resolution:

<table>
<thead>
<tr>
<th>Frame Rate (fps)</th>
<th>FASTCAM SA3 Model 8K Maximum Resolution (pixels)</th>
<th>FASTCAM SA3 Model 12K Maximum Resolution (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000fps</td>
<td>1024 x 1024</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>1,500fps</td>
<td>720 x 720</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>2,000fps</td>
<td>612 x 612</td>
<td>1024 x 1024</td>
</tr>
<tr>
<td>3,000fps</td>
<td>612 x 612</td>
<td>720 x 720</td>
</tr>
<tr>
<td>5,000fps</td>
<td>612 x 256</td>
<td>612 x 612</td>
</tr>
<tr>
<td>6,000fps</td>
<td>612 x 256</td>
<td>612 x 612</td>
</tr>
<tr>
<td>7,500fps</td>
<td>256 x 256</td>
<td>612 x 256</td>
</tr>
<tr>
<td>10,000fps</td>
<td>612 x 256</td>
<td>612 x 256</td>
</tr>
<tr>
<td>12,000fps</td>
<td>128 x 128</td>
<td>256 x 256</td>
</tr>
<tr>
<td>15,000fps</td>
<td>356 x 94</td>
<td>612 x 128</td>
</tr>
<tr>
<td>20,000fps</td>
<td>356 x 94</td>
<td>612 x 128</td>
</tr>
<tr>
<td>25,000fps</td>
<td>256 x 94</td>
<td>256 x 128</td>
</tr>
<tr>
<td>30,000fps</td>
<td>612 x 32</td>
<td>128 x 128</td>
</tr>
<tr>
<td>50,000fps</td>
<td>504 x 14</td>
<td>504 x 94</td>
</tr>
<tr>
<td>80,000fps</td>
<td>128 x 14</td>
<td>612 x 32</td>
</tr>
<tr>
<td>75,000fps</td>
<td>-</td>
<td>256 x 32</td>
</tr>
<tr>
<td>100,000fps</td>
<td>-</td>
<td>256 x 16</td>
</tr>
<tr>
<td>125,000fps</td>
<td>-</td>
<td>128 x 16</td>
</tr>
</tbody>
</table>

Recording duration at 1,000fps with 1,024 x 1,024 pixel image resolution:

<table>
<thead>
<tr>
<th>12-BIT recording mode</th>
<th>Standard 2GB memory capacity</th>
<th>Optional 4GB memory capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.36 seconds / 1,300 frames</td>
<td>2.72 seconds / 2,725 frames</td>
</tr>
</tbody>
</table>

- **Sensor**: CMOS (Bayer system color, single sensor) with 12-bit ADC and 17μm pixel size
- **Shutter**: Global electronic shutter from 16.7ms to 2μs independent of frame rate
- **Lens Mount**: Interchangeable F-mount and C-mount using supplied adapters. High-G block mount optional
- **Memory**: 2GB (standard), 4GB (optional)
- **Video Output**: NTSC PAL composite VBS (BNC), ability to zoom, pan and tilt within image via keypad (option). Live video during recording
- **Camera Control**: Through optional keypad with integrated controller and GPIO/IEEE488 protocol
- **Low light mode**: Low light mode selection for simple camera adjustment when working in low ambient light, high frame rate or short exposure modes.
- **Triggering**: Selectable positive or negative TTL 2Vpp or switch dosen
- **Trigger delay**: Programmable delay on external input and output triggers 100ms resolution
- **Phase Lock**: Enables cameras to be synchronized precisely together to a master camera or external source
- **Event markers**: Uses internal event markers and specific events within the image sequence in real time. Immediately accessible through software.
- **Recording Modes**: Start, End, Center, Manual, Random
- **Saved Image Format**: JPEG, AVI, TIFF, BMP, RAW (compressed or uncompressed) PNG and TIFF (8-bit). Images can be saved with or without image or comment data.
- **Data Display**: Frame Rate, Shutter Speed, Trigger Mode, Date and Time, Status (Playback/Record), Real Time, Frame Count and Resolution
- **Partitioning**: Up to 8 memory partitions may be set by the user.
- **Operating Temperature**: 0°C to 40°C
- **Mounting**: 1x 1/20 UNC, 1x 38-16 UNC, 6x M5
- **Dimensions and Weight**: 120mm H x 120mm W x 21mm D, weight 4.3kg (without lens)
- **Power requirements**: 100V - 240V AC ~1.5A, 50/60Hz optional DC operation 22-32 VDC, 6WVA

Specifications subject to change without notice.
Annex D. Photographic record

Laboratory tests with polyacrylamide:

Starting dosages of polyacrylamide (without agitation): 125:1 (top left), 250:1 (top right) and 375:1 (down).
Total of the tested samples of polyacrylamide (samples #1 to #9).
Example of the inclination test of the polyacrylamide.

Example of the dump test: the most diluted dosage (top left), intermediate dosage (top right), and a more concentrated dosage (down).
Example of the wettabily test of sample #5: paper inserted vertically (left) and paper placed horizontally on the hydrogel surface (right).

Remains of granules adhered to the paper of the sample #5 (left) and comparison of wettability test results (right).
Result of the dump test of the most concentrated sample (#9) (it does not overturn in the established test time, so it must be forced): spreading after the shock (top left), granules of the hydrogel (top right), remains adhered to the walls of the beaker (down).
Laboratory tests with surfactant:

*Foaming liquid specifications.*

*Inside of the foaming liquid carafe.*
Foam of sample #1 after the overturning of the foaming liquid (left) and generated foam after agitation of the three samples of foaming liquid (right).

Example of the use of the bubble blower in sample #1 (left) and generated bubbles (right).

Generated bubbles of sample #4 (dishwasher) where glycerin was added. Superficial tension allows bubbles to bounce off the ground without breaking.
Laboratory tests with the liner:

*Knots made as a method of closing the liner. This method prevent leakage of the mixture.*

*Liner closure by using tape, bending, and flanges. This method is not able to prevent the leakage of the mixture.*