Optimization study of shotcrete in Neves-Corvo Mine

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Keywords

Shotecrete; Support system; Thickness and Compression strength.

ABSTRACT

Shotcrete consists of a concrete produced under conditions by a certain basic composition, which is applied pneumatically at high speed, producing a dense and homogeneous mass by its own kinetic energy. The placing flexibility, compression and adherence ability to several types of surfaces, exemption of formwork and its role as a support system, favours the use of shotcrete on the mining industry.

This work aims to characterize the shotcrete, improve and optimize its application process inside Neves-Corvo Mine. To this end, it was required to perform a quantitative and qualitative analysis of the shotcrete properties, such as hardened concrete thickness (*in situ*) and compression strength (*in situ* and young concrete samples), modifying the shotcrete components on the last referred.

This study concludes that it is possible to reduce the costs related to the volume of shotcrete applied, without affecting a specified thickness demands. The modifications to its components also showed improvements on the young hardened concrete compression strength, meaning with this, a development and optimization of the shotcrete process.

CONTENTS

1. INTRODUCTION

Shotcrete is one of the most used support technic for rock masses. . It was introduced in 1914 in mining by the United States Bureau of Mines (USBM). It began to replace timbering with shotcrete in the Bruceton mine (Kovári, 2003a).

During the actual decades, new devices have been developed, new materials have been introduced, and this support technic's process has been improved. This system becomes more efficient when combined with other support and reinforcement elements in exploiting drifts (Hoeket al., 2002).

The several head work in simultaneous operation, hard access e load conditions, have contributed for development of innovating applications of shotcrete, making it necessary for safety e work progress on mining exploration.

Shotcrete is an expensive technic, therefore is on the companies' interest, it's cost optimization.

With Somincor's cooperation, this work aims to study the shotcrete elements' influence on its final cost and properties. Experimental tests have been carried out, measuring thicknesses and compressive strength, focusing its improving and optimization.

2. EXPERIMENTAL STUDY

2.1. Company description

All the shotcrete study was developed on Somincor, Neves-Corvo mine.

Table 1. Neves-Corvo mine's general characterization (adapted from LundinMining, 09.2013)

Localization	Alentejo region, located in the western zone of the Iberian Pyrite Belt
Ore type	Volcanogenic massive sulphide
Primary metal **Secundary metal**	Copper Zinc
Type of mine	Underground
Main development	Santa Barbara's shaft with 592m deep and Castro's ramp with 17m2 section and 12 and 18% slopes.
Processing plant	Copper plant, Zinc plant, tailings thickening and paste fill facility.
Mining methods	Are based in the principle of Cut and Fill: drift and fill, bench an fill and mini-bench and fill.
Ore deposits	Corvo, Graça, Neves, Zambujal, Lombador e Semblana.
2013's Goal **Copper Production** **Zinc Production**	 50,000 – 55,000 tons 14,000 – 50,000 tons

2.2. Shotcrete's characterization

Shotcrete is characterized by the mixture of cement, aggregates, water e admixtures, such as water reducer e setting accelerator. Accelerator is only added during concrete shooting. Fibers and additives can be added to improve concrete proprieties.

Shotcrete can be applied either by dry and wet process. On dry process, the materials are previously dryly mixed and introduced on shooting machine. During shotcrete transport, water and accelerator is introduced on the noozle, measured by the operator.

On wet process, the materials are mixed up with water and introduced on the shooting machine. In this case, only accelerator is added on the noozle (Hofler et al, 2011).

2.2.1. Cement

Portland traditional cement (CEM I) is the most used hydraulic binder on shotcrete shooting.

Table 2. Main components of Portland Cement (Coutinho, 1988)

Component	Abbreviation	Quantity
Tricalcium Silicate	C_3S	20 – 65 %
Dicalcium Silicate	C_2S	10 – 55 %
Tricalcium Aluminate	C_3A	0 – 15 %
Tetracalcium Aluminoferrate	C_4AF	5 – 15%
Calcium Sulphate	CaSO4	3 %

Cement's main components have diverse properties: calcium aluminates hydrate instantaneously, promoting a fast setting, and strength develops on the first days, while the silicate hydrate slowly allowing setting time and strength reach days or weeks.

The aluminates' high hydration heat production, is considered to be the main responsible for shrinkage and cracking. In order to control the aluminate reaction, calcium sulphate is added, to regulate setting time.

Cement is the main component of shotcrete's final characterization. Its main purpose is to reach a fast setting time and develop high initial strength gain, granting its durability.

The cement content should normally be between 400 and 500 kg/m^3 of concrete for the wet process (EFNARC – Guidelines, 1999).

● ***Cement used in the experimental study***

Cement used it Porland Cement CEM I 42,5 R. This one, is adequate for environmental exposal classes XA (chemical attack originated by underground soles and water), such as Neves-Corvo mine.

2.2.2. Aggregates

Aggregates' dimensions for shotcrete, variate from 0 to 8 mm. Size distribution is one of the most important aggregates' proprieties, followed by strength, which conditions the concrete compacity, pumpability and shooting.

Aggregates' size distribution curves should adjust the better possible to the reference shotcrete's curve edges, as presented on the following figure.

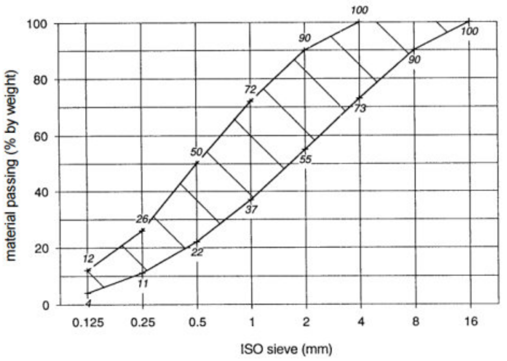

Figure 1. Limits the reference area of the aggregates (EFNARC – European Specification for Sprayed Concrete, p.4, 1996).

Fine quantity must be enough to ensure the correct pumpability and concrete mixture shooting. Coarse aggregates quantity should ensure correct compaction, strength and permeability requirements, keeping the minimal binder/aggregate ratio, in order to reduce shotcrete shrinkage and rebound (NP EN 14487-1, 2008).

Fine material, contained on sieve below 0,125mm, must be a minimal 4 to 5 % and maximum of 8 to 9 % of aggregates proportion. An excessive amount of fines causes a larger quantity of water and therefore problems with hardened shotcrete shrinkage. If fine amount is lower the indicated, the mixture can be submitted to an increase of segregation e equipment clogging danger (Melbye, 2006).

It is recommended that aggregates with size above 8mm, must be only 10% of the proportion, in order to minimize the rebound and pumpability problems (EFNARC – Guidelines, 1999).

● ***Aggregates used in the experimental study***

Aggregates used are washed sand and rolled gravel. Later on, washed sand was replaced by silica sand AS 30/40-G.

Aggregates are mostly composed by quartz, distinguished by the size distribution e particle shape.

Sand's size distribution variate from 0 a 4 mm, and rolled gravel's particles variate from 2 to 8mm.

2.2.3. Water

The water added to shotcrete, is the one added during production and the water inherent from aggregates. The consistency of the mixture is regulated by water and admixtures.

The mix water must not contain oil and grease, chemical or organic impurities and any other substances that may to be detrimental and affect the shotcrete hydration process (Hofler, 2011).

● ***Water used in the experimental study***

The water source for mix water is Santa Clara's dam. This is not potable water, but has adequate characteristics, for it is corrosives free, which could affect de steel fibers and the concrete itself.

2.2.4. Admixtures

The admixtures' function is to modify or improve concrete properties. Normally, they are used in 0,5 to 7 % proportion of either cement or binder (Hofler, 2011).

The main admixture effects on shotcrete are (Coutinho, 1988a):

- Improve workability;
- Accelerate or retard setting time;
- Accelerate the early hardening;
- Improve compression strength;
- Decrease liquid permeability;
- Help pumpability;
- Modify viscosity;
- Offset shrinkage.

● *Water reducers*

Water reducers either improve concrete workability and coesion without changing w/c ratio, promoting an improvement on pumpability, or, reduce water amount added to the mixture, promoting an strength gain.

The two types of water reducing admixture:

- Plasticizer
- Superplasticizer

Adsorption on cement particles occurs mainly on aluminates, which results on setting delay, for the admixture molecular adsorption of cement grains delays its contact with water (Coutinho, 1988; Melo, et al, 2008).

● ***Water reducers used in the experimental study***

It was only used superplasticizers on shotcrete mixture, namely Sikament 300 Plus and Sika ViscoFlow

45, referring the latter that was used on modifying mixture from early strength tests.

• *Setting and hardened accelerator*

This admixtures modify a solubility, e especially, dissolution speed of different cement components.

There are 4 types of setting accelerators:

- Alkaline free accelerator;
- Alkaline accelerator;
  - Aluminates;
  - *Waterglass* (silicates);
  - Silicates modified.

Right after mixing shotcrete with accelerator, the fast cement hydration process begins, which consists on the reaction of C_3A and calcium with water, forming ettringite (C_6 ASH_{32}), and afterwards, a slow silicate components hydration with the ettringite occurs to form hydrated silicate calcium (Figure 1).

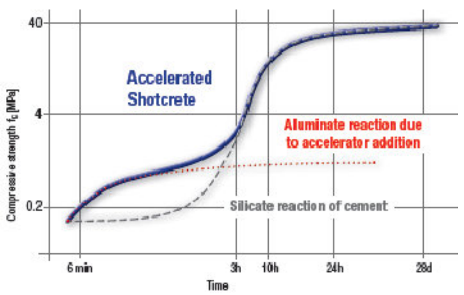

Figure 2. Interacting of aluminate and silicate reaction (Hofler, p.23, 2011).

Main characteristics of setting accelerators for shotcrete:

- Form ettringite, to promote setting and early strength development
- Decrease rebound
- Increase viscosity, allowing fixation of thicker layers
- Shooting concrete on wet surfaces

• *Accelerator used in the experimental study*

Only alkaline free setting accelerator were used on shotcrete, namely Sigunit L82 AF P and Sigunt T&M, referring the latter that was used on modifying mixture from early strength tests.

2.2.5. Additives

Aim of use of additives on shotcrete:

- Complement the absence of fine aggregates (≤ 0,125 mm);
- Improve durability;
- Increase water retention capacity;
- Improve pumpability;
- Replace the cement, decreasing costs;
- Develop early strengths.

There are 4 types of additives:

- *Silica Fume;*
- *Fly ash;*
- *Slag;*
- *Limestone Filler.*

• *Additive used in the experimental study*

The used additive on hardened concrete compression strength tests was limestone filler. It was used in order to make up the absence of silica sand fines, and as replacer of cement, to decrease shotcrete costs.

Studies revealed that C_3S e C_3A hydration process of cement are affected by the presence of limestone filler: hydration is accelerated, e the reactions release more heat, making the limestone filler a better cement replacer, for it provides early strengths improvements (3 to 7 days), but in the other hand, there is a long term strength decrease. (Bouasker, 2007 e Boubitsa, 2013).

Advantages of the limestone filler as shotcrete additive (Sezer, 2011):

- Increase on early strengths
- Goodd workability
- Low water demand
- Low production cost.

2.2.6. Steel Fiber

Using steel fibers provides the control crack spread. After cracking, the shotcrete capacity of energy absorption is improved, making a better shotcrete with better ductile characteristics. This occurs because fibers create connecting tension bridges through the cracks, maintaining a certain section bearing capacity.

• *Steel fiber used in the experimental study*

Steel fibers are used on Somincor's shotcrete are Dramix, RC 65/35 BN.

2.2. Requirements for shotecrete

2.2.1. Consistence

The necessary concrete consistence for the wet process depends on practical aspects, like pumpability; shotcrete mixture temperature; retention time on truck mixer.

The concrete slump should be maintained between 80 and 200mm, with variations limited to ±30mm, to produce better fresh and hardened concrete qualities (EFNARC - Guidelines, 1999, ACI 506.5R-9, 2009).

2.2.2. Temperature

Low temperatures retard both setting and hardening and concrete will not then achieve the early strength requirements, unless higher accelerator dosages are used, but this normally reduces the final strength. High temperatures shorten workability time and accelerate concrete stiffening and setting, losing then necessary "plasticity" to get good adhesion and cohesion of sprayed concrete (EFNARC - Guidelines, 1999).

The mix temperature should preferably be in the range +5°C to +35°C (ACI 506.5R-9, 2009).

2.2.3. Durability

The durability of shotecrete depends of environment conditions to which the concrete is exposed and activity within the concrete itself.

Durability is highly dependent on the permeability. How much high the porosity, bigger is the ingress of liquids and gasses that cause deterioration and on slowing down chemical reactions (EFNARC - Guidelines, 1999).

2.2.4. Mechanical properties

● *Early shotcrete compressive strength*

NP EN 14487-1 (2008) classifies the shotcrete in function on the early compression strength development, defining three classes, J1, J2 and J3 (figure 3). The shotcrete of J2 class is defined for drilling and detonation working zone, as in mining.

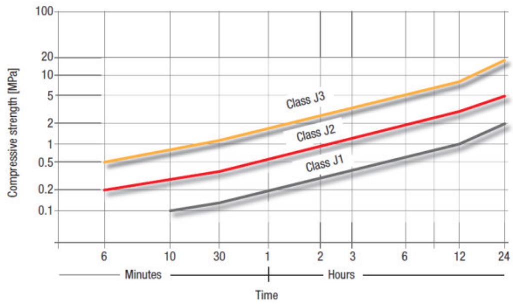

Figure 3. Shotcrete early strength classes according to NP EN 14487-1 (Hofler, 2011)

According to NP EN 14488-2 (2008), early shotcrete compression strength is determined through penetration method with a needle, and stud driving method with Hilti gun (Figure 4 and Table 2).

● *Hardened shotcrete compression strength*

According to Hofler, the water/cement ratio for shotcrete shooting by wet process must be limited to a maximum of 0,5 in order to obtain a better development on pumping and shooting. To improve shotcrete quality and strength, this must lowered to a limit of 0,48.

In order to control the hardened concrete compression strength, tests are carried out, using concrete cubes as NP EN 12390-2 (2009) suggests, or following NP EN 14487-1 (2008), through concrete coring.

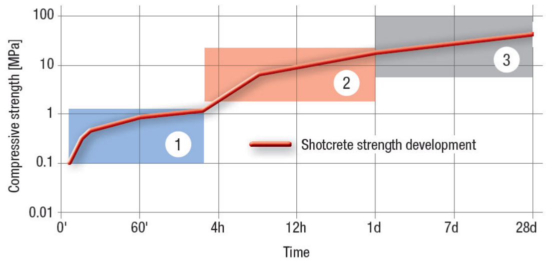

Figure 4. Strength development measurement (Hofler, 2011).

Table 3. Methods for strength development measurement (Hofler, 2011).

Development		Instrument	Strength (MPa)	Time
1	**Initial strength**	Penetrometer	0,2-1,2	0-3h
2		Hilti DX	3-20	3-24h
3	**Final strength**	Compression testing machine	5-100	1-28 d

The concrete compression strengths are mainly related with the cement type and quality, aggregates temperature and quality, water quality, type of additive, shotcrete thickness and setting accelerator dosage among the shooting (Hofler, 2011; EFNARC – Guidelines, 1999).

2.4. Execution of projection

2.4.1. Shotcrete's design

To determine the shotcrete volume to be applied, beyond the shooting area, the thickness (Q-System), rebound and substrate roughness should be accounted.

According to Vandewalle (2005), on mining using explosives, the theoretical concrete volume must multiplied by a correction coefficient, which variate from 1,3 to 1,8, and is a function of the substrate's roughness and rebound.

$$V_{betão} = A_t \times e_{min} \times CC\ (m^3)(Vandwalle, 2005)$$

$V_{betão}$ – Shotcrete theoretical volume;
A_t – Theoretical area;
e_{min} – minimum thickness.
CC – Correction coefficient;

Studies developed by Selmer (2014), that uses the scanner *Lidar* system to estimate the roughness, showed that this coefficient can be correlated with the Q-System and the joints number on the substrate (J_n) (Table)

Table 4. Roughness coefficient taking into account the rock mass quality and joints number(J_n) (Selmes, pp. 58. 2014).

1,56	1,5	1,44	1,42	1,38	1,3	**15**
1,31	1,25	1,21	1,19	1,16	1,09	**12**
1,27	1,22	1,18	1,16	1,12	1,06	**9**
1,22	1,17	1,13	1,11	1,08	1,02	**6**
1,21	1,16	1,12	1,10	1,07	1,01	**4**
1,2	1,15	1,11	1,09	1,06	**C. Rug.**	**J_n**
F	**E**	**D**	**C**	**B**		

● ***Shotecrete volume used in the experimental study***

Table 5. Values used for calculation of shotecrete volume.

Espessura mínima (m)	**0,05**
Coef. Rugosidade e *Overbreak*	0,75
Coef. Ressalto	0,15

$$V_{Betão} = A_{teórica} \times e_{mín} \times (1 + c.rug. + c.res.) \leftrightarrow$$
$$\leftrightarrow V_{Betão} = A_{teórica} \times 0{,}05 \times \mathbf{1,9} [m^3]$$

3. RESULTS AND DISCUSSION

The experimental campaign's goals were evaluating the shotcrete thickness and compression strength.

The thickness control was performed in situ, through destructive drilling tests on hardened shotcrete in several working heads of Neves-Corvo mine.

Referring the strengths, two studies were carried out. The first one refers to early strengths, which were measured in situ, through penetration testes of several young shotcrete mixtures. The mixtures were reformulated from the basic mixture, by modifying the admixtures and aggregates. The second study refers to the compression strengths measured in lab, through the performing of cubic samples using different shotcrete mixtures, adding an additive.

3.1. Shotecrete thickness

The thickness control testes were carried out with the aim to understand if the actual applied thicknesses followed the requirements defined by the geological and geotechnical studies. This study defined that the thicknesses for the actual sole type on Neves-Corvo mine must be 5cm. For the determined thicknesses in situ, it was possible to determine the correction coefficient to use on shotcrete volume dimensioning.

The use method to determine the shotcrete thickness after shooting, refers to NP EN 14488-6 (2008).

● ***Mixture used in the experimental study***

Components	Quantity (kg/m^3)
Washed sand/ AS30/40-G 0/4mm (70%)	1100
Gravel 2/8mm (30%)	475
Cement I 42,5R	400
Superplasticizer – Sikament 300 Plus (1%)	4
Accelerator– Sigunt L82 AF P (8%)	32
Water	200
Steel fiber	20-30

● ***Determination of new correction coefficient***

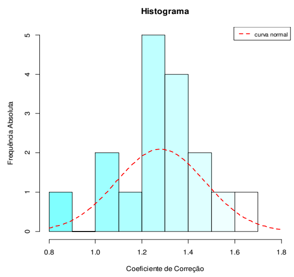

Figure 5. Histogram of correction coefficients.

So the settled value for CC was 1.3. It was checked that the previous value (1,9) was over dimensioned.

In order to choose for a more conservative support system, through the develop table 3 (by Selves), e know that the rock mass is type D, with a J_n higher than 15, the correct value is 1,6 (1,44 of roughness plus 0,15 of rebound). Analysing a more critical scenario (rock mass type F), the determined value is 1,7.

● ***Economic analysis***

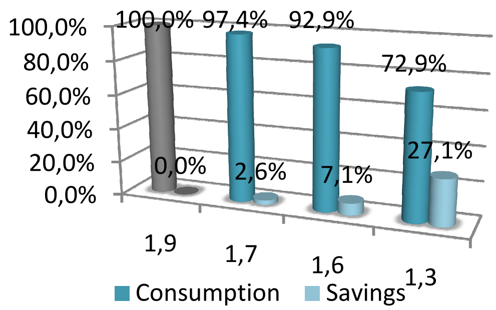

Figure 6. Consumption vs. savings of correction coefficients

3.2. Initial compressive strength

In order to better understand if the shotcrete mixture quality follows da requirements, as a type of support, was necessary to perform young shotcrete compression tests, and check if it fit the strength class defined as J2, as stressed out on chapter 1.5.4.

The used method to determine young shotcrete compression strength in situ was referring to NP EN 14488-2 (2008). This norm describes two principals of use, defines the method to use to measure the compression strengths during the first 24 hours (Table 2).

● ***Base mixture used in the experimental study***

Components	Quantity (kg/m^3)
Washed sand/ AS30/40-G 0/4mm (70%)	1100
Gravel 2/8mm (30%)	475
Cement I 42,5R	400
Superplasticizer – Sikament 300 Plus (1%)	4
Accelerator– Sigunt L82 AF P (8%)	32
Water	200
Steel fiber	20-30

This basic mixture was changed with the aim of obtaining a mixture that would fit in the J2 class. The change was made through modifying the admixture, aggregates and its proportions.

● ***Determining the shotcrete mixture for J2 class***

		Dosage (%)		
Superplasticizer	*Sika ViscoFlow 45*	0,75		
Accelerator	*Sigunt T&M*	6	8	10

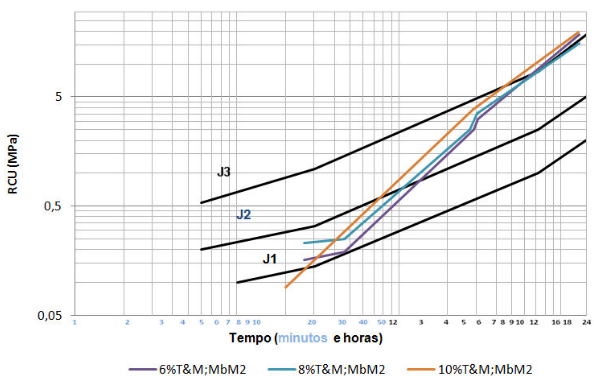

Figure 7. Shotcrete early strengths development (Sigunit T&M and Sika ViscoFlow 45 with 0,75%)

None of the mixtures satisfied the J2 strength class. The early strength in the first hours delayed to reach admissible values for J2 class. This means the superplasticizer may have an excessive dosage, affecting the early aluminate reaction and these strength's developments.

		Dosage (%)		
Superplasticizer	*Sika ViscoFlow 45*	0,55		
Accelerator	*Sigunt T&M*	6	8	10

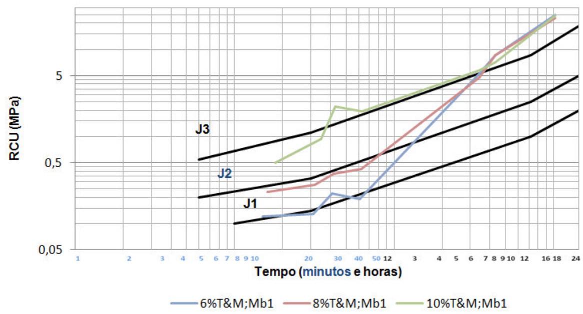

Figure 8. Shotcrete early strengths development (Sigunit T&M and Sika ViscoFlow 45 with 0,55%)

The strengths on the first hours acquired very satisfying values, which can be justified by the smaller quantity of superplasticizer used.

		Dosage (%)					
Superplasticizer	Sikament 300 Plus	1					
Accelerator	Sigunt T&M	4	5	6	7	8	10

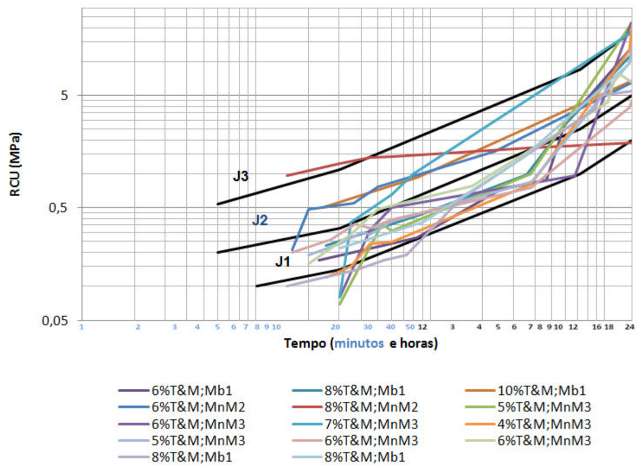

Figure 9. Shotcrete early strengths development (Sigunit T&M and Sikament 300 Plus with 1%)

Some mixtures are in the J2 strength class. The new modified mixture 2 (MnM2) and the basic mixture (Mb1) reach favourable results, for such at first minutes as well as along the hours developed strengths always inside the J2 boundaries. It is then concluded, that the superplasticizer (Sikament 300 Plus) used on the mixture can be applied, without its replacing by other superplasticizer (Sika ViscoFlow 45).

		Dosage (%)	
Superplasticizer	*Sikament 300 Plus*	1	
Accelerator	*Sigunt L82 AF P*	8	9

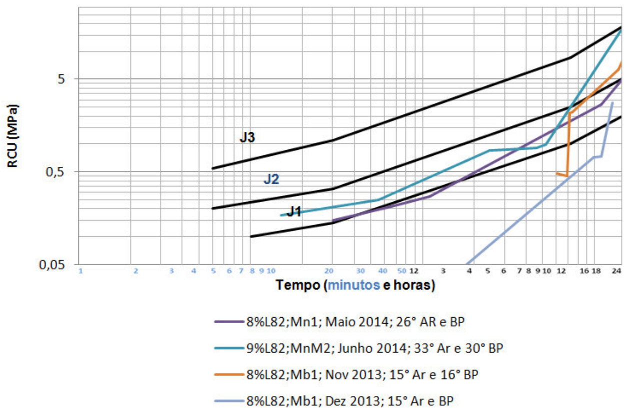

Figure 10. Shotcrete early strengths development (Sigunit L82 AF P and Sikament 300 Plus with 1%)

The combination of these two admixtures using this dosages wasn't the most advisable in order to obtain a J2 strength class concrete.

Through this chart it is also possible to check that the temperature has influence on the strength's development, for it has been checked that the lower the temperatures, more affected were the strengths.

The problem may be not only an admixture and temperature's consequence, for other factors may be involved, such as, cement chemical composition or the presence of organic matter on the aggregates.

- ***Economic analysis***

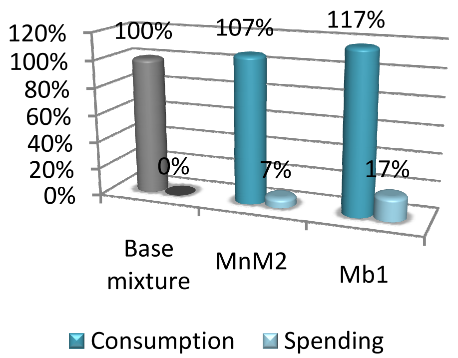

Figure 11. Consumption vs. Spending of shotcrete with the best early strength.

3.2. Final compressive strength

The main goal of these tests was to reduce costs and improve the shotcrete's quality through the replacement of the cement and additive quantities, carrying out a laboratory study focusing the evaluation of different possible scenarios.

This modification is due to the fact of the new sand AS30/40-G added, has a high fines deficit. It is causing some segregation on the mixture e its consequent equipment clogging.

The used methods to determine compression strengths on hardened shotcrete samples, were referring to NP EN 12390-2 (2009) and NP EN 12390-3 (2009).

- ***Standard mixture used in the experimental study***

Components	Quantity (kg/m^3)
AS30/40-G 0/4mm (60%)	962
Gravel 2/8mm (40%)	642
Cement I 42,5R	400
Superplasticizer – Sikament 300 Plus (1,1%)	4,4
Water	228
Steel fiber	20
Air (%)	4

- ***Reformulation of mixtures used in the experimental study***

	Test -Std	T1-20	T1-40	T2-20	T2-40
AS30/40-G - 60% (kg/m^3)	**962**	962	961	962	961
Gravel - 40% (kg/m^3)	**642**	641	640	641	640
CEM I 42,5R(kg/m^3)	**400**	380	360	380	360
***Filler* (kg/m^3)**	**-**	20	40	20	40
Water (kg/m^3)	**228**	228	228	218	218
Fiber (kg/m^3)	**20**	20	20	20	20
Sikament 300 Plus - 1,1% (kg/m^3)	**4,4**	4,2	4,0	4,2	4,0
Air (%)	**4**	4	4	5	5
Water/binder	**0,52**	0,53	0,55	0,51	0,52
Cost (%)	**100**	**98,3**	**96,6**	**98,3**	**96,6**
***Slump* (0 min) (cm)**	22	25	25	22	26
***Slump* (30 min) (cm)**	18	21	22	16	20
***Slump* (1h) (cm)**	13	17	-	9	-

Figure 12. Characteristics of different reformulated mixtures.

- ***Determination of the mixture with the best compression strength***

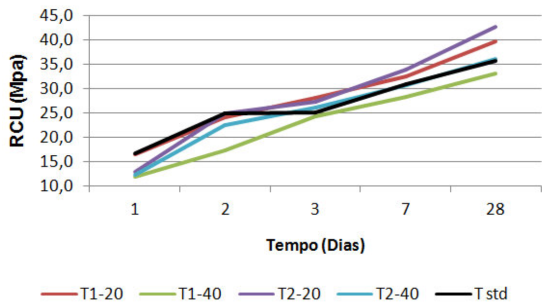

Figure 13. Uniaxial compressive strength for each mixture

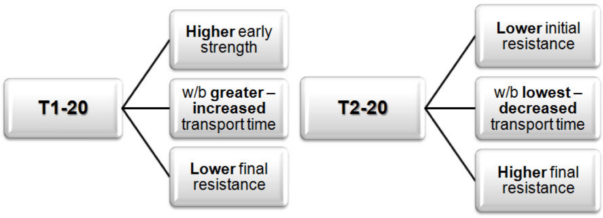

Figure 14. Summary results.

Replacing cement for additives with quantities of 20 kg/m^3 of concrete, caused an increase on the shotcrete strength. The compression strengths were improved and the costs were decreased.

- ***Economic analysis***

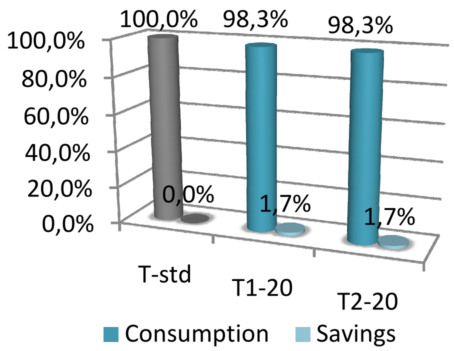

Figure 15. Consumption vs. savings among the best mixtures

4. CONCLUSION

With the study developed and thickness tests performed to the shotcrete, it was possible to conclude that the volume of shotcrete applied was normally higher than it should.

With a correction coefficient of 1,7 it was possible to reduce the shotcrete volume in 2,6% e with a correction coefficient of 1,6 and 1,3 it was possible do reduce respectively 7,1 and 27,1% of the shotcrete volume used.

This cost reduction was extremely important when optimization is intended, for from this reductions on, it was possible to propose a shotcrete quality improvement, through the introduction and modification of new components. This way, it was necessary to perform two more tests related with the shotcrete mechanical properties, such as early and hardened shotcrete uniaxial compression strength.

Through a group of early concrete compression strength, it was possible to improve the shotcrete strength class to a J2 one.

After the performing of these tests it was possible to conclude that, introducing Sigunt T&M and increasing the resulting season temperatures, developed a J2 strength class concrete. This improvement on the shotcrete's quality didn't provide the cost reduction, and on the other hand, the costs increased.

In accordance with the acquired results e not representing such a high cost, the best solution was replacing the setting accelerator used on the basic mixture (MB), for the new accelerator Sigunit T&M using a dosage of 6%, conducting to an increase of 7,1% over the total shotcrete costs.

The introduction of the limestone filler additive when replacing the cement, provided the increase of the hydration ratio and a better engagement of the aggregates paste, making the concrete's matrix more dense, which provided improvements on the final hardened concrete strengths and a decrease of 1,7 % on costs.

To conclude, it was possible to reduce concrete costs by introducing a new correction coefficient of 1,6. Regarding the introduction of a new accelerator, the Sigunit T&M, the concrete costs increased, but if the correction coefficient of 1,6 applied the costs stayed equal. The introduction of the limestone filler additive, in addition of providing an strength improvement, conceded a 1,7% overall costs shotcrete reduction.

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