Measurement of the In-Hole Density of Gassed Explosives at Peruvian Mines

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Abstract

We present the results of our field research on the variation of the density of the gassed explosives and their influence on the blasting results in the Peruvian mines: Yanacocha, Toquepala and Antamina. Currently, 90% of Peruvian mines uses gassed explosives, for their economic and technical benefits. But new practices and design criteria have had to be adopted, and the most important a careful control of the *in-hole density*, whose variation in the depth of the hole strongly affects the detonation process.

For gassed explosives the density varies gradually according to the depth in the hole, due to the pressure on the bubbles by its own weight. The density at the bottom of the hole can reach critical values, which directly affects the start of the detonation in the booster zone with a high probability of nitrous fumes formation. On the other hand, density translates into the amount of explosive and energy available. Therefore, for the optimum performance of the explosive, the minimum and maximum values of the *in-hole density* must be determined.

For the cases studied, the maximum *in-hole density* and the maximum charge length have been determined. When the charge length is greater than 7.0 m [23 ft.] special care must be taken with the cup density, which as a general rule should not exceed the value of 1.15 g/cm^3 [71.8 lb/ft^3] at the risk of losing the sensitivity at the bottom, also increasing the probability of nitrous fumes, bad fragmentation and finding intact explosive after blasting.

In the large holes in Toquepala and Antamina mines, where the charge length can be greater than 9.0 m [29.53 ft]. If the cup density is greater than 1.15 g/cm^3 [71.8 lb/ft^3] the *in-hole density* can easily reach a high value of 1.30 g/cm^3 [81.16 lb/ft^3].

Introduction

Yang (2011) has concluded that *“All void-sensitized explosives have a general density-VOD relationship, as illustrated in Fig. 6. In the figure, a failure density of 1.38 g/cm^3 [86.15 lb/ft^3] is assumed. Under dynamic or static pressure, a low-density product has more room for its density to rise before its VOD starts to drop into low-order detonation (producing fumes) in comparison with a high-density product”*. Therefore, if we have a low density this may increased before and during the detonation, and would not reach critical levels. But if we have a high density, it will increase by the explosive´s own weight before blasting, and will increase even more during the detonation process. Finally the density will reach critical levels, resulting in sub order detonations or deflagration with the consequent fumes formation. Agrawal & Mishra (2018) have measured VOD at different densities of the gassed explosive, finding that the highest VOD is obtained when the densities are around 1.12 g/cm^3 [69.9 lb/ft^3]. Cavanough (2015), proposed a method to measure the explosive pressure using pneumatic probes, the same method we applied in this investigation.

Gassed explosives

Gassed explosives are emulsion based mixtures. The emulsion is sensitized by nitrogen bubbles. Nitrogen is the product of a chemical gasification reaction between the emulsion and a solution of sodium nitrite. The emulsion must be chemically prepared to react. The gasification process takes place in a static mixer that is coupled to the explosives truck system.

A first approach to the In-Hole Density Model

To find a mathematical relation between the pressure and the in hole density of the explosive, let's take a segment of the explosive column, with stable density (final density of the gassing process) "D_g". Let us mentally separate the compressible gas phase from the rest of the non-compressible components such as the matrix emulsion and the ammonium nitrate. The gas phase occupies a volume V_1 and will withstand a pressure P_1 at a certain depth h_1. But at a greater depth h_2, the pressure P_2 will be greater and the volume will be compressed to V_2.

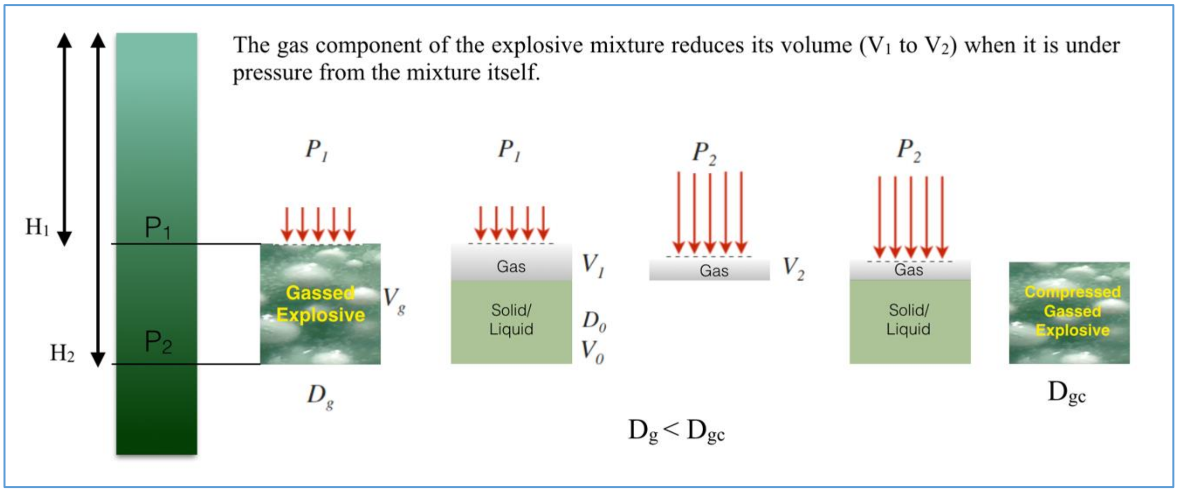

The gas component of the explosive mixture reduces its volume (V_1 to V_2) when it is under pressure from the mixture itself.

Fig 1: Relationship between pressure and density

Since the volume and pressure are inversely related, it can be demonstrated that the density of the explosive gassed under pressure “D_{gc}” can be calculated by:

$$D_{gc}=\frac{1}{\frac{1}{D_0}+\frac{P_1}{P_2}\left[\frac{1}{D_g}-\frac{1}{D_0}\right]}$$

Equation 1

Where:
D_{gc} : Density of compressed gassed explosive
D_0 : Density of the non-gasified explosive mixture
D_g ,V_g : Density and Volume of the gasified explosive under pressure P_1 at H_1
P_1 : Pressure at H_1
P_2 : Pressure at H_2

We have two reference states of well-known density, the first is before the gasification of the explosive whose density is "Do", in the second state the explosive is already gassed but out of the hole, this is the cup density which is representative only for the upper part of the explosive column, where there is no hydrostatic pressure. In other words, when $H_1 = 0$, the density Dg becomes the cup density, which is easily measured in the field. Therefore, using equation 1 we can calculate the “relative in-hole density” at any depth. The problem has been reduced to measuring the pressures P_1 and P_2 at least two different depths (H_1 ,H_2).

As Cavanough (2015) proposed, pneumatic probes were used. The probes are like inflatable balls which transmit the pressure changes from the bottom of the hole, through hoses to electronic sensors on the surface, which transduce the pressure into a proportional electrical signal. For this purpose, a measuring device called Depth Density Tester (DDT) has been designed and manufactured, which is capable of capturing and storing the pressure data that will be analyzed by software.

Fig 2. DDT device in surface

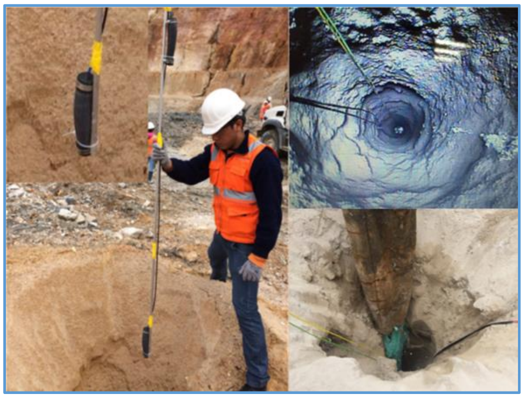


Fig 3. The probe and hoses

Methodology

Step 1: In an empty hole the pneumatic probes are introduced. After loading the explosive, air must be blown into the probes. This increases the volume of the probe and puts pressure on the elastic walls, outwards of the probe. At this time a peak of pressure is reached (Peak 1 in the figure 4), at this time the inflation must stop, closing the valve. A balanced pressure plateau will be formed (Plateau 2 in the figure 5). The air inside the probe withstands two pressures, that of the surrounding explosive (Pe) and the "return pressure" of the elastic walls (Ps).

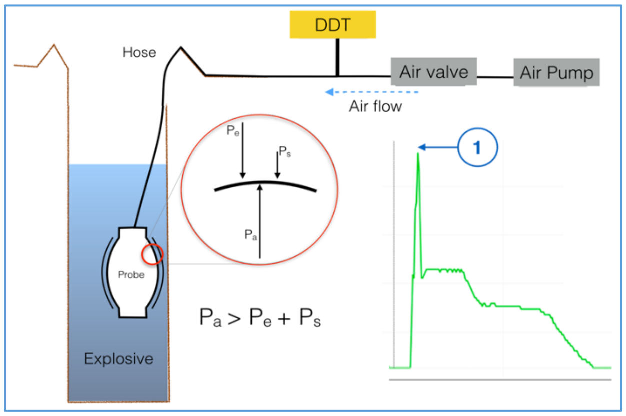


Fig 4. Pressure Peak

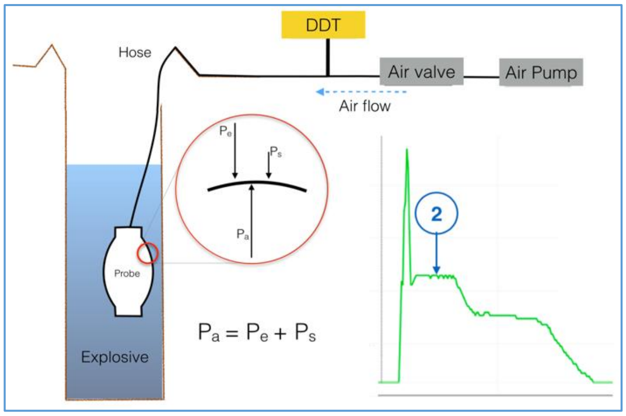


Fig 5. Balanced Pressure Plateau

Step 2: The "return pressure" (Ps) must be removed to read only the explosive pressure (Pe). This is achieved by slowly deflating the probe, opening the valve. In the deflation process (Slope 3 in figure 6), there is a time when the return pressure of the walls becomes "zero", at this time an "plateau" is exponentially formed in the curve (Plateau 4 in figure 7). Therefore there is a balance between the pressure of the surrounding explosive (Pe) and the air pressure of the probe (Pa). In this way we can measure the explosive pressure (Pe), which corresponds to the value on the plateau. At the end of the deflation process, the explosive pressure is higher than the air pressure of the probe and rapid deflation occurs (Slope 5 in Figure 7).

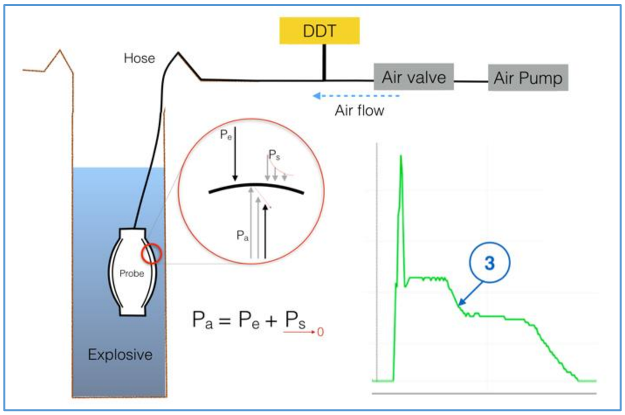


Fig 6. Slowly Deflation

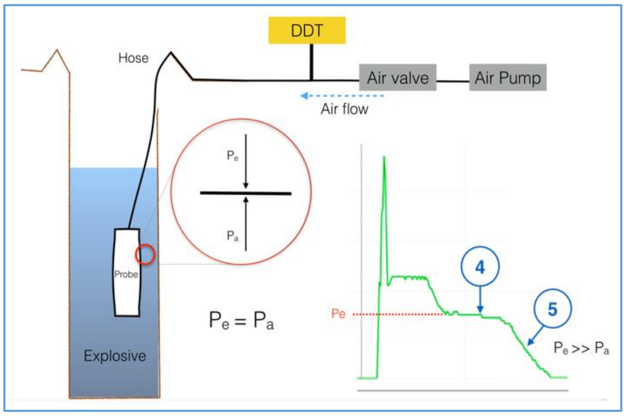
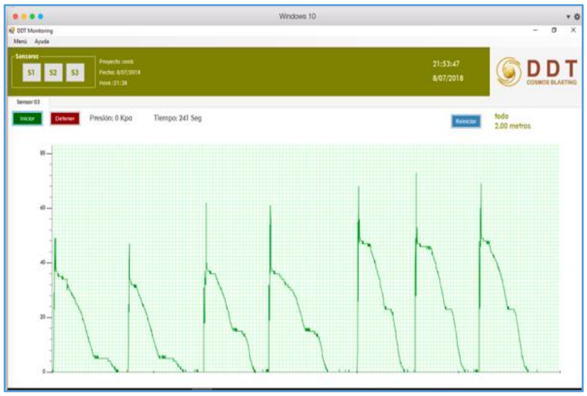


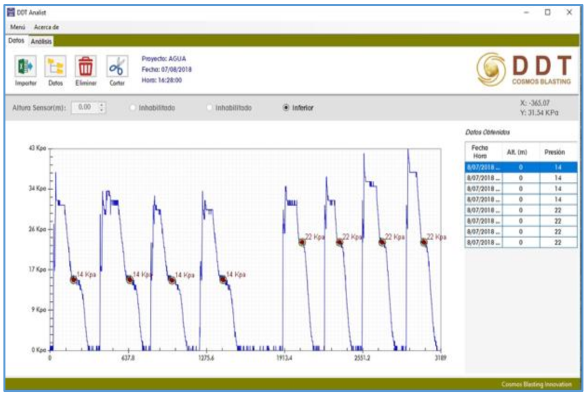
Fig 7. Pressure of the Explosive

Step 3: The pressure is displayed in real time by the interface software of the DDT device (Figure 8). The plateaus that correspond to the explosive pressure can be easily identified. Using the DDT analysis software (Figure 9), the exact value of the explosive pressure that is required by Equation 1 to determine the relative density is captured. The pressure data is stored in a table (Figure 10) with the measurement date and the location of the corresponding probe with respect to the bottom of the hole.



Proyecto: [illegible]
Fecha: 8/07/2018
Hora: 21:38
21:53:47
8/07/2018
Presión: 0 Kpa
Tiempo: 241 Seg
todo
2.00 metros

Fig 8. Real Time Pressure DDT Software



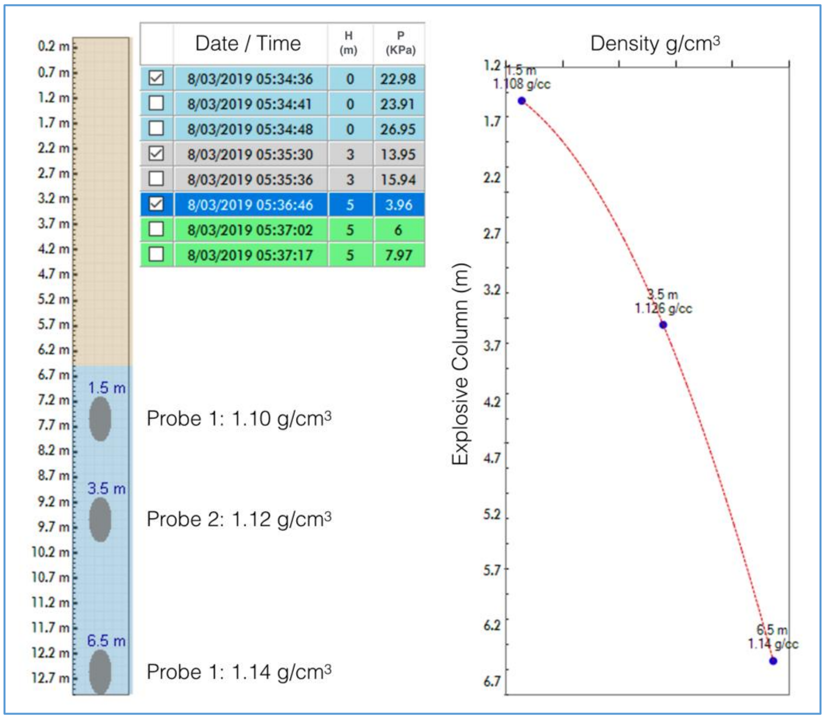
Proyecto: AGUA
Fecha: 07/08/2018
Hora: 16:28:00
Altura Sensor(m): 0.00
X: -365.07
Y: 31.54 KPa

Datos Obtenidos

Fecha Hora	Alt. (m)	Presión
8/07/2018 ...	0	14
8/07/2018 ...	0	14
8/07/2018 ...	0	14
8/07/2018 ...	0	14
8/07/2018 ...	0	22
8/07/2018 ...	0	22
8/07/2018 ...	0	22
8/07/2018 ...	0	22

Fig 9. The Analysis DDT Software

The analysis software calculates and reports the *in hole density* values at different depths inside the hole. If the explosive sleep loaded for several days and the pneumatic probes can still be connected and inflated, you can continue to "measure the pressure" and check the changes in the *in hole density* of the explosive due to the sleep time. The influence of time is very important under certain confinement conditions, such as water, chemical reactivity of the rock, chemical stability of the explosive, sudden temperature changes, among other factors



	Date / Time	H (m)	P (KPa)
☑	8/03/2019 05:34:36	0	22.98
☐	8/03/2019 05:34:41	0	23.91
☐	8/03/2019 05:34:48	0	26.95
☑	8/03/2019 05:35:30	3	13.95
☐	8/03/2019 05:35:36	3	15.94
☑	8/03/2019 05:36:46	5	3.96
☐	8/03/2019 05:37:02	5	6
☐	8/03/2019 05:37:17	5	7.97

Fig 10. The In-Hole Density Report DDT Software

Results

Yanacocha Mine

In April 2018, four measurements were made in three different conditions. The blasting parameters in Yanacocha mine are: 10 m [32.8 ft] height bench, 250.82 mm [9.875 in] in diameter, explosives in use are based on gassed emulsion doped with Anfo 73 (70% of Emulsion), the cup density of the explosive mixture is 1.1 g/cm^3 [68.67 lb/ft^3], charge length 6.5 m [21.3 ft]. The results are summarized in the following table. Probes were located at depths from 2.8 to 5.5 m. m [9.2 – 18.0 ft].

Tab 1. Measurements in Yanacocha mine

Test	Date	Place/Mine	Explosive Mix	Cup Density (g/cm³)	Charge Length above the probe (m)	After-Loaded Time	In Hole Density (g/cm³)
1	Mar, 28, 2018	La Quinua	Gassed HAnfo73	1.10	5.5	120	1.27
2	Abr, 03, 2018	Quecher	Gassed HAnfo73	1.10	5.5	90	1.27
3	Abr, 05, 2018	Yanacocha	Gassed HAnfo73	1.10	3.0	50	1.22
4	Abr, 06, 2018	La Qunua	Gassed Emulsion	1.11	2.8	100	1.23

The *in-hole density* was found to reach a maximum of 1.27 g/cm^3 [79.28 lb/ft^3] at the bottom of the explosive column, for a cup density of 1.10 g cm^3 [68.67 lb/ft^3]. The following figure shows the location of the probes and the corresponding in hole density. At the middle of the column, the *in-hole density* is 1.22 g/cm^3 [76.16 lb/ft^3], under 3.0 m [9.84 ft] of charge length. At the bottom of the column, under 5.5 m [18 ft] of charge length the in-hole density is 1.27 g/cm^3 [79.28 lb/ft^3].

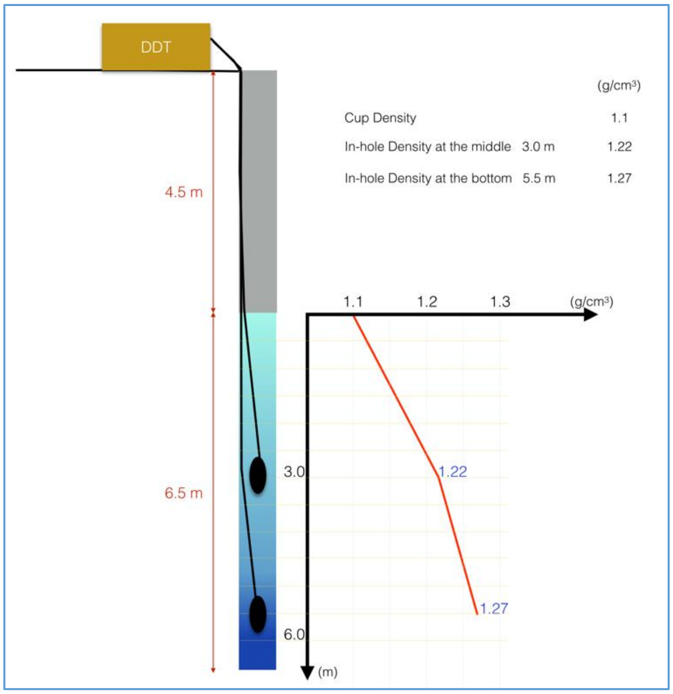
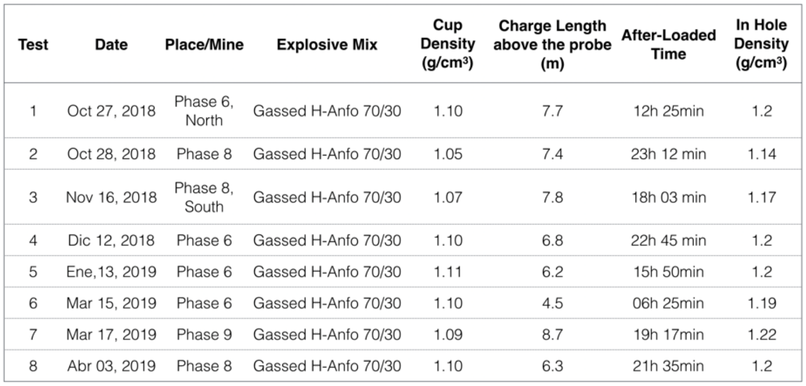


Fig 11. Measure arrange and densities in Yanacocha mine

Antamina mine

The measurements were made in October 2018. The blasting parameters in Antamina mine are: 15 m [49.21 ft] height bench, 311 mm [12.25”] diameter hole, the type of explosive is gassed emulsion doped with Anfo 73 (70% of Emulsion), 9.0 m [29.53 ft] charge length. Before the tests the cup density varied between 1.0-1.1 g/cm^3 [62.43-68.67 lb/ft^3]. The table shows the field data.

Tab 2. Measurements in Antamina mine



Test	Date	Place/Mine	Explosive Mix	Cup Density (g/cm³)	Charge Length above the probe (m)	After-Loaded Time	In Hole Density (g/cm³)
1	Oct 27, 2018	Phase 6, North	Gassed H-Anfo 70/30	1.10	7.7	12h 25min	1.2
2	Oct 28, 2018	Phase 8	Gassed H-Anfo 70/30	1.05	7.4	23h 12 min	1.14
3	Nov 16, 2018	Phase 8, South	Gassed H-Anfo 70/30	1.07	7.8	18h 03 min	1.17
4	Dic 12, 2018	Phase 6	Gassed H-Anfo 70/30	1.10	6.8	22h 45 min	1.2
5	Ene,13, 2019	Phase 6	Gassed H-Anfo 70/30	1.11	6.2	15h 50min	1.2
6	Mar 15, 2019	Phase 6	Gassed H-Anfo 70/30	1.10	4.5	06h 25min	1.19
7	Mar 17, 2019	Phase 9	Gassed H-Anfo 70/30	1.09	8.7	19h 17min	1.22
8	Abr 03, 2019	Phase 8	Gassed H-Anfo 70/30	1.10	6.3	21h 35min	1.2

In the following graph note that the *in hole density* increases directly with the charge length. The red line is for cup densities above 1.1 g/cm^3 [68.67 lb/ft^3] witch is the most common cup density used in the mine. We can see that the density at the zone of the booster is about 1.22 g/cm^3 [76.16 lb/ft^3], thus the density at the bottom can be greater than 1.25 g/cm^3 [78.03 lb/ft^3], increasing the probability of deflagration.

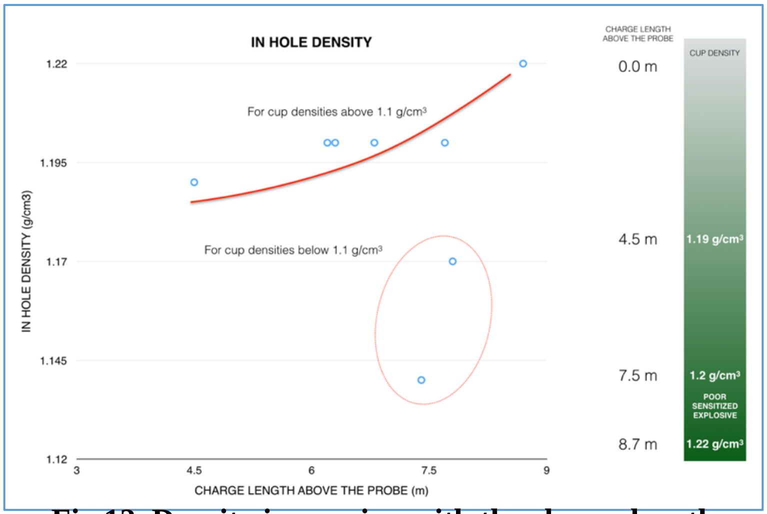


Fig 12. Density increasing with the charge length

Before the tests, 80% of the blasts produce orange fumes, the result was worse with 3 or 4 days of permanence after loading the explosive. It was decided to reduce the cup density from 1.1 g/cm^3 [68.67 lb/ft^3] to 0.95 g/cm^3 [59.31 lb/ft^3], after this action the fumes decrees considerably. Currently 35% of blasting produce fumes. We are studying other causes for the formation of fumes such as pre-compression induced by the initiation sequence and the chemical stability of the explosive.

Toquepala mine

In this mine, more attention was given to the variation of the in-hole density with respect to the time the explosive remains charged (sleeping time). Density was measured 1 hour after loading, 24 hours later and so up to 3 days after. With the intention of estimating the maximum "sleep time" that the explosive can remain stable, before suffering changes in its nature due to the conditions of confinement in the hole, typical of the mine. In Toquepala, the blast holes are 17.0 m [55.77 ft] in deep, 311 mm [12.25"] in diameter, 9.0 m [29.53 ft] charge length. The explosives in use is gassed emulsion doped with Anfo 73 (70% of Emulsion). Before the test the density was very high, in order of 1.17 g/cm^3 [73.04 lb/ft^3]. We found that the explosive pressure increased rapidly in the first hour after loading. The following figure shows how the density increases over time.

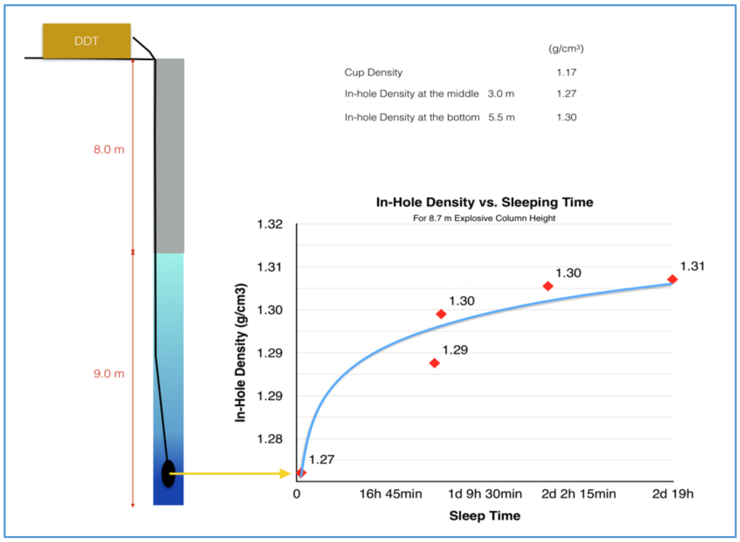


Fig 13. The effect of increase in density over time

The probe was placed at only 0.3 m [0.98 ft] from the bottom, thus supporting 8.7 m [28.54 ft] of charge length. After 2 days and 19 hours, the last measured pressure was 130.66 KPa [18.95 psi], which gives us a in hole density 1.305 g/cm3 [81.47 lb/ft3]. The obtained in hole density is very close to a "critical density", above which the sensitivity of the explosive at the bottom is lost, Ruilin Yang (2011). This can be evidenced by the formation of nitrous fumes. The recorded video of the blasting (Figure 11) shows that in the area where the explosive remained charged for almost 3 days orange fumes formed.

Fig 14. Fumes due to high in-hole density

Density and VOD

VOD was measured when the cup density was 1.20 g/cm3 [74.91 lb/ft3]. The graph showed "difficulty" at the start of detonation (booster location); there was only full detonation at the top 4 m [13.12 ft] of the explosive column. The low order VOD in the boot zone is related to the high in-hole density and loss of sensitivity.

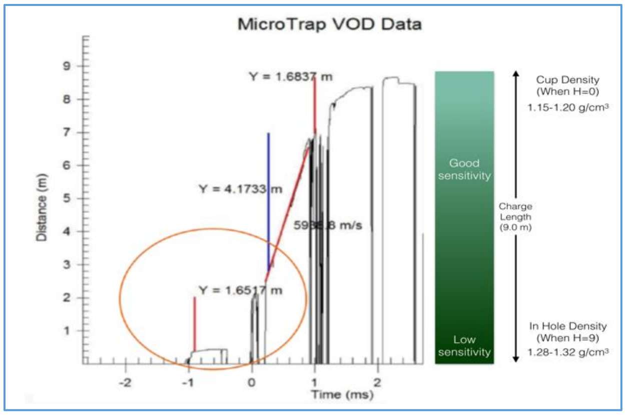


Fig 15. VOD at high densities

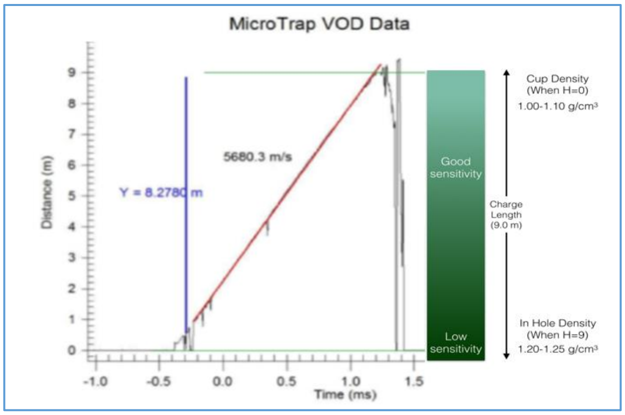


Fig 16. VOD at low densities

Then it was decided to lower the cup density to values between 0.9 to 1.10 g/cm^3 [56.18 to 68.67 lb/ft^3]. VOD measurements now show a more continuous graph across the entire length of the explosive column. For this case, we obtain a VOD 5680 m/s for gassed emulsion doped with Anfo 73, hole was 311 mm [12.25”] in diameter.

Rock Conditions

The pressure in well-formed blast holes filled with water dramatically increases the *in-hole density*, reducing the sleep time of the explosive. In cracked holes, the pressure can reduce over time. The explosive migrates through the small cracks and becomes contaminated, again giving conditions for deflagration. In addition, some rocks may contain a type of salts that can chemically affect the explosive.

Economic impact

By reducing the in-hole density, benefits have been found in the performance of the explosive and therefore in the fragmentation and minimization of nitrous fumes. In addition, the economic benefit related to lower density and consumption has been achieved.

Conclusions

- Gassed explosives without adequate control of the in-hole density would increase the possibility of losing the sensitivity at the bottom and the resulting poor fragmentations and fumes.
- There are two restrictions when designing a blast using gassed explosives: first the cup density and second the charge length.
- When the charge length is shorter, for example 6.0 m [19.68 ft] in Yanacocha mine, the effects of hydrostatic compression are also minor.

- In the case of Antamina and Toquepala mines, the charge length can be greater than 9.0 m, therefore the effect of compression is more important.
- Based on the measurements of *in hole density* and VOD, the reduction of the cup density to values between 0.9 to 1.10 g /cm^3 [56.18 to 68.67 lb/ft^3] has been satisfactory.
- On the other hand, the sleep time and the conditions of the environment influence even more when the *in-hole density* is high, above 1.25 g/cm^3 [78.03 lb/ft^3]. For this reason, the high compressed explosive column in Toquepala mine produces fumes, only 3 days after loaded.
- Although the diameter is not related to the hydrostatic compression model, it is related to the detonation process in a favorable way. For this reason, despite having a difficult start at the bottom, the explosive gets to detonate and do fragmentation work, but producing nitrous fumes.
- This investigation has allowed us to measure the pressure and density of the explosive in "real conditions" in the field, confined in the blast holes. It has improved our understanding of gassed explosives.

Acknowledgements

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A very special thanks to the engineers Luis Cardenas, Ronald Añazco and Alejandro Ramirez, who being part of the Peruvian explosives companies Famesa and Exsa, showed their interest in measuring the *in-hole density* of their explosives in the mines where they operate. During the field tests the contributions of the engineer Victor Hugo Paredes Canto have been very valuable, to whom I express my gratitude. I also want to thank the engineer Jaime Aranibar with whom we began the investigation on the compressibility of gassed explosives, in Cuajone mine in 2015. We are very grateful to all the people who at the time supported us in various ways to carry out this research. We will continue this type of work, which is useful for improving the quality of explosives and blasting results.

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