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EXPERIMENTAL CHARACTERIZATION OF THE FLOWABILITY OF MATERIAL IN BLOCK/PANEL CAVING

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN MINERÍA

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RESUMEN

En minas de *block/panel caving* las características del flujo gravitacional del material afectan fuertemente la recuperación y productividad de un yacimiento. Debido a esto, es que las características de flujo del material hundido juegan un rol fundamental en la determinación, a nivel ingenieril, del diseño óptimo de la malla de explotación. Hasta el momento se han realizado pocos estudios sobre la fluidez del material en minería de caving, por lo que resulta trascendental estudiar esto.

El objetivo de esta investigación es cuantificar la influencia de fino, humedad, distribución granulométrica, y cargas verticales en la fluidez de mezclas de materiales finos y gruesos, usando un modelo físico escalado (1:75). Este modelo permite realizar experimentos de flujo confinado; bajo estas condiciones se pueden replicar los esfuerzos presentes en minas de *block/panel caving*. Por medio del análisis de Janssen-Walker, es posible calcular, de forma teórica, los esfuerzos en las paredes de un bunker completamente lleno de una sección transversal cualquiera. En consecuencia, se pueden escalar los esfuerzos existentes en una mina.

La fluidez del material puede ser cuantificada por medio de las colgaduras observadas en los puntos de extracción de una mina Lo mismo se aplica al modelo experimental, donde los factores que afectan son la distribución granulométrica y su relación con el tamaño de apertura de los puntos, la presencia de finos y agua, la carga vertical, el ángulo de fricción del material, e inclinación de las paredes del punto de extracción.

Los experimentos realizados se clasificaron en dos tipos dependiendo de las variables estudiadas. Con respecto a los resultados obtenidos, la fluidez se caracterizó tanto de forma cuantitativa como cualitativa. La fluidez se definió de forma cuantitativa como el número de colgaduras durante la extracción de 1000 toneladas de roca. Mientras que la fluidez se definió de forma cualitativa como “Flujo Libre”, “Flujo Intermitente”, “Flujo Asistido”, y “Sin Flujo”.

Dentro de las principales conclusiones se tiene que, las grandes colpas son el principal factor de colgaduras en los puntos de extracción y que la fluidez disminuye (aumento de colgaduras) al incrementar el confinamiento y el porcentaje de finos presente, y al haber presencia de humedad. En presencia de finos y humedad se tiene que el flujo disminuye considerablemente, pudiendo observarse experimentos donde el flujo de material debió ser asistido y otros donde simplemente, el flujo era inexistente. También, durante los experimentos de flujo confinado, se encontró la formación de colgaduras en altura, las cuales eran imposibles de descolgar y daban por finalizados los experimentos. Estas colgaduras varían de altura y diámetro dependiendo de la presencia de humedad y finos, siendo de menor altura, las que presentan mayor porcentaje de los factores antes mencionados.

El modelo a escala fue útil para comprender los efectos del confinamiento, la humedad y la presencia de finos en la fluidez del material. Los experimentos de flujo confiado mostraron potencial para ser aplicados en diseño minero.

ABSTRACT

In block/panel caving mines the characteristics of the gravitational flow of the material strongly affect recovery and productivity of a mine. Because of that, the attributes of the caved ore flow play a fundamental role in determining the optimum design of the mine layout. Until now only a few studies about the fluidity of the material in cave mining have been conducted. Given that, it is important to study about this.

The conducted research aims to quantify the influence of fine material, humidity, particle size distribution and vertical loads on the flowability of mixes of fine and coarse material, using a scaled (1:75) physical model. This model allows to conduct confined flow experiments; under these conditions the stresses which exist in block/panel caving mines can be replicated. Using the Janssen-Walker analysis it is possible to calculate, theoretically, the stresses in a wall of a completely full bunker of any transversal section. Hence, the existing stresses in a mine can be scaled.

The material's ability to flow in a mine can be quantified in terms of the observed hang-ups in the drawpoints. The same can be applied in the experimental model where the factors that control the flow are as follows: the friction angle, the applied vertical load, the inclination of the walls of the drawpoint, the water presence, and the particle size.

The experiments conducted were classified in two types depending on the studied variables. Regarding to the obtained results, flowability was characterized both quantitatively and qualitatively. Quantitatively, flowability was defined as the number of hang ups occurrences during the extraction of 1000 tons of broken rock. On the other hand, flowability was qualitatively characterized as "Free Flow", "Intermittent Flow", "Assisted Flow", and "No Flow".

The main conclusions of the research are that coarse material is largely responsible for hang ups in the drawpoints, and that the flow decreases (hang ups increase) when confinement and/or fines presence increase, and when there is water content. With the presence of humidity and fines the flow decreases considerably. Correspondingly, some of these experiments proved the necessity to assist the flow of material while others had no flow at all. Also, during the confined flow experiments, high hang ups were formed. These hang ups made it impossible to continue the experiments. Furthermore, the hang ups varied in height and diameter depending on the presence of fines and humidity, those with more of both of the former having a lower height.

The scaled model was successful for understanding the effects of confinement, humidity and fine percentage on the flowability of rock material. The experiments demonstrate the potential application of the scaled laboratory tests of confined flow towards mine design application.

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Introduction

Introduction

In the last decades, most of the world's gold and copper production has been obtained from open pit mines, having as exception the gold produced in deep mines at South Africa. Nevertheless, in the mining industry it can be observable that the depths of the open pits cannot increase. Not only costs favor underground mining methods when in open pits the strip ratio increases, but the uncertainty that the engineering capacity can assure the stability, the security and the productivity for deep open pits. Additionally, open pits have an environmental impact much higher than underground mines of the same production capacity. Furthermore, many of the already known ore deposits, and those that are being discovered are at depths higher than those reached by the nowadays deepest open pits. Mine deepening has made necessary to study new factors related to the nature and geomechanical behavior of the rock (Chacón et al. 2004). All of the above is reflected in that two of the biggest and oldest open pits, Chuquicamata and Bingham Canyon, are starting transitions to underground mines of caving (Carter & Rusell 2000, Flores 2004 and 2005).

Caving mining refers to every mining operation where the ore body is naturally collapsed after its base is extracted from drawpoints (Laubscher 1994). Block/Panel caving methods will be a key factor in the future of the mining industry due to its capacity to exploit massive low grade ore bodies and its costs, which are the lowest compared to other underground methods. Another factor that makes block/panel caving methods attractive, is that compared to other underground methods, they have the highest productivity per worker and automation potential (Brown 2007). These mining techniques are considered as the most productive underground mining methods provided that material flows steadily through the openings in the drawbell. In block/panel caving ore production is greatly affected by operational interferences associated with the caving process, especially those related to the gravity flow. The gravitational flow directly impacts mine design, productivity and mine recovery (Chitombo 2010). Consequently, the mine design capability to provide a given production rate is affected, among other factors, by the ore flow. Since hang up existence is the most common event which interrupts the flow of material, this phenomenon is frequently used to analyze the flow condition of broken rock (Troncoso 2006).

Motivation

As mentioned, nowadays massive mines are deepening (Castro 2014, Figure 0-1). This makes researching about block/panel caving methods a necessity because they are adequate for exploiting massive and low grade deposits. These methods' productivity depend on the operational interferences. The most critical interferences are hang ups and oversizes. Both depend on the ore properties, the stress conditions and size distribution among other factors. They are also affected by the secondary fragmentation, the vertical load and the fine migration.

It is important to research these interferences because they must be considered on the mine planning, mine design and the equipment selection. All of the mentioned factors affect the revenue of the project.

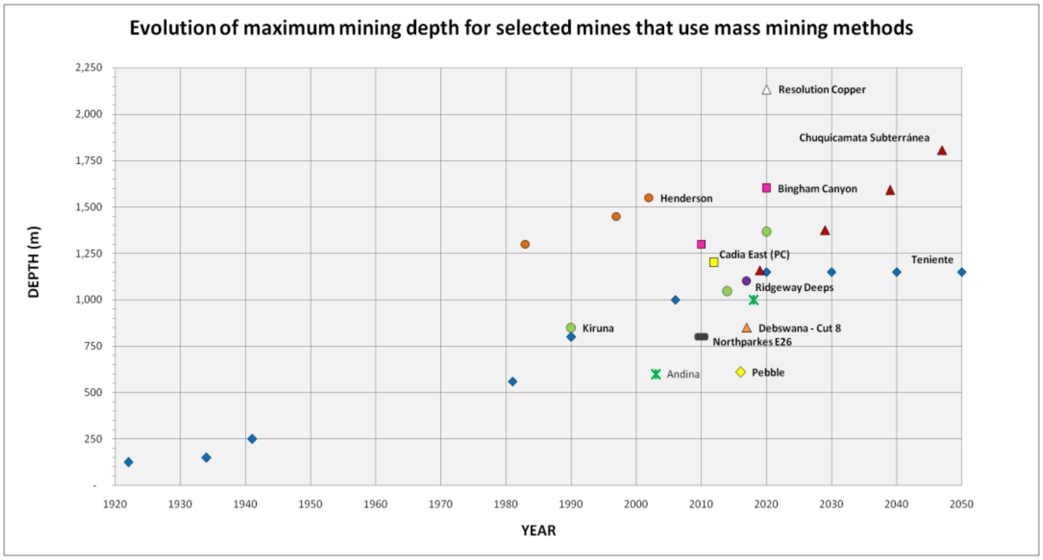

Figure 0-1: Evolution of maximum mining depth for selected mines that use mass mining methods (After Brown 2004)

Research objectives

The general and specific objectives of this research are as listed.

General objective

The main objective of this research is to experimentally quantify the influence of fine material, particle size distribution changes, and humidity on the confined gravitational flow.

Specific objectives

In order to achieve the main objective, the following specific objectives had to be accomplished:

- Research the state of the art of the effect of the humidity, fines presence, and particle size distribution changes on confined gravitational flow.
- Design and build an experimental set adequate for conducting the planned experiments.
- Quantify the number, measure the dimensions and qualify the type of hang ups obtained in the experiments. Additionally, define the flow condition of each experiment.
- Study the effect of the vertical load, humidity, and different particle size distributions on the flowability of the material regarding the experimental results. Furthermore, observe the effect of the previously mentioned variables on the flow zones.
- Generate an application on caving methods which relates the studied variables with the characteristics observed at mine scale.

Research scope

The scope of this research was the following:

- The research was conducted at laboratory scale with an experimental model with 1:75 scale.
- One or two drawpoints were used depending on the experiment. The material was extracted until a certain number of cycles were completed or until the experiment could not be continued.
- The effect of the following parameters were studied:
  - Particle size distribution
  - Fines presence
  - Water presence
  - Vertical load

Research methodology

The methodology of this research aimed to achieve the objectives, general and specifics. The following steps were proposed in order to fulfill the objectives.

1. Determine the variables to study: In order to generate an investigation methodology it was necessary to determine what was important to research and why it had to be researched. Then, the variables that impact the research objective were determined.
2. Design and build the laboratory equipment: Since there was no standard equipment for this kind of experiments, it was necessary to design and build some of the equipment to be used, being in this case, the drawbell and the extraction system.
3. Characterize the properties of the material: It was fundamental to know the characteristics of the material to be experimented since these characteristics defined the behavior of the flow of the material. Particle size distributions were determined together with the shape factor and the uniaxial compression strength of the material.
4. Experimental plan: In order to determine the experiments to be conducted it was necessary to study the ranges used for each of the studied variables.
5. Experiments: The determined experiments were conducted and the extracted mass, the number, type and height of hang ups, and the number of extraction cycles were determined. Additionally, the recovered markers were registered.
6. Experimental results analysis: Once the experimental results were obtained, they were analyzed and discussed in order to obtain conclusions about the effect of the studied variables.
7. Caving mining application: Once the data is analyzed, it was possible to obtain multivariable models capable of predicting hang ups.

In Figure 0-2 there is a diagram which shows the research methodology previously explained.

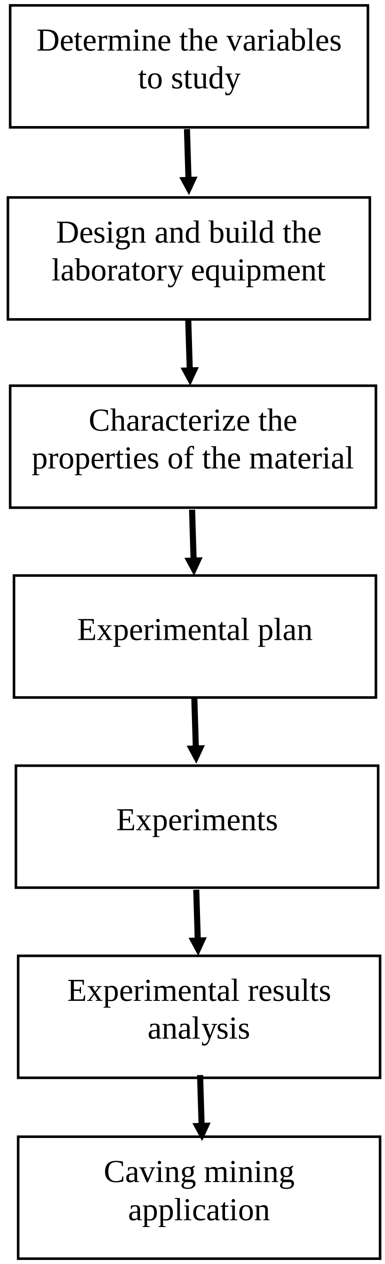

Figure 0-2: Research methodology

Thesis outline

The results of this research are presented in the following articles:

- Article 1: "Use of experiments to quantify the flow-ability of caved rock for block caving". Gómez, R., Castro, R. and Olivares, D., 2014, in Proceedings Caving 2014, Santiago, Chile, pp 299-306.
- Article 2: "Influence of fine material, humidity and vertical loads on the flowability of caved rock". Olivares, D., Castro, R., and Hekmat, A., 2015. Paper 582 of the 49th US Rock Mechanics/Geomechanics Symposium, San Francisco, United States of America, presented in Technical Session 28.
- Article 3: "Experimental characterization of the flowability of granular material in block caving mining". Castro, R., Olivares, D., Palma, S., and Hekmat, A., 2015. Paper sent to the Journal of the Southern African Institute of Mining and Metallurgy.

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Use of experiments to quantify the flow-ability of caved rock for block caving

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1.1. Abstract

Block/panel caving mining is a massive underground method, in which an ore column of broken rock is generated above the production level, as the cave propagates upwards through the ore body. As reserves deplete from near surface, the next generation of block caves will be carried out in deeper conditions than those currently known, with large column heights and therefore higher vertical stresses. There are unknowns related to the flow characteristics that deeper caves would face. The aim of this study is to quantify the impact of large vertical pressure on the flow-ability of fragmented rock. For this reason, experiments representing the stress and geometry conditions of deep caves were conducted under a range of vertical pressures, materials and humidity conditions. The results indicate that the flow-ability of caved rock depends on the vertical stresses, fines content and humidity conditions.

Keyword: caving mining, flow-ability, hang up, vertical stresses, fines and humidity content.

1.2. Introduction

In block/panel caving, ore production is affected by interferences associated with the caving process, especially those related to the gravity flow, such as hang ups and over size rocks. The mine design capability to provide a given production rate is affected, among other factors, by the ore flow.

Flow-ability is defined as the flow condition or ability of a granular material to flow under a given set of material properties, infrastructure geometry, and stress conditions. The flow-ability can be classified into free flow, intermittent flow, assisted flow, and no-flow (Castro, 2014). Kvapil (2008) indicates that flow-ability depends on many parameters including particle size, extraction rate, particles shape, surface roughness between particles, friction between particles, moisture content, compressibility, compaction, particle resistance, and magnitude, distribution and direction of external loads, and forces. However despite being listed the flow-ability under all those sets of parameters has not been quantified.

Flow-ability could be characterized both qualitatively and quantitatively. In terms of qualitative characterization, the flow could be qualified as free flow, intermittent flow and no flow depending on the ratio between particle size and opening (Laubscher, 2006). Studies on gravel have shown also that the flow-ability of granular material is influenced also by the vertical load (Fuenzalida, 2012). Castro et. al (2014) have proposed a flow-ability chart for coarse and dry rock which is presented in terms of vertical stress and drawpoint width/d_{50}.

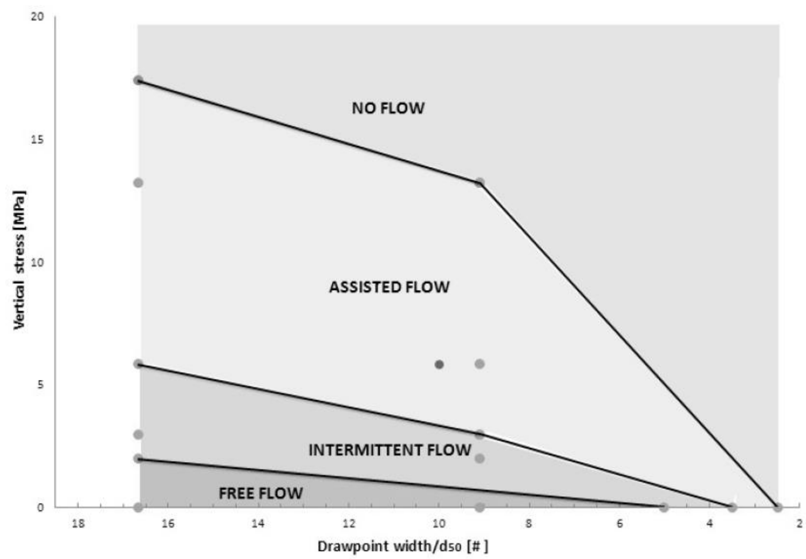

Figure 1-1: Influence of vertical stress in flow-ability

In quantitative terms flow-ability can be characterized in terms of the number of hang ups every 1000 tons or broken rock drawn. Hang ups are one of the flow interferences that affect productivity. Moreover, hang ups can be used to measure the flow-ability of material because when a hang up occurs it means the flow of material has been interrupted and the broken rock cannot be extracted (Troncoso, 2006). Two kinds of hang ups can be formed in coarse material: cohesive and mechanical (Kvapil, 2008. Beus et. al, 2001. Hadjigeorgiou & Lessard, 2007). The formation of arches on a rough wall is generated by the rotation of the principal stresses on the wall and by induced wall pressures (Handy, 1985). The dimensions of the arch depends on the friction angle of the material, depth or vertical stress, inclination of the walls in a drawpoint, draw rate, shape and strength of the particles, and humidity (Kvapil, 2008). At the mine it has been observed that as more material is extracted from a drawpoint the frequency of the hang ups decreases (Maass, 2013). This phenomenon is probably related to the decrease of the particle size during the extraction of an ore column (Montecino, 2001).

There are many unknowns related to the flow of materials especially under confined conditions. For example what is the role of the fines, water and stresses on the flow-ability of the broken rock. In this article we present the experiments conducted to evaluate the flow-ability of caved rock under high vertical load for different fines and humidity conditions. Extraction is carried out by a scaled LHD system to represent current caving characteristics.

1.3. Laboratory scaled model and material characterization

1.3.1. Experimental set up and materials

The experiments were conducted in a set up to study confined flow. This consist of a steel cylinder which is filled with broken rock (70-80 kg of crushed ore) under a hydraulic press machine with a capacity of 1,800 kN. The steel cylinder has diameter of 340 mm, as shown in Figure 1-2. A cylindrical shape was chosen to avoid the concentration of stresses at singularities. The height of the designed cylinder is 700 mm in order to hold the desired volume of gravel and to suit the emulated Andina mine drawbell with a scale of 1:75 (see Figure 1-2-b), with a rectangular opening of 53 x 96 mm^2. Since the drawbell is located in the center of the cylinder, flow zones will not intersect the walls of the model. A steel extraction system was built to replicate the extraction the same as LHD does from an extraction point (see Figure 1-2-a).

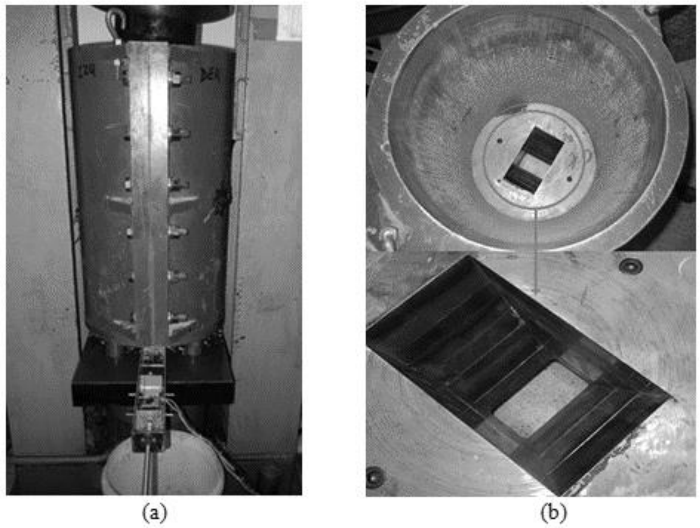

Figure 1-2: Experimental equipment: (a) cylindrical model in a press machine which changes the vertical load, σV, and (b) extraction system, located in the bottom, center of the model

The material used in the experimental tests was crushed sulphide ore with a high aspect ratio to represent the geometry of caved rock (sphericity of 0.58 and a roundness of 0.25). Two different particle size distributions of this material were prepared and tested: one with a passing size d_{80} of 11.8 mm and the other one with a d_{80} of 15.6 mm. Both samples have the same uniformity coefficient (C_u=d_{60}/d_{10}) of 2. Those particle size distributions were scaled from the size distribution of the primary fragmentation curve of the underground´s Chuquicamata project (Figure 1-3). Table 1-1 summarizes the characteristics of the samples.

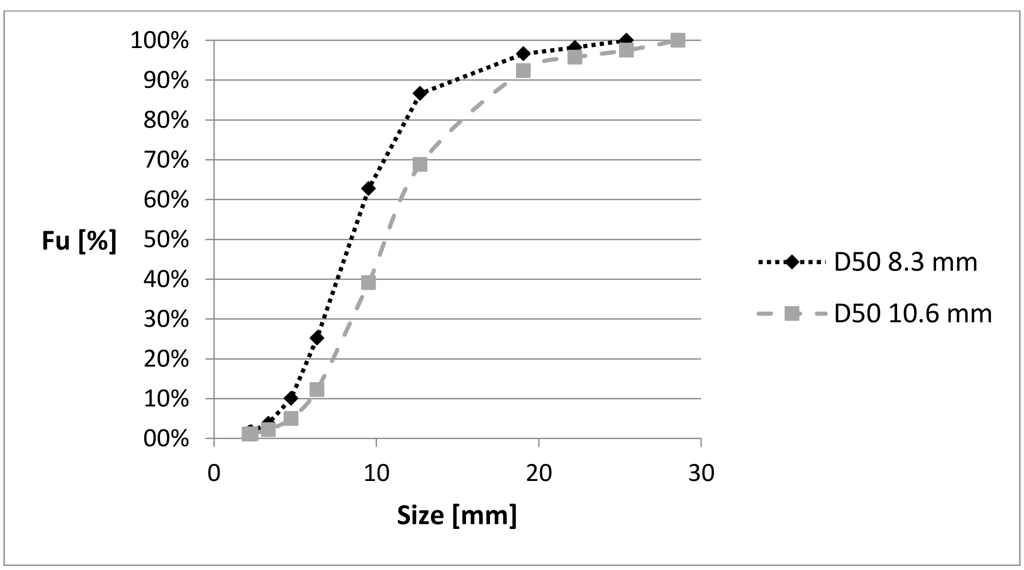

Figure 1-3: Particle size distribution of samples used in the experiments

Table 1-1: Samples characteristics

Media	Average size d_{50} [mm]	d_{80} [mm]	Uniformity coefficient Cu	Drawpoint width*/d_{50}	Point load index I_S50	Initial humidity [%] (solid by weight)	Density [kg/m^3]
9 mm	8.6	11.8	2.0	7.9	6.2	0.8	2,600
11 mm	10.8	15.6	2.0	6.3			

**Drawpoint width for non-square geometry can be represented by hydraulic diameter (Jennings & Parslow, 1988).*

1.3.2. Experiments

A total of 18 experiments have been carried out to date described in Table 1-2. Ten experiments were performed without fines or humidity in order to define a base case considering different vertical loads. Then humidity and fines were added to the samples to measure their impact on the flow-ability. Fine material used in this study has a uniform distribution with d_{100} equals 1 mm. Humidity used in this study is 1.5 liters per 10kg of fine material that is 15% of water.

Table 1-2: Summary of experimental conditions

Test	Material	Vertical load σ_v [MPa]	Humidity [%]	Fines [%]	Size d_{80} [mm]
1	A_1	0	0	0	11.8
2		1.5	0	0	11.8
3		3	0	0	11.8
4		6	0	0	11.8
5		10	0	0	11.8
6	A_2	0	0	0	15.6
7		1.5	0	0	15.6
8		3	0	0	15.6
9		6	0	0	15.6
10		10	0	0	15.6
11	B	0	0	20	15.6
12		6	0	20	15.6
13	C	0	0	40	15.6
14		6	0	40	15.6
15	D	0	15	20	15.6
16		6	15	20	15.6
17	E	0	15	40	15.6
18		6	15	40	15.6

1.4. Results

The experiments were performed twice for coarse ore and once for fine material (the latter only for one particle size distribution). During the tests, the flow-ability, the hang up frequency and the hang up height were recorded.

1.4.1. Flow-ability

Flow-ability is classified into free flow, intermittent flow, assisted flow, and no-flow (Figure 1-1). In terms of flow-ability the results (Table 1-3) indicate that for materials A_1 and A_2 flow-ability decreased from free flow to no flow when vertical load increased from 0 to 10 MPa. When fines were added without humidity, the flow condition was intermittent or assisted. When water was added the flow was assisted flow and, when there were a 40% of fines, the flow condition was no flow at all.

Table 1-3: Summary of experimental results

Test	Material	Vertical load σ_v [MPa]	Flow condition	Interferences [g/hang up]	Standard dev. [g/hang up]
1	A_1	0	Free Flow	1246	640
2		1.5	Assisted Flow	928	371
3		3	Intermittent flow	1068	256
4		6	Assisted Flow	368	246
5		10	No Flow	0	-
6	A_2	0	Free Flow	1177	471
7		1.5	Intermittent flow	1036	471
8		3	Intermittent flow	761	356
9		6	Assisted Flow	599	276
10		10	No Flow	0	-
11	B	0	Intermittent flow	1014	248
12		6	Assisted Flow	586	312
13	C	0	Assisted Flow	501	153
14		6	Assisted Flow	475	180
15	D	0	Assisted Flow	352	97
16		6	Assisted Flow	378	112
17	E	0	No flow	0	-
18		6	No flow	0	-

1.4.2. Hang up frequency

During the experiments it was possible to detect flow interruptions or hang ups which were recorded in terms of mass and height. The hang up frequency (*Hg)* is defined as the amount of material that can be drawn before an interruption happens. The experimental results of Hg as a function of the vertical stress for each laboratory test are presented in Figure 1-4.

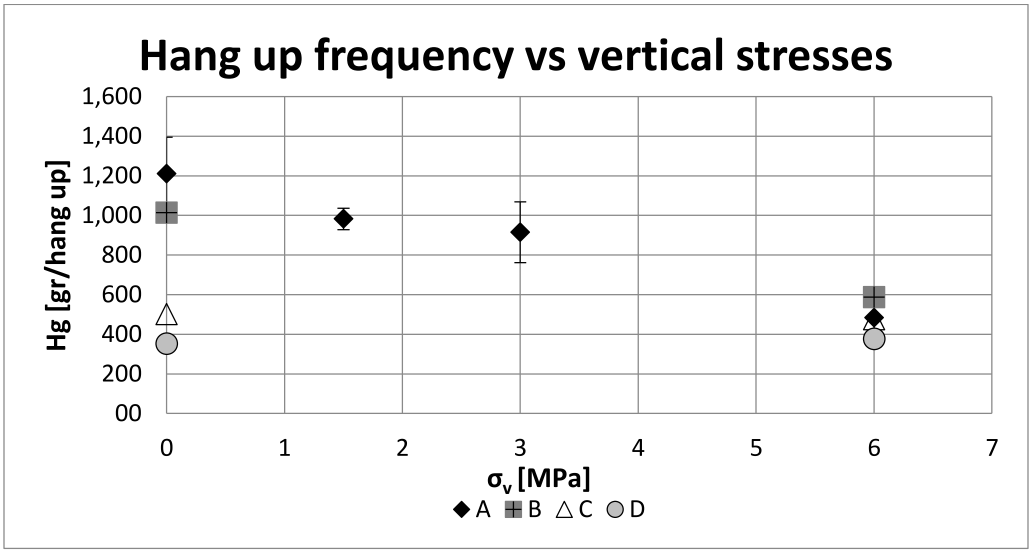

Figure 1-4: Hang up results in laboratory test. A: coarse material test (duplicates included), B: 20% of fine material, C: 40% of fine material and D: 20% of fine material with humidity

The experimental results in coarse material (A) shows that increasing the vertical stress decreases the flow-ability of material. For the media B, that is the one with 20% of dried fines, the hang up frequency number decreased. For materials C and D, the vertical load had no significant influence in the frequency of hang ups as they were not able to flow.

Field measured hang ups are quantified by their hang ups index (number of hang ups per 1000 ton of ore). The measured hang ups index in the experiments is similar to the observed index of primary sulphides in mines. The index varies from 1.6 to 3.6 in mines and, as can be seen in Table 1-4, the scaled experimental index varies from 0.75 to 3.95.

Table 1-4: Scaled hang up indexes

Vertical load [MPa]	Hang ups index [# hang up/ 1000 ton]	
	A_1	A_2
0	1.05	2.05
1.5	1.26	2.29
3	1.09	3.11
6	3.17	3.95
10	0.75	3.32

For the experiments with vertical load 10 MPa the material got strongly compacted over the drawbell generating a great hang up above the drawbell and almost no hang ups of lower height.

1.4.3. Height of hang ups

A classification was made according to the height of the hang up:

- Low: in extraction point.
- Medium: in drawbell (0-13.5m from the roof of the production level)
- High: Above drawbell (over 13.5 m).

The geometry of the drawbell from which the dimensions were scaled is represented in Figure 1-5.

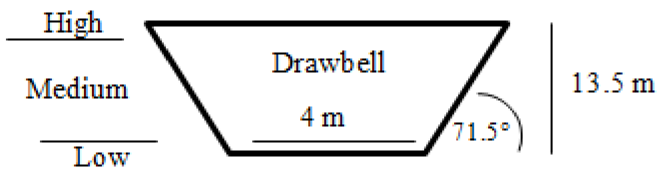

Figure 1-5: Drawbell geometry in real size

Average hang up height of each experiment based on the vertical stress is shown in Figure 1-6. It can be seen that as the vertical stress increases, the height of the hang ups increases simultaneously. The dimensions of each observed hang up were scaled in order to quantify their height in the mine.

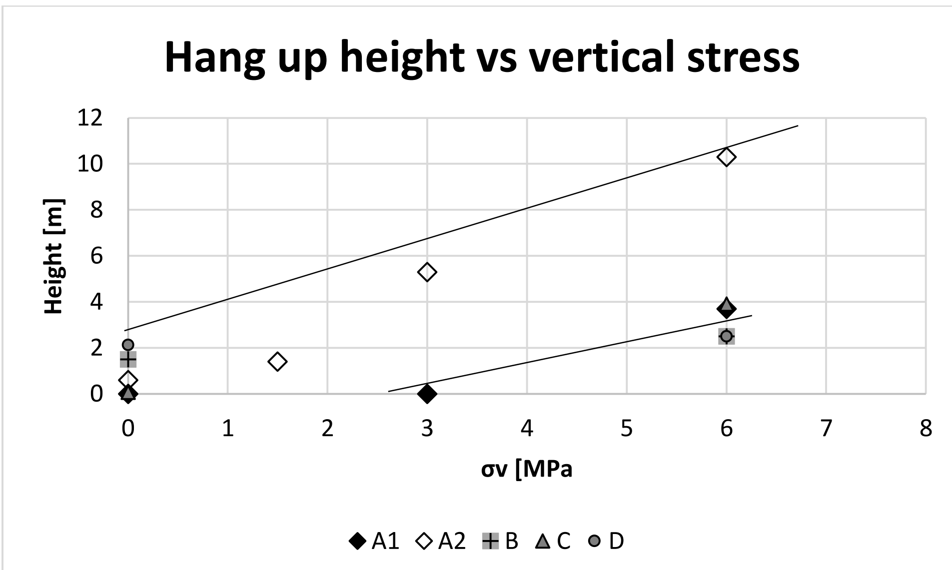

Figure 1-6: Hang up heights in laboratory test. On coarse material A_1: d_{80}=15.6 [mm], A_2: d_{80}=11.8 [mm], B: 20% of fine material, C: 40% of fine material and D: 20% of fine material with humidity

In general, the height of the hang ups increases with the vertical pressure for the coarse material (A1 and A2). In the case of the addition of fine (materials B and C) the results indicate that vertical load has a small impact in the increase of the height of the hang ups. When fines and water were added (material D) there is no effect of the vertical load on the height of the hang ups.

1.5. Conclusions and discussion

Based on experimental tests, this paper shows that particle size, as well as the moisture content, and vertical stress have a noticeable impact on the flow-ability of caved rock. The number and height of hang ups increases as the vertical load increases. Fines and humidity increase the number of hang ups. Also, high hang ups occurs when a vertical pressure was applied or when humidity and fines were acting together.

The scaled model was successful in understanding how confinement, particle size distribution, humidity and fines presence affect the flow-ability of material. It is expected that as block caves get deeper the number of hang ups would increase if fragmentation keeps constant. The results of the above experiments shows that the hang up´s number for mine design applications could be obtained from this kind of experiments. This would require further research and analysis. It is expected that this kind of experiments would be in the future standards to the caving industry, especially for future and unknown conditions.

1.6. Acknowledgements

We want to thank Patricio Ávila and Alonso Vives for their help in these experiments, the staff of Block Caving Laboratory for their support and encouragement and Asieh Hekmat for her advices. This project was conducted under the partial funding of the basal project for Basal Excellences, which is an initiative of the Chilean government.

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Influence of fine material, humidity and vertical loads on the flowability of caved rock

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2.1. Abstract

Flowability is defined as the flow capability of a given granular material to flow under a given drawbell geometry and vertical stress condition. Gravity flow interferences of the broken material at a drawpoint (hang ups) highly influence the efficiency and production rate in block/panel caving mines. Despite its importance in underground block/panel, there is a lack of methods to estimate the flow-ability and hang up frequency for a given set of geotechnical conditions (vertical stress, particle size, fine content, drawbell geometry). The main objective of this article is to describe research conducted at the University of Chile, Block Caving Laboratory aimed to quantify the influence of the fine material, humidity and vertical load on the gravitational flow of caved rock. Experiments were conducted using a 1:75 scaled physical model to evaluate the flowability of caved rock under high vertical loads and with various percentages of fine material and humidity. The results show that vertical pressure fine contents and humidity highly influence flowability and hang up frequency.

2.2. Introduction

Block/panel caving mining methods are adequate for exploiting massive, low-grade ore bodies because of their low productions costs, compared to other underground mining methods. High productivity and low operational cost, in addition to automation potential, make these methods a key factor in future massive deposits mining (Brown 2007).

In block/panel caving, ore production is affected by interferences associated with the caving process, especially those related to the gravity flow (Chitombo 2010). Hang ups and oversize rocks are the most common phenomena, which affect the mine design, draw strategies, mine recovery and, consequently, production rate.

Ore flow depends on ore properties, infrastructure geometry, and stress conditions. The flow condition or ability of a granular material to flow is defined as flowability. The flowability can be qualitatively classified into free flow, intermittent flow, assisted flow, and no-flow (Castro 2014). This classification depends on the ratio of particle size to opening size of the drawpoint (Laubscher 2000). Kvapil (2008) indicated that flowability depends on many parameters including particle size, extraction rate, particles´ shape, surface roughness between particles, friction between particles, moisture content, compressibility, compaction, particle resistance as well as magnitude, distribution and direction of external loads and forces. However, to-date, the flow characteristics have not been well defined quantitatively (Gómez et al 2014). Studies using gravel show that the flowability of granular material is influenced by the vertical load (Fuenzalida 2012). Castro et al (2014) proposed a chart to present flowability of coarse and dry material in terms of vertical stress and drawpoint width/d50 (Figure 2-1). These charts were derived based on the experiments carried out using dry material and without the presence of fines.

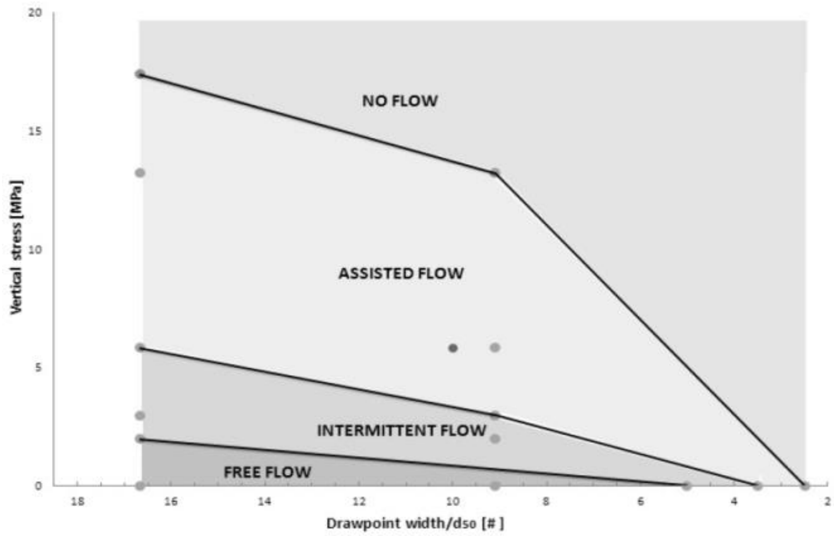

Figure 2-1: Influence of vertical stress in flowability (Castro et al, 2014)

Flowability is defined as the flow capability of a given granular material to move for a given drawbell geometry and vertical stress condition. As shown Figure 2-1, four different modes of flow have been observed when under confinement: (a) Free Flow: the material flows freely through the point of extraction without interruption; (b) Intermittent Flow: the material flows with intermittent interruptions due to arches formed by mechanical compaction of the material. The particles break apart due to the vertical force applied by the hydraulic press; (c) Assisted Flow: the material flow is assisted by manual intervention, which disrupts the mechanical arches; (d) No Flow: the material is stationary, even when manual intervention is made.

Flowability can be quantitatively measured in terms of the number of hang ups in every 1000 tons of drawn broken rock. Hang ups are defined as events when the flow of material is interrupted and the broken rock cannot be extracted (Troncoso 2006). Generally, two types of arches can form hang ups in coarse material: cohesive and mechanical (Kvapil 2008; Beus et al 2001; Hadjigeorgiou & Lessard 2007). The formation of arches against a rough wall is generated by the rotation of the principal stresses on the wall, due to induced wall pressures, in the case of cohesive arches, (Handy 1985) and due to particle size, in the case of mechanical arches. The dimensions and frequency of the arches depend on the friction angle of the material, depth or vertical stress, inclination of the walls in a draw-point, draw rate, shape and strength of the particles, particle size, dilution entry, draw-point spacing, and humidity (Laubscher 1994, Kvapil 2008 & Maass 2013).

Even though the hang ups affect productivity, mine recovery and costs, hang ups characterization in caving operations are not well studied and are generally limited to hang ups in ore passes.

In this article, a physical model to test granular flow under confined conditions is used to quantify the role of the amount of fines, humidity and vertical load on flowability. In the scale model, extraction was carried out using a scaled LHD system to represent current extraction condition in caving mines.

2.3. Laboratory scaled model and experiments

The experiments were conducted using a physical model designed to study confined flow. The laboratory set up consisted of a steel cylinder filled with broken rock (70-80 kg of crushed ore) placed under a hydraulic press machine with a capacity of 1,800 KN. The inner diameter of the steel cylinder was 340 mm (Figure 2-2). A cylindrical shape was selected to avoid the concentration of stresses at singularities. The height of the cylinder was 700 mm to hold the desired volume of material and to suit the 1:75 scalability of the Andina mine drawbell (see Figure 2-2-b), with a rectangular opening of 53 x 96 mm^2. Since the drawbell was located in the center of the cylinder, it was assumed that the flow zones will not intersect the wall of the model. An extraction system was built to replicate LHD performance at drawpoints according to the current practices at the mines (see Figure 2-2-a).

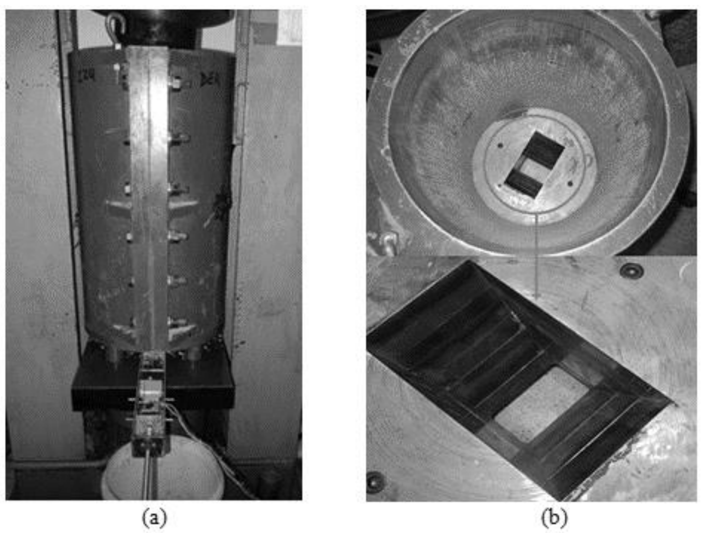

Figure 2-2: Physical model: (a) cylindrical model with a press machine exerting different vertical loads, σ_V; and (b) Drawbell with a rectangular opening, centered at the bottom of the cylinder

2.3.1. Material Characterization

The material used in the experimental tests included crushed sulphide ore with a high aspect ratio to represent the geometry of a caved rock (sphericity of 0.52 and a roundness of 0.53)[1] (Cho et al 2006). The particle size distribution was scaled (1:75) from the expected size distribution of the primary fragmentation of the underground´s Chuquicamata project (Figure 2-3). This specific size distribution was considered as the base distribution (Sample 1); two other samples were composed by adding 20% (Sample 2) and 40% (Sample 3) of fine

[1] *Sphericity* measures the degree to which a particle approaches a spherical shape and *Roundness* refers to the sharpness of the corners and edges of a grain (Cho et al 2006)

material to the base size distribution. The fines used in this study were dried tailings with d_{100} = 1 mm. The fine material corresponded to rock particles at the mine scale having a maximum size of 75 mm. Therefore, three samples have been used in this research. Table 2-1 summarizes the characteristics for each size distribution, with and without fines.

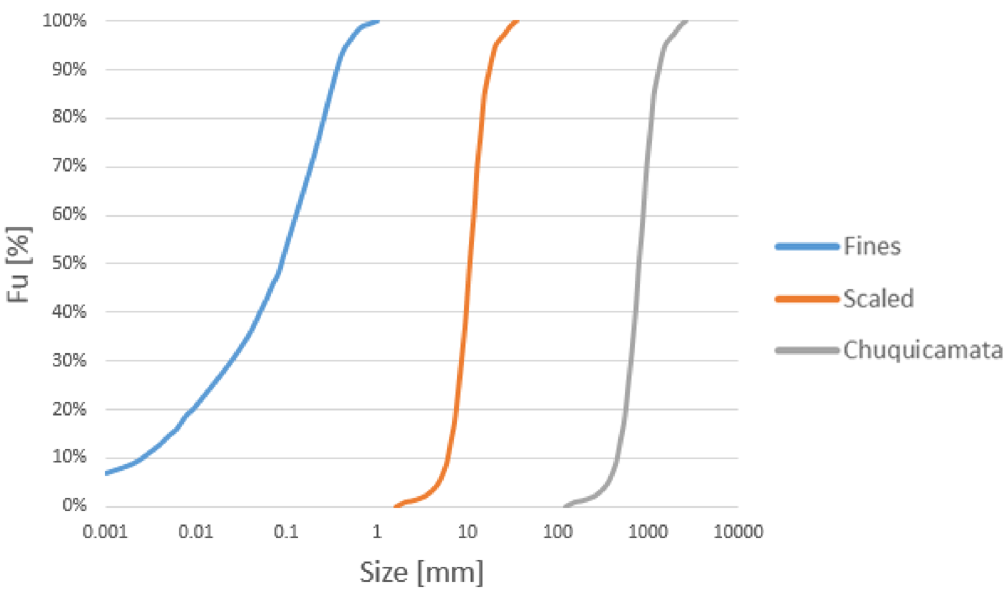

Figure 2-3: Particle size distributions used in the experiments

Table 2-1: Sample characteristics

Parameter	Value		
	Sample 1	Sample 2	Sample 3
Fines [%]	0	20	40
Average size (mixed with fines) d_{50} [mm]	10.6	9.3	7.1
d_{80} [mm]	15.6	13.8	12.5
Coefficient of uniformity $C_U = \frac{D_{60}}{D_{10}}$	1.96	118.5	465.8
Coefficient of curvature $C_Z = \frac{D_{30}^2}{D_{60}D_{10}}$	1.2	44.9	0.2
Drawpoint width/d_{50}	5.0	5.7	7.5
Point load index IS50 [MPa]	5.1		
Initial humidity [%] (solid by weight)	0.8		
Density [kg/m^3]	2,600		

2.3.2. Experiments

A total of 18 experiments were carried out, as described in Table 2-2, where "X" indicates that the experiments were completed and "-" indicates that the experiments were not attempted (for reasons explained in the next paragraph). Five experiments were carried out without fines to define flow behavior of base case considering different vertical loads. Subsequently, various percentages of fine material and humidity were added to the samples to measure their effects on the flowability.

In the experiment without fines and with 10 MPa of vertical load, the material was strongly compacted and generated a high hang up above the drawbell. Consequently, the hang up frequency and hang up index could not be quantified; therefore, experiments with fines and vertical load of 10 MPa were not performed.

Table 2-2: Summary of experimental conditions

Variables			Vertical load σ_v [MPa]				
Size d_{80} [mm]	Fines [%]	Humidity [%]	0	1.5	3	6	10
15.6	0	0	X	X	X	X	X
13.8	20	0	X	X	X	X	-
12.5	40	0	X	X	X	X	-
13.8	20	3	X	X	X	X	-
12.5	40	6	X	-	-	-	-

2.4. Experiments outcomes

2.4.1. Flowability

As indicated in Figure 2-1, flowability is classified as free flow (F F), intermittent flow (I F), assisted flow (A F), and no-flow (N F). The results of the experiments shown in Table 2-3 indicate that for the base case material distribution, flowability can range from free flow to no flow condition with the increase in the vertical load from 0 to 10 MPa. When fines are added to the base coarse material, the flow conditions ranged from intermittent to assisted flow. When both fines and humidity are added to the coarse fraction (F40H6), flow was not possible (N F condition).

Table 2-3: The influence of vertical load and fine material on flowability

Sample ID	Variables		Vertical load σ_v [MPa]				
	Fines [%]	Humidity [%]	0	1.5	3	6	10
F0H0	0	0	F F	I F	I F	A F	N F
F20H0	20	0	I F	A F	A F	A F	-
F40H0	40	0	A F	A F	A F	A F	-
F20H3	20	3	A F	A F	A F	A F	-
F40H6	40	6	N F	-	-	-	-

2.4.2. Hang up frequency

The hang up frequency (Hg*)* is defined as the average amount of material that can be drawn between 2 hang up events. Figure 2-4 illustrates the experimental results of Hg under varying vertical loads. In general, Hg declines with rising vertical loads. The increase in fine percentage decreases the free flow of the material. The results for F40H0, Figure 2-4, indicate that, for high percentage of fine material, the vertical load has a minimum influence on Hg.

For unconfined flow (σ_v=0), the hang up frequency for the base case (F0H0) is higher than for any other cases. By increasing the vertical load to 1.5 MPa, Hg of F0H0 reduces considerably and reaches the value close to F20H0. Moreover, increasing humidity decreases the influence of vertical load on Hg (see curves F20H0 and F20H3 curves in Figure 2-4). In summary, the amount of fine material and the humidity are shown to have a high influence on Hg.

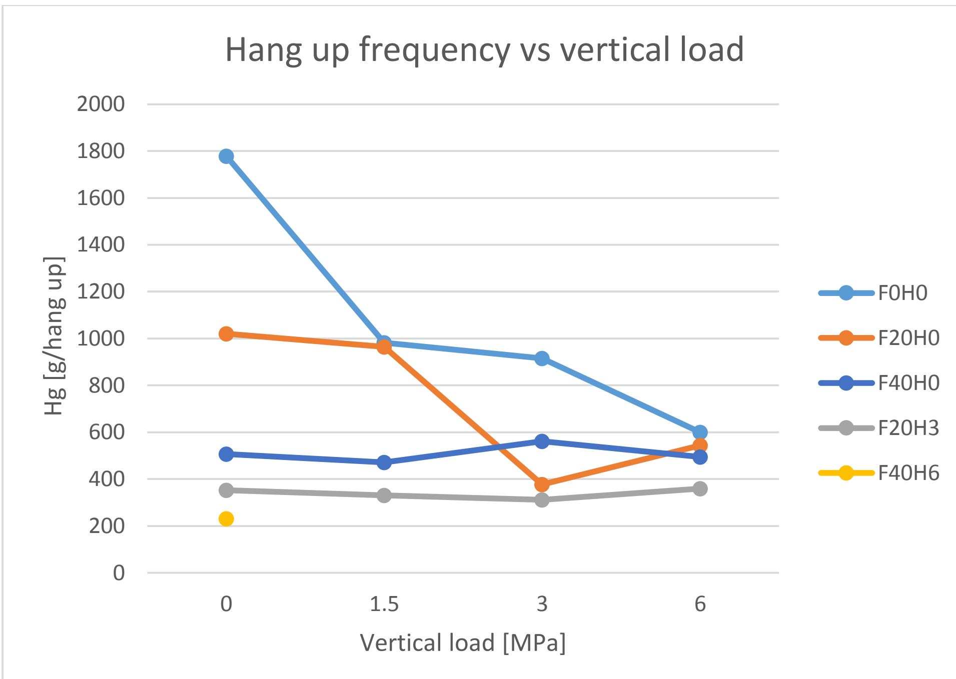

Figure 2-4: Hang up frequency in laboratory tests. F0H0: coarse material (0% of fine material and 0% humidity), F20H0: 20% of fine material and 0% humidity, F40H0: 40% of fine material and 0% humidity, F20H3: 20% of fine material and 3% humidity, F40H6: 40% of fine material and 6% of humidity

Hang up index is used to quantify hang ups in mines. This index measures the number of hang ups per 1000 tonnes of extracted ore. During the experiments (Table 2-4), the hang up index was varied from 1.33 to 4.79 for experiments without humidity; similar indexes are found in primary sulphides mines, between 1.6 and 3.6 (Maass 2013).

The experimental results show hang up indexes higher than those observed in mines for coarse fragmentation when humidity percentage is increased. Therefore, it is expected that humidity and fines could create condition that may result in the failure of the caving process as the ore will not flow.

Table 2-4: Scaled hang up index [# hang up/1000 ton]

Variables		Vertical load σ_v [MPa]				
Fines [%]	Humidity [%]	0	1.5	3	6	10
0	0	1.3	2.4	2.6	4.0	-
20	0	2.3	2.5	6.3	4.4	-
40	0	4.7	5.0	4.2	4.8	-
20	3	6.7	7.2	7.6	6.6	-
40	6	10.3	-	-	-	-

2.4.3. Height of hang ups

Hang ups occur when a large amount of fragments interlock in a drawbell. The height of hang ups depends on the location where the rock blocks are wedged in the drawbell. Figure 2-5 shows a sectional view of a drawbell and the location of different heights of hang ups.

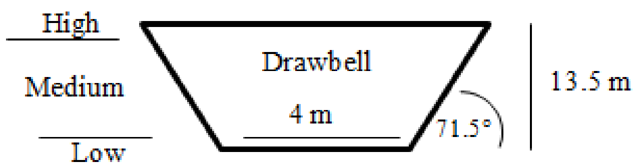

Figure 2-5: Drawbell geometry - real size

Hang up events in block caving operations can be classified according to the height of the hang up as:

- Low: These types of hang ups generally occur at extraction points and require drilling and blasting before the material flows.
- Medium: This type occurs in drawbells at a height from 0m to 13.5m from the roof of the production level). To clear these hang ups, explosives are placed next to the weakest interlocking point and the material is blasted from a safe distance to dislodge the blockage.
- High: This type of hang ups appear above drawbell (over 13.5 m from the roof of the drift), and rarely occur. Removing high hang ups is complicated. Changing draw rate drawpoints may change the state of the induced stresses and might clear the hang ups.

For each experiment, average height of hang ups was determined for different vertical stress (Figure 2-6). It is clear that the hang ups increase as the vertical stress is increased. Note that the dimensions of each observed hang up were scaled up to compare their height with real mine conditions.

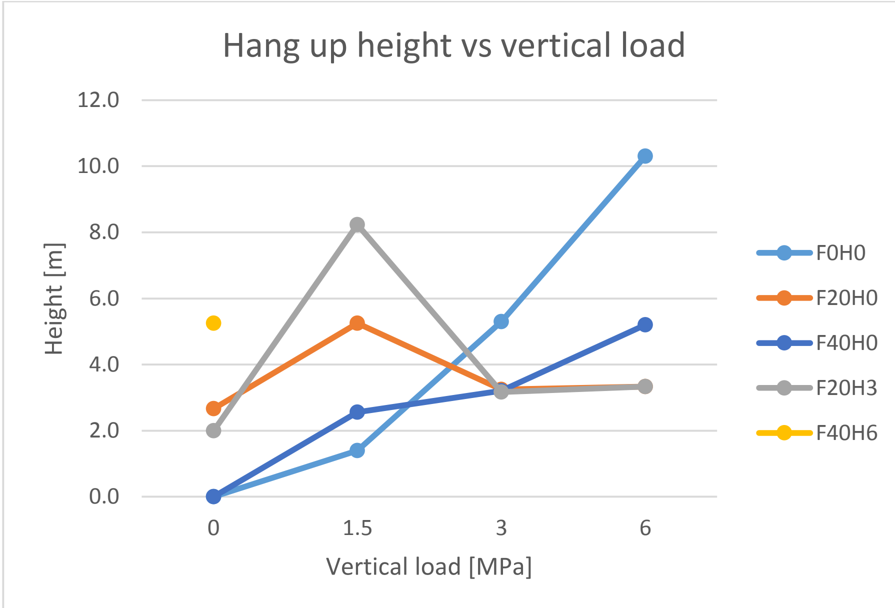

Figure 2-6: Scaled hang up height results in laboratory test. F0H0: coarse material (0% of fine material and 0% humidity), F20H0: 20% of fine material and 0% humidity, F40H0: 40% of fine material and 0% humidity, F20H3: 20% of fine material and 3% humidity, F40H6: 40% of fine material and 6% of humidity

In general, the height of the hang ups increases with the vertical pressure for F0H0 and F40H0. For F20H0 and F20H3, the results indicate that vertical load has a small impact on the height of the hang ups. High hang ups were observed only when vertical loads above 3 MPa were applied.

2.5. Flowability assessment of caved rock

Figure 2-7 characterizes the flow as a function of the amount of fines, the vertical load and the d_w/D_{50} ratio (humidity is not considered in Figure 2-7). It is evident that with the increase of fines, the ratio of d_w/D_{50} increases as D_{50} decreases.

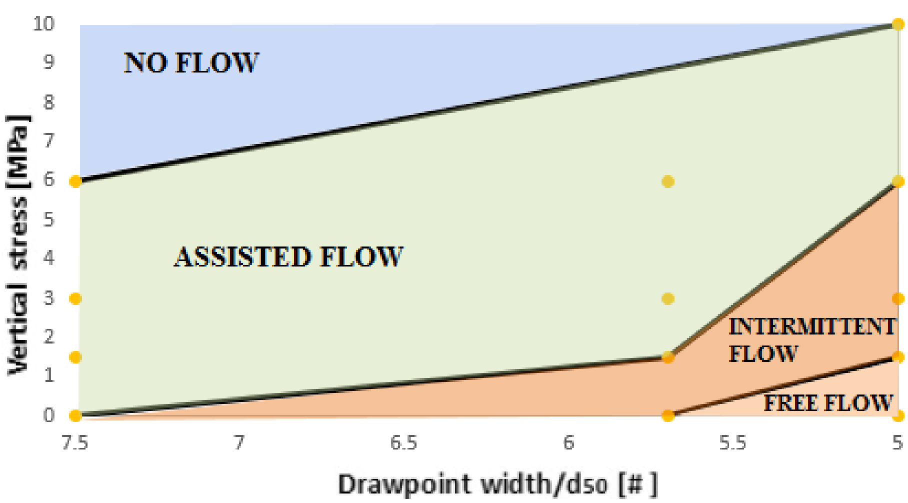

Figure 2-7: Flowability as a function of vertical load, d_w/D_{50} ratio and percentage of fines

According to Figure 2-7, Free Flow occurs only for coarse material and low vertical loads. For high percentage of fine material, increasing the vertical loads does not changes the state of the material flow.

Hang up frequency (H_g) can be predicted based on Equation 2-1, which is an empirical multivariable model determined based on experimental outcomes.

$$H_g\left[\frac{tonne}{hang\ up}\right] = C - a * \sigma_v^b * \left(\frac{c}{c+F}\right) * \left(\frac{d}{d+H}\right) - e * F - f * H + \sigma_v * F * g$$

Equation 2-1: multivariable model

where:

σ_v = vertical load (MPa)

F = Fines presence [%].

H = Humidity [%].

C = Fitted parameter related to the hang up frequency observed in base case.

a, b, c, d, e, f, g = Fitted parameters.

The fitted parameters were determined with the objective of achieving the best adjustment to the experimental results. Table 2-5 lists the fitted parameters used to adjust the multivariable model.

Table 2-5: Fitted parameters for hang up frequency

C	a	b	c	d	e	f	g
696.2	185.9	0.5	62.9	1.7	11.3	105.1	1.1

Figure 2-8 illustrates the adjusted curves for different percentage of fine material. The adjusted curves for F0H0, F20H0, F40H0 and F20H3 are AF0H0, AF20H0, AF40H0 and AF20H3, respectively.

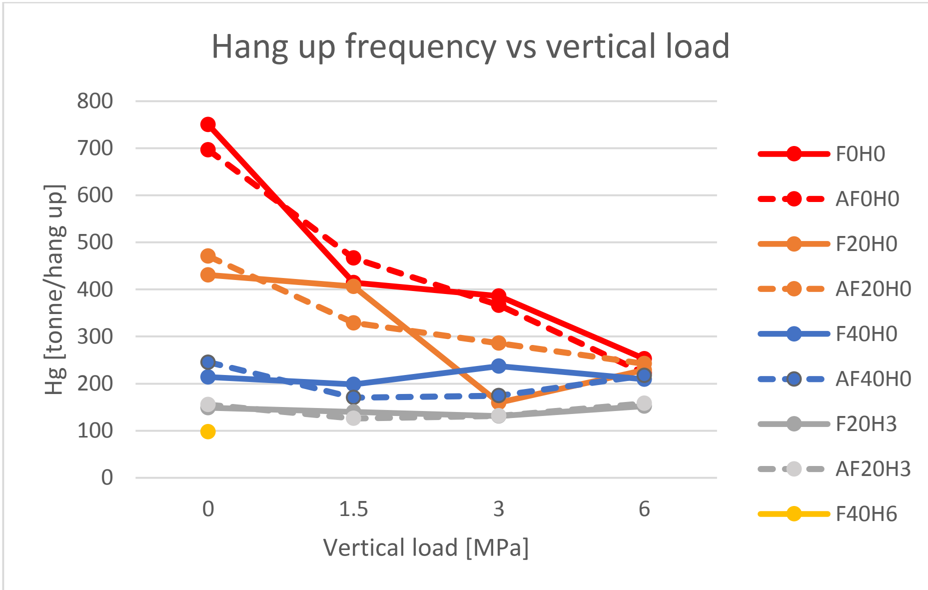

Figure 2-8: Hang-up frequency as a function of vertical load, humidity and fines presence

It must be noted that Equation 1 is only applicable at the ranges of vertical loads used in this investigation. However, it can be concluded that increasing the percentage of fines or humidity will decrease the influence of vertical loads on hang up frequency.

2.6. Conclusions and discussion

In this research, a scaled physical model was used to evaluate the flowability of caved material under various vertical loads and different percentages of fine material and humidity. The experimental results show that particle size, noted as fines presence, humidity and vertical stress have a noticeable impact on the flowability of the caved rock. The number and height of hang ups increase as the vertical load increases. The same results are obtained for high percentage of fine material or humidity.

The applied scaled model was successful in understanding the effects of confinement, humidity and fine percentage on the flowability of the rock material. It is expected that during material extraction of deep deposits, when the column height increases and the presence of fines, the hang ups characteristics (height and frequency) will change due to variation in vertical loads. The experiments demonstrate the potential application of the scaled laboratory tests of confined flow towards mine design application. Further laboratory studies are being planned to further quantify the flow characteristics.

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Experimental characterization of the flowability of granular material in block caving mining

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3.1. Abstract

Block and Panel caving methods continue to be the prime choice for deep, massive low grade ore bodies, because of their high potential production rates and low operating costs. These methods use gravity to break and exploit massive, steeply dipping ore bodies. Likewise, the profitability of the method depends on the in situ stresses and the host rock ability to fracture. In spite of the interest of Block/ Panel methods, low cave ability, large fragments, hang ups and in general, poor flowability will cause these methods to be unfeasible. Despite of its importance, there are unknowns related to the flowability of the caved material under high stresses conditions. This paper presents a research to quantify the influence of fine material, humidity, particle size distribution and vertical loads on the flowability of caved rock, applying a scaled physical model. The results show the significant impact of these parameters on the flow zones and the flowability such as increasing the number of hang ups up to 300% and causing no flow conditions.

Keywords: Gravity flow, flowability, hang ups, fines, confined flow.

3.2. Introduction

Block and Panel caving refer to the mining methods in which the ore body is extracted based on two principal processes. First, the small broken rocks created by blasting from the initially solid rocks are removed. Then, the ore resulting from the progressive caving of the ore column is drawn. The caving is due to the stress propagation generated by the extraction process. These mining techniques are considered as the most productive underground mining methods provided that material flows steadily through the openings in the funnel. In block/panel caving, ore production is highly affected by operational interferences associated with the caving process, especially those related to the gravity flow. The gravitational flow directly affects mine design, productivity and mine recovery (Chitombo, 2010). Consequently, the mine design capability to provide a given production rate is greatly affected, among other factors, by the ore flow. Since hang up existence is the most common event which interrupts the flow of material, this phenomenon is frequently used to analyze the flow condition of broken rock (Troncoso, 2006).

A hang up is an interlocking arch of broken rock that lies throughout the drawpoint and hampers the flow of material. The dimensions of the arch depend on the friction angle of the material, depth or vertical load, inclination of the walls in a drawpoint, draw rate, shape and strength of the particles, and humidity (Kvapil, 2008). According to Handy (1985) hang ups on a rough wall are generated by the rotation of the principal stresses on the wall and by induced wall pressures. Altogether, hang up formation is influenced by particle size distribution, draw strategy, drawpoint spacing, and humidity (Laubscher, 1994 and Maass, 2013). Mine observations display that the number of hang up decreases during the extraction of an ore column. This phenomenon is probably related to the decrease of the particle size during the extraction of an ore column, due to secondary fragmentation (Montecino, 2011; Gómez *et al.* 2014). Despite the significant influence of hang ups in the flow interferences, productivity, mine recovery, and mining costs, hang up studies of qualitative and/or quantitative methods to characterize hang ups are scarce. Moreover, the hang up analyses have mostly been concerning hang ups in ore passes (Heslop 2000; Summers, 2000). Therefore, the frequency of hang ups and oversize rocks in the extraction points have been analyzed under "flowability" in different mining circumstances.

The flow condition or ability of a given granular material to flow through the specific infrastructure geometry, and stress conditions is defined as "flowability". Kvapil (2008) indicated that flowability depends on many parameters including particle size and shape, extraction rate, surface roughness and friction between particles, moisture content, compressibility, compaction, particle resistance and magnitude, distribution and direction of external loads, and forces. Experimental studies on physical scaled models using gravel show that the flowability of granular material is also influenced by the vertical load (Fuenzalida, 2012). However, despite its importance, the flowability has not been thoroughly studied under all those sets of parameters. Hadjigeorgiou *et al*. (2007) summarized experiments and numerical modeling under low confined conditions. Based on this study, the importance of the ratio of the particle size to the ore pass diameter on flow condition was shown. However, low confined condition tests could not imitate the overload of the in-situ column of caved material, which induces fragmentation and compaction. In this case, the application of confined flow experiments allowing the evaluation of the impact of vertical load and fragment size on flowability becomes necessary (Fuenzalida 2012; Castro *et al*. 2014; Gomez *et al*. 2014; Olivares *et al*. 2015). Castro *et al.* (2014) proposed a flowability chart to predict the flow condition of coarse and dry material in terms of vertical load and the ratio between drawpoint width and mean diameter of particle size (d_{50}).

There are many unknowns related to the flow of materials especially under confined conditions; for instance the roles of fines, water and stresses on the flowability on the broken rock. In this research several experiments at laboratory scale were conducted in order to unravel some of the unknowns. These experiments were classified in two types and were carried out to evaluate the flowability of ore, hang ups characteristics and flow zones for different particle size distributions, fines presence, humidity and vertical loads. Regarding to the obtained results, flowability was characterized both quantitatively and qualitatively. Quantitatively, flowability was defined as the number of hang ups occurrence during the extraction of 1000 tons of broken rock. Besides, flowability was characterized qualitatively as "Free Flow", "Intermittent Flow", "Assisted Flow" and "No Flow". Free Flow was assigned to the materials which flow freely through the point of extraction without any interruption. In the cases that flow took place with intermittent interruptions due to arches formed by mechanical material compaction, the flow was classified as Intermittent Flow. In this type of flow the arches broke apart due to the vertical load applied by the hydraulic press. In Assisted flow condition, manual intervention was required to disrupt the mechanical arches. While, No Flow referred to the materials which were completely stagnant, even when disturbed manually (Castro, 2014). It is important to mention that this qualification depends on the ratio between particle size and opening dimension (Laubscher, 2000).

3.3. Experimental methodology

3.3.1. Experimental set up

The experiments were conducted in a physical model specifically designed for confined flow experimentation. This model consisted of a steel cylinder which was filled with broken rock (70-80 kg of crushed ore) and placed under a hydraulic press machine with capacity of 1,800 kN. The cylinder had an inner diameter of 340 mm and a height of 700 mm (Figure 3-1). The height was determined in order to hold the desired volume of material and to suit the 1:75 scaled drawbell (Figure 3-1(b)). The drawbell had a rectangular opening of 53 x 96 mm^2 placed at the center of the cylinder. The extraction system placed at the bottom of the cylinder replicated the performance of two LHD and the current caving characteristics at drawpoints (see Figure 3-1(a)).

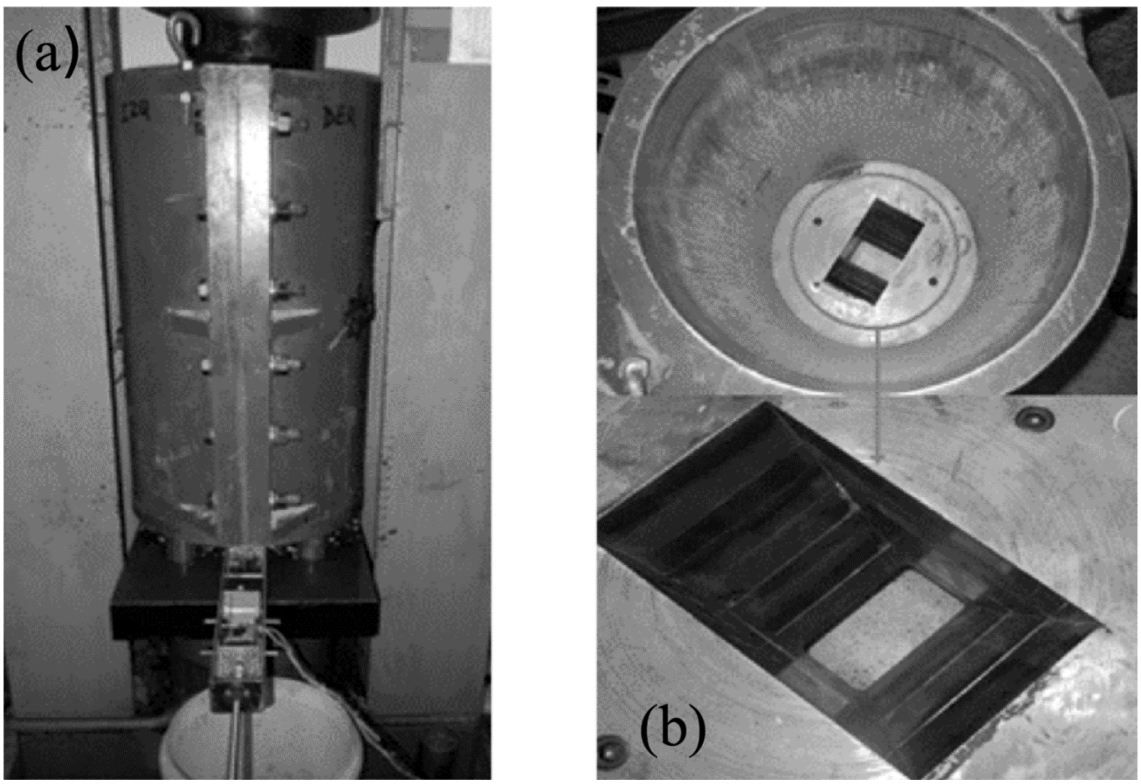

Figure 3-1: Physical model: (a) cylindrical model in a press machine which exerts different vertical loads, σ_V, and (b) Drawbell with a rectangular opening, located at the bottom center of the model.

The design of the physical model, drawbell and extraction systems allowed the study of flowability of granular material considering the boundary conditions related to geometry emulating a mine site. The cylindrical shape of the cylinder would avoid the concentration of stresses at singularities. Moreover, the location of the drawbell, at the center of the cylinder, avoids the intersection of flow zones with the walls of the model.

3.3.2. Material characterization

Crushed sulphide ore from a copper mine was used in the experimental tests. This ore had a high aspect ratio which represented the geometry of caved rock (sphericity of 0.52 and roundness of 0.53). Sphericity measures the degree to which a particle approaches a spherical shape and roundness refers to the sharpness of the corners and edges of a grain (Cho *et al.* 2006). Also, fines were used in this research. The fine material selected was dried tailings with d_{100} = 1 mm. Regarding the representativeness of the fines, they would correspond to particles at mine scale of 75 mm of maximum size.

3.3.3. Similitude analyses

It is required to analyze the similitude conditions, which depend on the characteristics of the problem to be solved, in order to use scaled models for engineering purposes. For studying the flow of granular materials in block caving in a large physical model, Castro *et al*. (2006, 2014) proposed six criteria's to achieve kinematic similitude including: geometrical similitude (particle shape and size, and drawpoint geometry), friction angle (residual friction angle and boundary friction angle), bulk density (related to particle size distribution), and time (draw rate). Additionally, dynamic similitude has to be considered, which is conducted by scaling the most important forces within the model.

The main forces in gravity flow in block caving are the vertical loads, friction and cohesion. In summary, a scaled model should preserve the geometry, and the acting forces of the system under study (prototype). However, distortions are likely to occur due to the appearance of misleading forces that may affect the scaled system. The scale factors that must be considered are listed in Table 3-1. The factors are scaled in accordance with the geometric scale factor ($1:\lambda_L$).

Table 3-1: Similitude analysis variables scaling parameters

Variable	Scale factor
Length	λ_L
Area	λ_L^2
Volume	λ_L^3
Velocity	$2\lambda_L^{1/2}$
Time	$\lambda_L^{1/2}$
Weight	λ_L^3
Density	1
Friction Angle	1

It has been documented that vertical loads influence production level stability, secondary fragmentation and compaction. These phenomena's have not been observed in free flow experiments. The introduction of vertical loads requires scaling the strength of the rock mass to achieve dynamic similitude. To overcome this, Castro *et al*. (2014) presented the design and results of an experimental setup to research confined flow. That setup was the same that was used in the experiments presented in this article. It must be noted that this setup may not be available to all physical modelers.

3.3.4. Experimental procedure

To conduct the experiments the material had to be prepared once the particle size distribution was defined. Once the extraction system was positioned in the press, the cylinder had to be loaded with the material as well as the markers (if included). The press was started and a constant vertical load was maintained during the experiment. The extraction began in one or two drawpoints, depending on the type of the experiment, drawing once per drawpoint until a hang up occurred. The extraction continued until 100 cycles were completed. The material drawn was weighed in each cycle. If a marker appeared during a cycle, the information about it (number) was noted. Before each cycle, the instantaneous angle of repose was calculated in order to determine if a hang up had occurred. If a drawpoint presented a hang up, the extraction continued in the other drawpoint until the hang up collapsed or 5 cycles were completed. If after these 5 extractions the hang up did not collapse, the hang up height was measured and then the hang up had to be collapsed manually. If the extraction was conducted from only one drawpoint, the hang up also had to be collapsed manually after its height was measured. The sequence continued until reaching 100 cycles or until a hang up above the drawbell appeared and then the data was collected.

3.3.5. Flow interferences measurement

The flow interferences or hang ups were measured as hang ups frequency (g/hang up), which was defined as the amount of material (grams) that passed between hang ups. Therefore, the hang up frequency was quantified by counting the number of hang ups and weighing all the extracted material during an experiment. The hang up index [hang up/g] was also calculated, which showed the number of hang ups per gram of material extracted. Both could be scaled to (ton/hang up) and (hang up/kt) by using the volume scale factor (λ_L^3) and scaling from (g) to (t) with $1\ (g) \cdot {\lambda_L^3}/{10^6} = 1\ (t)$.

Three kinds of hang ups were found during the experiments. The hang ups in the extraction point (Figure 3-2(a)) depended on the repose and friction angle. The angle of repose during the experiments was obtained by measuring the distance from a fixed point in the drift to the material. To calculate the angle, the distance from the point to the beginning of the drawbell had to be known in order to determine if there was a hang up or not. If the angle matched or was more than the flow angle, ${\phi}/{2} + 45°$, then there was a hang up.

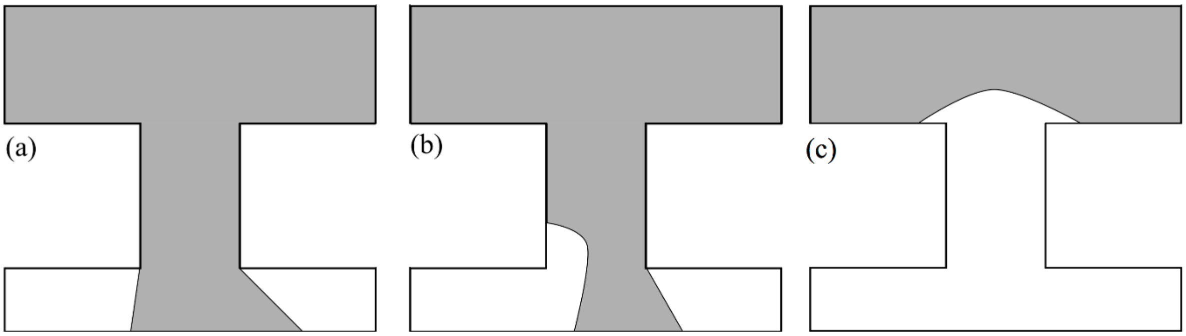

Figure 3-2: Hang up types: (a) in drawpoint, (b) in drawbell, (c) above drawbell.

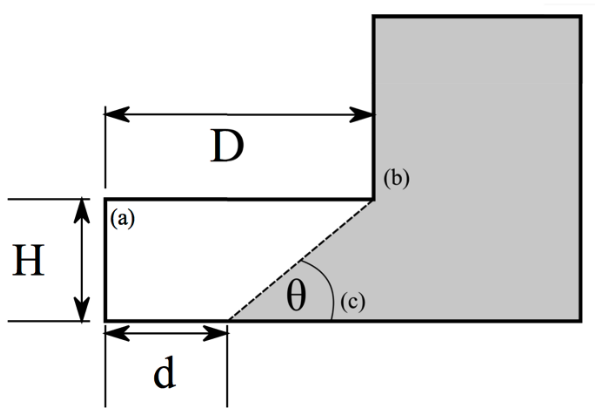

Figure 3-3: Angle of repose. (a) Fixed point, (b) Drawbell beginning, (c) Instantaneous angle of repose.

The instantaneous angle of repose could be calculated using Equation [1] and Figure 3-3.

$$\tan\theta = \frac{H}{(D-d)} \qquad \textbf{[1]}$$

It was considered as a hang up when the instantaneous angle of repose was 67.5° (friction angle of 45°).

The hang ups in the drawpoints were considered to have zero height; to get the material to flow at mines, drilling and blasting are required. For the hang ups that occurred in the drawbell, it was necessary to quantify the height of the hang up, its height was measured from the brow of the drift as shown in Figure 3-2(b). At mines, to remove this type of hang ups, explosives are placed and the material is blasted from a safe distance. In some cases, it is possible to remove these types of hang ups (at drawpoints and drawbell) by extracting material from the adjacent drawpoint.

Finally, hang ups above the drawbell stopped the experiment due to this particular kind of hang up was impossible to break (Figure 3-2 (c)). At mine scale this kind of hang up would mean a hang up at over 13 m above the roof of the production level and removing them is complicated and dangerous.

3.3.6. Experimental conditions

The particle size distributions used in the experiments were scaled (1:75) from particle size distributions of prototypes (Figure 3-4). One of the scaled distributions was Sample 1, and two other samples were composed by adding 20% (Sample 2) and 40% (Sample 3) of fine material to Sample 1 distribution. The extraction was performed from only 1 drawpoint for these 3 Samples. The objective of experimenting with these 3 samples was to study the flowability, and hang up characteristics for different particle size distributions, fines presence, humidity and vertical loads.

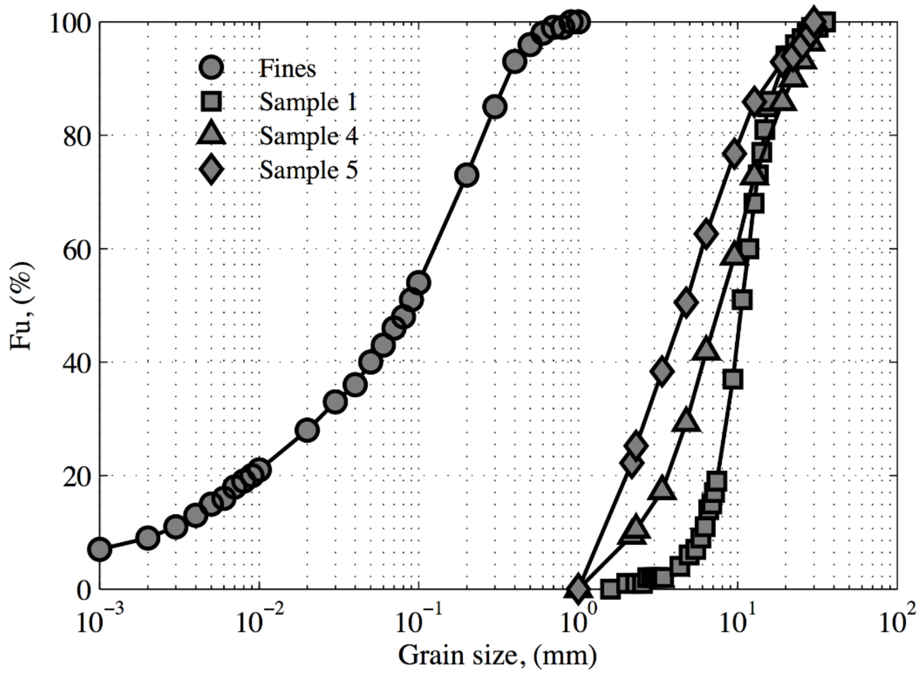

Figure 3-4: Particle size distributions used the experiments

Samples 4 and 5 (Figure 3-4) corresponded to different draw stages of an in.situ column height. Another particle size distribution (Sample 6) was created by adding 20% of fines to Sample 5. The experiments with these 3 samples were conducted by extracting the material from two drawpoints and adding markers in order to observe the behavior of the flow zones. The objective of experimenting with these 3 samples was to study the flowability, hang up characteristics and flow zones for different particle size distributions and vertical loads. Table 3-2 summarizes the characteristics of each size distribution, with and without fines, used in every experiment. Coefficient of uniformity refers to the ratio of $C_U = {D_{60}}/{D_{10}}$ and the coefficient of curvature to $C_Z = {D_{30}^2}/{D_{60}D_{10}}$.

Table 3-2: Sample characteristics

Parameter	Experiment type A			Experiment type B		
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Fines (%)	0	20	40	0	0	20
Average size (mixed with fines) d_{50} (mm)	10.6	9.3	7.1	7.8	4.7	3.2
d_{80} (mm) (mixed with fines)	15.6	13.8	12.5	15.2	11.8	9.1
Coefficient of uniformity	1.96	118.5	465.8	4.26	4.35	9.4
Coefficient of curvature	1.2	44.9	0.2	1.02	0.85	1.22
Drawpoint width/d_{50}	5	5.7	7.5	6.8	11.2	16.5
Point load index IS50 (MPa)	5.1					
Initial humidity (%) (solid by weight)	0.8					
Density (kg/m^3)	2,600					

A total of 30 experiments were carried and they are described in Table 3-3. In this table the symbol "X" indicates that the experiment was conducted and the symbol "O" indicates that was not. Experiments with Sample 1 included five experiments that were carried out without fines in order to define the flow behavior of the base case considering different vertical loads. Afterwards, different percentages of fine material and humidity were added in order to measure their impact on the flowability (Samples 2 and 3). As for the other samples, four experiments were carried out for Sample 4, which is considered as coarse, four experiments for Sample 5, which is finer, and four experiments for Sample 6, which is Sample 5 with the addition of fines.

Table 3-3: Experimental conditions

Sample	Sample ID	Variables		Vertical load σ_v (MPa)				
		Fines (%)	Humidity (%)	0	1.5	3	6	10
1	F0H0	0	0	X	X	X	X	X
2	F20H0	20	0	X	X	X	X	O
3	F40H0	40	0	X	X	X	X	O
2	F20H3	20	3	X	X	X	X	O
3	F40H6	40	6	X	O	O	O	O
4	-	0	0	X	X	X	X	O
5	-	0	0	X	X	X	X	O
6	-	20	0	X	X	X	X	O

Five different vertical loads were tested in order to measure its impact on the flowability and the flow zones. In the experiment with Sample 1 and 10 MPa of vertical load, the material became strongly compacted and caused a no flow state. Consequently, the flowability could not be quantitatively quantified; therefore, other experiments with vertical load of 10 MPa were not performed. Additionally, for Sample 3 and 6% of humidity, the material could not flow when the vertical load was 0 because of the characteristics of the sample. Henceforth, other experiments with Sample 3 and 6% humidity were not conducted. The vertical loads values were obtained from Janssen's formula and they represented depths of up to 1500 m (Castro *et al.* 2015). As mentioned, markers were used in the experiments with Samples 4, 5 and 6. The pattern utilized is shown in Figure 3-5.

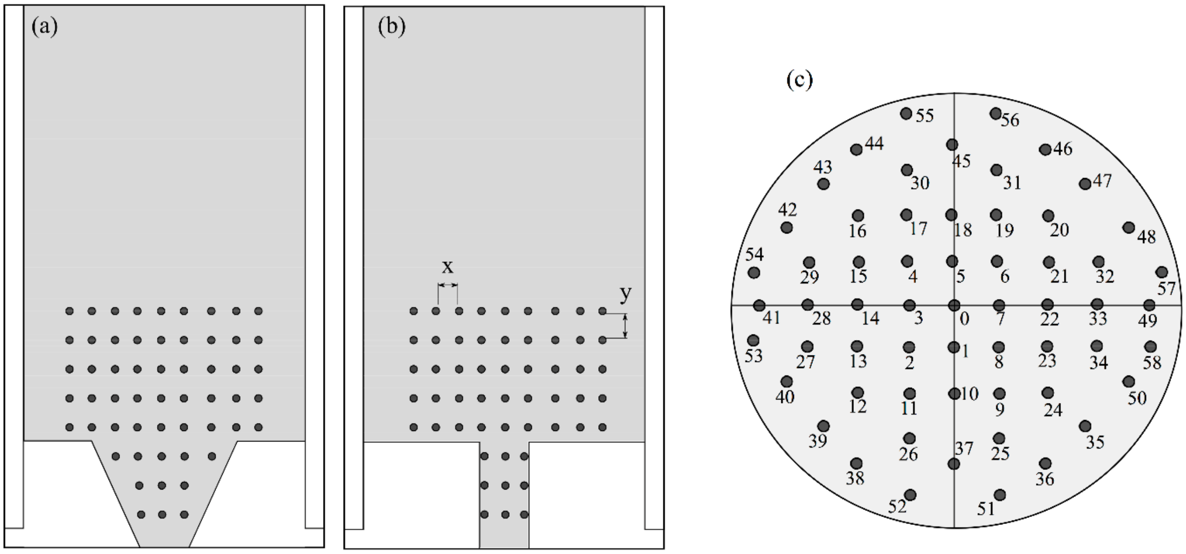

Figure 3-5: Markers pattern, (a) cross view, (b) longitudinal view, (c) top view

The markers were carefully positioned in order to obtain accurate results. Figure 3-5 (b) shows how the markers were separated by 5 cm (y) between each layer and 3 cm (x) between each other in the same layer. The horizontal distance between markers was chosen according to the biggest particle size (3 cm), as a result, there would not exist any particle with 2 markers over it. In Figure 3-5(c) there is a top view of the pattern of the markers. The markers' size was similar to the d_{50} of the sample. All markers were painted in red and numbered from 0 to 58, being 59 markers per layer. Another digit was added at the beginning so the level of the layer could be known. The material used for markers is the same ore of the samples. The layers inside the drawbell used less markers since the area to cover was smaller; thus 9 markers were placed in the first two layers and 15 in the third.

3.4. Results and discussion

3.4.1. Flowability

Flowability is classified as free flow (F F), intermittent flow (I F), assisted flow (A F), and no flow (N F). The results (Table 3-4) indicate that for the Sample 1 flowability ranged from free flow to no flow when the vertical load was increased. When fines were added (Samples 2 and 3), the cohesion between coarse and fine material caused that the flow condition only ranged from intermittent to assisted flow. An extreme case occurred when 40% of fines and humidity were added and the flow was not possible even without vertical load (no flow condition). For Samples 4 and 5, flowability changed from free flow to assisted flow when the vertical load was increased. The same occurred when fines were added (Sample 6).

Consequently, it was inferred that for every experiment, the influence of the vertical load on the compaction of the material caused the flowability to decrease.

Table 3-4: Flowability results

Sample	Sample ID	Variables		Vertical load σ_v (MPa)				
		Fines (%)	Humidity (%)	0	1.5	3	6	10
1	F0H0	0	0	F F	I F	I F	A F	N F
2	F20H0	20	0	I F	A F	A F	A F	-
3	F40H0	40	0	A F	A F	A F	A F	-
2	F20H3	20	3	A F	A F	A F	A F	-
3	F40H6	40	6	N F	-	-	-	-
4	-	0	0	F F	A F	A F	A F	-
5	-	0	0	F F	A F	A F	A F	-
6	-	20	0	F F	I F	A F	A F	-

3.4.2. Height of hang ups

Hang ups occur when a large amount of fragments interlock in a drawbell and its height depends on the location where the rock blocks are wedged in a drawbell. The obtained results were scaled to mine scale and are shown in Figure 3-6.

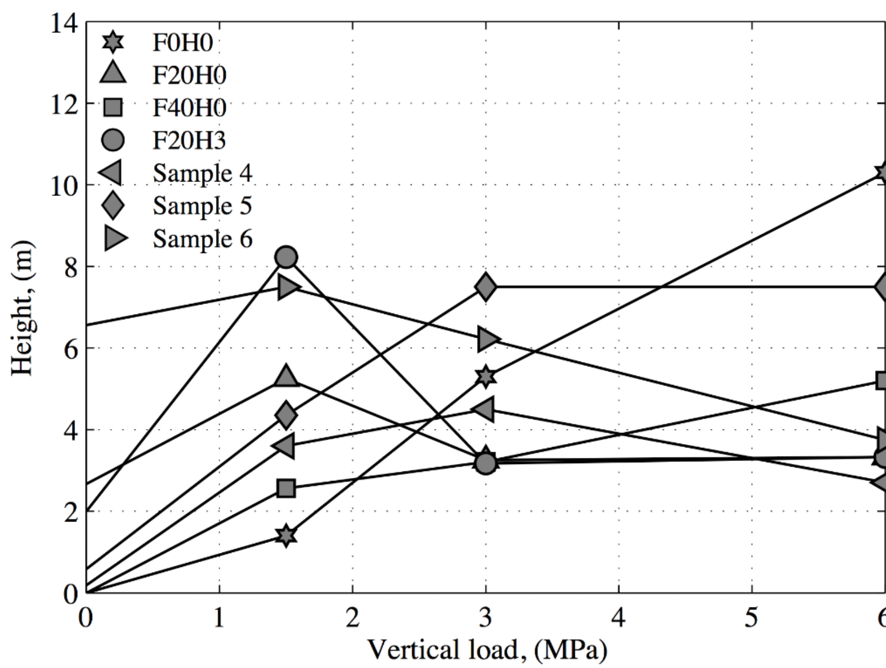

Figure 3-6: Scaled hang up height. The solid lines are for visual aid purposes

In general, the height of the hang ups increased with the vertical load for F0H0, F40H0, Sample 4 and Sample 5. For F20H0, F20H3, and Sample 6 the results indicated that the vertical load had a small impact on the height of the hang ups, indicating that the vertical load influence did not dominate over the fines presence on the height of the hang ups. For

F0H0, F20H0, F40H0 and F20H3 hang ups above the drawbell were observed only when vertical loads beyond 3 MPa were applied due to the compaction generated by the load. For Samples 4 and 5, high hang ups were observed only when vertical loads above 1.5 MPa were applied. For Sample 6, high hang ups were observed for every vertical load tested.

3.4.3. Hang up frequency and index

As previously explained, hang up frequency (Hg) is defined as the average amount of material that can be extracted between two hang ups. Figure 3-7 shows the experimental results of the hang up frequency for the experiments varying the vertical load. In general, Hg decreased when the vertical load augmented or the fines presence was increased due to the compaction and cohesion generated. The results for F40H0 (Figure 3-7) indicated that, for high percentage of fine material, the vertical load had a minimum influence on Hg because what dominated the formation of hang ups was the percentage of fines. For unconfined experiments (σ_V=0), the hang up frequency tended to be higher compared to any other load. By increasing the vertical load to 1.5 MPa, Hg of F0H0 reduced considerably and reached almost the same value as F20H0. Moreover, increasing humidity decreased the influence of vertical load on Hg (see curves F20H0 and F20H3 in Figure 3-7). In summary, the amount of fine material and humidity had a high influence on Hg. It could also be observed for Sample 6 that when the particle size distribution decreased, the hang up index increased even when this decrease of the particle size was caused by the addition of fines. This effect may be caused by the difference in size distributions, having that a broader distribution caused more hang ups.

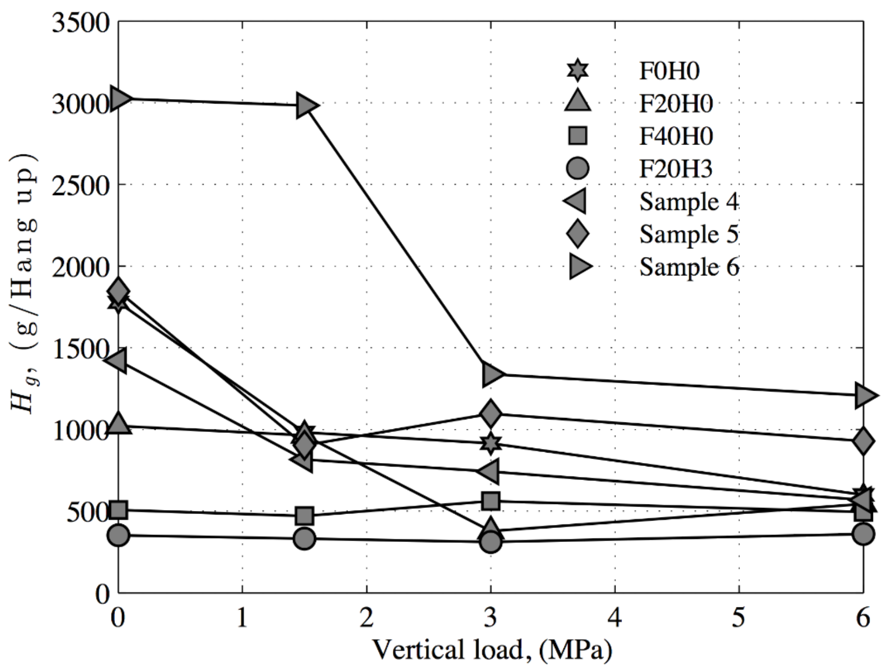

Figure 3-7: Hang up frequency. The solid lines are for visual aid purposes

Hang up index is used to quantify hang ups in mines measuring the number of hang ups per 1000 tonnes of extracted ore. During the experiments, the hang up index varied from 1.3 to

6.7 (Table 3-5) for experiments without humidity and extracting from 1 drawpoint. Meanwhile, for samples 4, 5 and 6, where the extraction was performed from 2 drawpoints, the indexes ranged from 0.8 to 4.2. These indexes were similar to those found in primary sulphides mines where there are indexes between 1.6 and 3.6 (Maass 2013).

Table 3-5: Scaled hang up index [# hang up/1000 ton]

Sample	Sample ID	Variables		Vertical load σ_v (MPa)				
		Fines (%)	Humidity (%)	0	1.5	3	6	10
1	F0H0	0	0	1.3	2.4	2.6	4	-
2	F20H0	20	0	2.3	2.5	6.3	4.4	-
3	F40H0	40	0	4.7	5	4.2	4.8	-
2	F20H3	20	3	6.7	7.2	7.6	6.6	-
3	F40H6	40	6	10.3	-	-	-	-
4	-	0	0	1.7	2.9	3.2	4.2	-
5	-	0	0	1.3	2.6	2.2	2.6	-
6	-	20	0	0.8	0.8	1.8	2.0	-

In the experiments, hang up indexes higher than those seen in mines were observed when humidity was added. Therefore, it is expected that the combination of fines and humidity may cause a condition where the ore will barely flow which may result in the failure of the caving process and the mining method. Additionally, hang up frequencies lower than those observed in mines were obtained when fines were added in Sample 6. Therefore, it is expected that the addition of fines may cause a condition where the ore will flow will improve.

3.4.4. Mine application

For mine application, hang up frequency (Hg) (tonne/hang up) can be predicted based on Equation [2].

$$H_g = \alpha_0 - \alpha_1 \exp(\sigma_v^{\alpha_2}) * \left(\frac{\alpha_3}{\alpha_3 + F + 1}\right) - \alpha_4 * F - \alpha_5 * H + \alpha_6 * \frac{D_w}{d_{50}} - \alpha_7 * \sigma_v * \frac{D_w}{d_{50}} + \alpha_8 * \sigma_v * F \quad \textbf{[2]}$$

Where: σ_v = vertical load (MPa), F = fines presence (%), H = humidity (%), D_w = drawpoint width (m), d_{50} = average particle size, and α_0, α_1, α_2, α_3, α_4, α_5, α_6, α_7, α_8= fitted parameters. The fitted parameters were determined with the objective of achieving the best adjustment to the experimental results. Table 3-6 lists the fitted parameters used to adjust the multivariable model.

Table 3-6: Fitted parameters for hang up frequency

Parameter	Unit	Value	Comments
α_0	(tonne/ hang up)	371.52	Independent constant that determined, among 2 other parameters, the hang up frequency when there was no vertical load, humidity or fines.
α_1	(tonne/ hang up)	160.59	It decreased the hang up frequency when the vertical load increased.
α_2	-	0.01	It decreased the hang up frequency when the vertical load increased.
α_3	-	2.62	It regulated the effect of the fines on the hang up frequency.
α_4	(tonne/ hang up)	13.67	It decreased the hang up frequency when the fine presence increased.
α_5	(tonne/ hang up)	70.52	It decreased the hang up frequency when the humidity increased.
α_6	(tonne/ hang up)	61.66	It increases the hang up frequency when the ratio $\frac{D_w}{d_{50}}$ increased.
α_7	(tonne/ hang up·MPa)	6.42	It regulated the hang up frequency when the vertical load and the ratio $\frac{D_w}{d_{50}}$ increased because the vertical load affected differently the frequency for different ratios.
α_8	(tonne/ hang up·MPa)	0.80	It increased the hang up frequency when the vertical load and the fines presence increased. This parameter regulated the decrease of hang ups frequency generated by the increase of the vertical load when fines were present.

Figure 3-8 illustrates the adjusted curves for different Samples. The adjusted curves for F0H0, F20H0, F40H0, F20H3, Sample 4, Sample 5 and Sample 6 are shown.

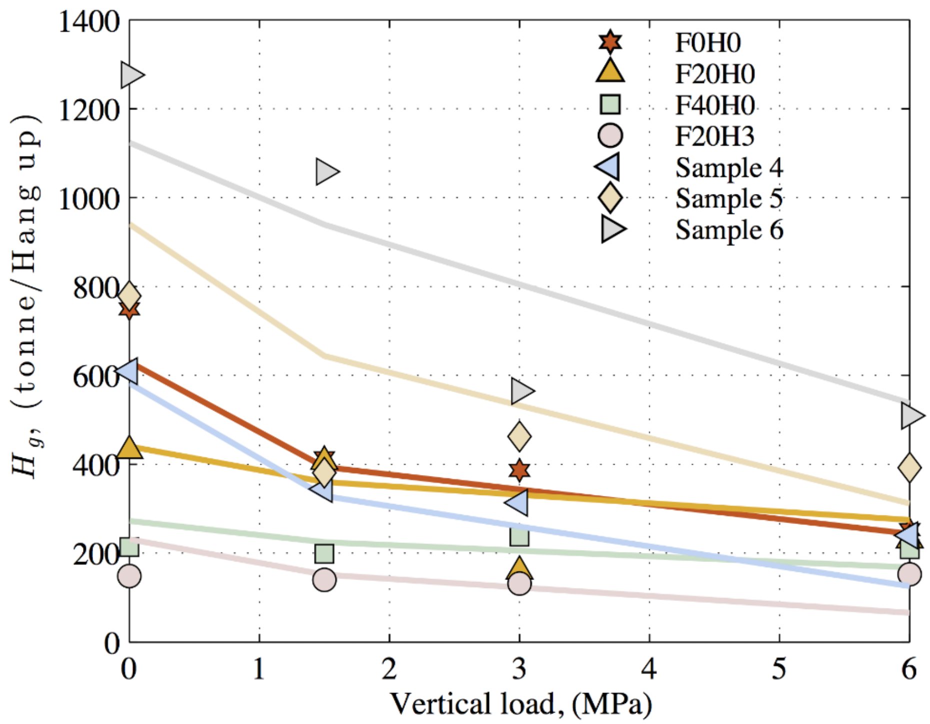

Figure 3-8: Hang up frequency predictive model

The predictive model is only applicable to the ranges of vertical loads used in these experiments. However, it could be concluded that increasing the percentage of fines or humidity decreased the influence of vertical loads on the hang up frequency, and that in some cases, depending on the ratio $\frac{D_w}{d_{50}}$, increasing the fines percentage would augment the hang up frequency.

An example of the application of the hang up frequency predictive model is explained as follows. The Janssen's formula was used (Equation 3) to quantify the vertical load in a granular media.

$$\sigma_v = \frac{R_h\gamma}{ktan(\phi)}\left[1 - \exp\left(\frac{ktan(\phi)z}{R_h}\right)\right] \quad \textbf{[3]}$$

Where σ_v is the vertical load, R_h is the hydraulic radius (area/perimeter) of the draw area analyzed, γ is the density of the media, ϕ is the friction angle of the rock, z is the height of the ore column, and k is an earth pressure related constant whose value depends on the failure mode of the granular material. Taking R_h=70 m; γ=2200 kg/m^3; ϕ =38°, k=1-sinϕ =0.38, and z=200 m the vertical load obtained was 2.91 MPa. Considering the calculated vertical load (2.91 MPa), a media with 20% of fines and 1% of humidity, and a ratio $\frac{D_w}{d_{50}}$ of 7, the resulting hang up frequency was 326.1 tonne/hang up. In order to measure the impact of each variable on the hang up frequency, a sensibility analysis was conducted (Table 3-7).

Table 3-7: Hang up frequency sensibility analysis

Case	Variable						
	Ore column height (m)	Vertical load (MPa)	Fines (%)	Humidity (%)	D_w/d_{50}	Hang up frequency (tonne/ hang up)	Variation (%)
Base Case	200	2.91	20%	1%	7	326.1	0.0%
Ore column decreased	100	1.76	20%	1%	7	359.6	10.3%
Ore column increased	300	3.66	20%	1%	7	304.3	-6.7%
Fines decreased	200	2.91	10%	1%	7	403.5	23.7%
Fines increased	200	2.91	30%	1%	7	227.3	-30.3%
Humidity decreased	200	2.91	20%	0%	7	396.6	21.6%
Humidity increased	200	2.91	20%	2%	7	255.6	-21.6%
Ratio D_w/d_{50} decreased	200	2.91	20%	1%	5	240.2	-26.4%
Ratio D_w/d_{50} increased	200	2.91	20%	1%	9	412.0	26.4%

The impact of each variable on the hang up frequency was measured by calculating the variation of the hang up frequency in each case compared to a base case. The base case was the one previously calculated. It can be observed that when the ore column's height varied ±100 m, the hang up frequency was affected from -6.7 to +10.3%. Regarding the fines presence, when it was varied ±10%, its impact was from +23.7 to -30.3%. When humidity was varied by only ±1%, it caused an effect of ±21.6% on the hang up frequency, making this variable the most important for the hang up frequency. Finally, varying the ratio D_w/d_{50} by ±2 caused the hang up frequency to vary ±26.4%.

3.4.5. Flow zones

The markers analysis was performed in three different views. The first one is shown in Figure 3-9 and it is the section that crossed the center of the drift (or drawbell). The analyses only considered the first 4 kg of material drawn since it was not possible to draw more than 4 kg in every experiment.

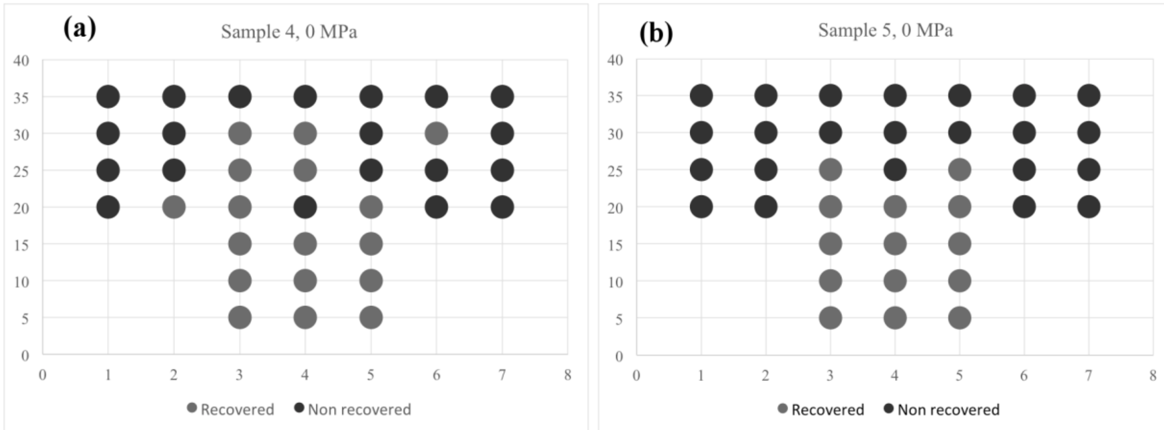

Figure 3-9: Drawbell view

The other views were above each drawpoint, defined by where the markers were positioned. In Figure 3-10 it can be seen the recovered and non-recovered markers for Samples 4 and 6 at drawpoint 1 without vertical load.

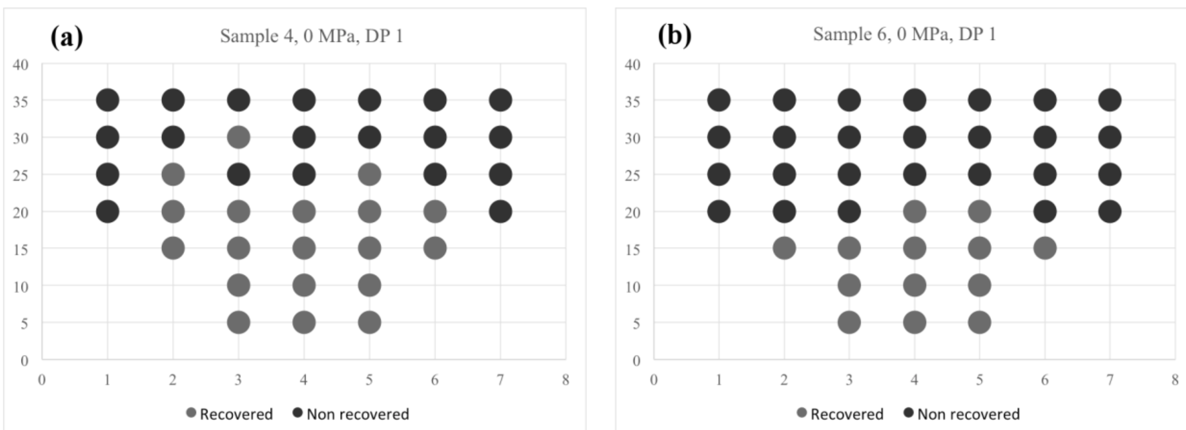

Figure 3-10: Drawpoint 1 view

The analysis of the flow zones was carried out considering the height and width of the extraction zone, where the recovered markers were. The aspect ratio, which is defined in Equation [4], was used to characterize the flow zones.

$$R = \frac{h}{w} \quad [4]$$

In Figure 3-11 there are the results for the aspect ratio vs vertical load for each experiment. The aspect ratio was calculated for each of the studied views and the mean between the three sections is what is represented in Figure 15.

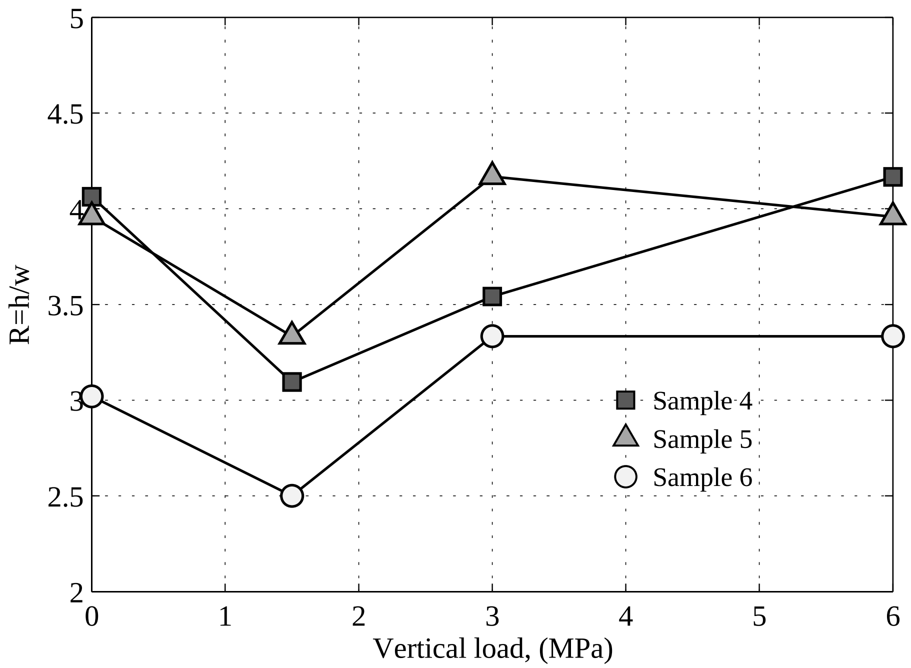

Figure 3-11: Aspect ratio vs vertical load

For the three samples it was observed that when the vertical load was 1.5 MPa the aspect ratio decreased from 10 to 20% compared to the unconfined case. Additionally, when the vertical load increased, the ratios for the three samples increased. Comparing Samples 4 and 5 it was observed that their ratios are similar for vertical loads of 0 and 6 Mpa, but when the vertical load was 1.5 or 3 Mpa, the ratio for Sample 5 was higher. Sample 6 always had a lower aspect ratio than the two other samples.

3.5. Conclusions

In this research, a scaled physical model was used to evaluate the flowability of caved ore with varied particle size distributions under various vertical loads, fines percentage presences and humidity. A method to estimate hang up frequency and index was used showing good correlation with what has been observed at mines.

Flowability was negatively affected by the increase of the vertical load for both types of experiments. In contrast to what was observed in experiments with Samples 1, 2 and 3, in the experiments with Sample 6, it was observed that when fines were added the flow conditions improved. Another key point is that the worst scenarios were obtained when humidity was added in Samples 2 and 3.

For Samples 1, 2 and 3 the height of hang ups increased with the vertical load when there was no humidity. Similarly, for Samples 4, 5 the height of the hang ups increased with the vertical load. Nonetheless, when there were fines and humidity, there was no significant effect of the vertical load on the height of the hang ups.

The hang up index (hang up/kton) increased when the vertical load increased for every sample. It is important to realize that for Samples 1, 2 and 3, the obtained results showed that, when fine material or humidity were present, the hang up index increased unlike Samples 4, 5 and 6, where the addition of fines decreased the hang up index. Additionally, for Samples 1, 2 and 3, increasing the percentage of fines or humidity decreased the influence of vertical loads on hang up frequency. Meanwhile, the improvement of the flow condition and the decrease of the hang up index when fines were added in experiments with Sample 6 was caused due to the smaller particle size distribution of Sample 5 compared to Sample 1. Accordingly, the difference in size generated fewer cohesive and mechanical arches which included coarse and fine material, allowing the material to flow. Therefore, it is inferred that more hang ups are formed when the particle size distribution is broader.

The flow zones analysis showed that the aspect ratio for Sample 6 was lower than for samples 4 and 5. It is evident that this behavior was due to when the fines were added, the apparent density of the sample increased, causing that when a certain amount of material is extracted, the volume of material would be lower for Sample 6 than for Sample 4 or Sample 5. Consequently, less markers would be recovered. Meanwhile, when Samples 4 and 5 were compared, it was observed that their ratios were similar for vertical loads of 0 and 6 MPa. On the other hand, when the vertical loads were 1.5 or 3 MPa, the ratio for Sample 5 was higher, which was expected for a finer particle size distribution since they tend to generate flow zones with less diameter than the coarser particles.

The scaled model was successful in understanding the effects of confinement, humidity and fine percentage on the flowability of the rock material. Also, predictive models were generated from the experiments. In the future, it is expected that during material extraction of deep deposits, when the column height increases and the presence of fines increases, the hang up characteristics (height and frequency) will change due to the variation of the vertical loads.

The experiments demonstrate the potential application of the scaled laboratory tests of confined flow towards mine design application. More laboratory studies, and numerical simulations using discrete element particles are being planned to further quantify the flow characteristics.

3.6. Acknowledgements

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Conclusions

General conclusions

The experiments conducted with the scaled physical model permitted the study of the effect of the vertical load, the particle size distribution, the humidity, and the fines on the flowability of caved rock. Due to the results of the experiments, it is expected that the number of hang ups increase as the mines get deeper if the particle size distribution remains unchanged. A method to estimate hang up frequency and index was used, showing good correlation with what has been observed at mines.

Regarding the experiments conducted with different samples, the following was concluded:

- Flowability was negatively affected by the increase of the vertical load for every experiment. In contrast to what was observed in experiments with Samples 1, 2 and 3, it was observed in Sample 6 that when fines were added the flow conditions improved. Another key point is that the worst scenarios were obtained when humidity was added in Sample 2 and 3.
- When humidity was present, the flow had to be assisted and it was even inexistent. Consequently, these experiments had the highest number of hang ups.
- For Samples 1, 2 and 3 the height of hang ups increased with the vertical load when there was no humidity. Similarly, for Samples 4 and 5 the height of the hang ups increased with the vertical load when there were no fines. Nonetheless, when there were fines and humidity, there was no significant effect of the vertical load on the height of the hang ups.
- The hang up index (hang up/kton) increased when the vertical load increased for every sample. It is important to realize that for Samples 1, 2 and 3, the obtained results showed that, when fine material or humidity were present, the hang up index increased. On the other hand, in Sample 6 the addition of fines decreased the hang up index. Additionally, for Samples 1, 2 and 3, increasing the percentage of fines or humidity decreased the influence of vertical loads on hang up frequency. Meanwhile, the improvement of the flow condition and the decrease of the hang up index when fines were added for Sample 6 is caused due to the smaller particle size distribution of Sample 5 compared to Sample 1. Accordingly, the difference in size generated fewer cohesive and mechanical arches which included coarse and fine material, allowing the material to flow. Therefore, it is inferred that more hang ups are formed when the particle size distribution is broader.
- The flow zones analysis showed that the aspect ratio for Sample 6 was lower than for Samples 4 and 5. It is evident that this behavior was due to when the fines were added, the apparent density of the sample increased, causing that when a certain amount of material is extracted, the volume of material would be lower for Sample 6 than for Sample 4 or Sample 5. Consequently, less markers would be recovered. Meanwhile, when Samples 4 and 5 were compared, it was observed that their ratios were similar for vertical loads of 0 and 6 MPa. On the other hand, when the vertical loads were 1.5

or 3 MPa, the ratio for Sample 5 was higher, which was expected for a finer particle size distribution since they tend to generate flow zones with less diameter than the coarser particles.

- Finally, the obtained results are similar to what can be observed at mines. The range of hang up indexes of the experiments and the formation of "chimneys" due to compaction resemble the mine data.

The scaled model was successful in understanding the effects of confinement, humidity and fine percentage on the flowability of the rock material. Also, predictive models can be generated from these experiments. In the future, it is expected that during material extraction of deep deposits, when the column height increases and the presence of fines increases, the hang up characteristics (height and frequency) will change due to the variation of the vertical loads.

Future work

Since the experimental set was designed to replicate a drawbell, and considering the number of experiments conducted, there are still variables that must be considered in the future. Some of the experiments could test other vertical loads, fines presence, humidity, and particle size distributions. Additionally, other drawbells and more than one drawbell have not been tested.

The experiments demonstrate the potential application of the scaled laboratory tests of confined flow towards mine design application since the hang up frequency can be predicted. It is expected, once further research is conducted, that this type of experiments will become a standard in caving mining, especially considering the unknown future conditions.

More laboratory studies, and numerical simulations using discrete element particles are being planned to further quantify the flow characteristics. Moreover simulations of the effect of the hang ups on the productivity can also be researched.

Furthermore, there is a lack of studies about the secondary fragmentation produced by the vertical load and the stresses distribution generated on the confined material. Additionally, the stresses in the extraction system and its fill factor can be studied.

Finally, it is necessary to validate the results and the obtained models with mine data. In other words, take ore and its particle size distribution from a certain mine, scale it and conduct experiments with it in order to compare the results with that particular mine.