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# Investigation into the development of foam mine fill

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## Abstract

*This study is part of large and an ongoing investigation into the development of a light-weight and highly fluid mine fill for various applications in mining and civil operations. Foam mine fill (FMF) is the new material proposed for backfilling mines, and is fabricated by mixing stable foam into a mixture of tailings, binders, and water. This paper presents the results of a preliminary experimental study, in which FMF samples were prepared under different binder dosages, pulp densities, and amount of air entrained.*

*FMF samples were prepared using tailings from a copper mine as the inert material, Normal Portland Cement as the main binding agent, and a foaming agent with a foam generator. Samples were cured for 28 days and subjected to unconfined compressive strength (UCS) testing. Select samples were subjected to mercury intrusion porosimetry to study the microstructural properties. An empirical model was developed using a response surface methodology to determine the optimal settings for the factors investigated, and to produce the first reference sample with a 28 day UCS value of 1 MPa.*

## 1 Introduction and background

The disposal of mine tailings is a significant issue in the mining industry, particularly as mine production increases. Many mines re-use mine tailings for backfilling, as a method of reducing environmental exposure to tailings, maintaining underground stability and increasing ore recovery (Benzaazoua et al. 2002).

In this paper, a new type of backfill called 'foam mine fill' is introduced. This new proposed backfill material is similar to cellular concrete, where air bubbles are entrained in cement or lime mortar, resulting in a cellular structure (Narayanan & Ramamurthy 2000). Air voids can occupy up to 70% of the volume of concrete, which makes it light in weight, and can thus be used for a wide range of civil applications, including backfilling (Tarasov et al. 2010; Panesar 2013). Unlike cellular concrete, the incorporation of air bubbles into a mixture of tailings, binder and water makes foam fill a new potential backfilling material. This new lightweight material would provide safer working conditions for miners, especially in underhand cut and fill mining where miners work beneath the backfilled stopes. Some claim that the new material has many advantages, especially in terms of weight reduction, rheology improvement and cost minimisation (Cellcrete Technologies Inc. 2013).

This research aims to carry out an in-depth study of FMF by producing consistent FMF samples, investigating its mechanical and physical properties, and ultimately exploring its potential applications and advantages. The paper presents the results of a preliminary laboratory experimental study, in which FMF samples were prepared and tested for UCS after 28 days of curing. Furthermore, response surface methodology (RSM) has been adopted, in order to produce the first reference FMF sample with a UCS value of 1 MPa; which is generally the compressive strength required for cut and fill mining (Hassani & Archibald 1998).

# 2 Experimental program

## 2.1 Materials

### 2.1.1 *Tailings*

In this research, a copper tailings with specific gravity of 2.9 g/cm$^3$ was used to prepare the FMF samples. The tailings primarily consists of quartz and albite, as well as small amounts of calcite, muscovite, actinolite, rhodoch anorthite, chalcopyrite, biotite, pyrrhotite, epidote, and chlorite. The particle size distribution of the tailings, as shown in Figure 1, was determined using sieve analysis in accordance with ASTM C136-06 (ASTM International 2006a).

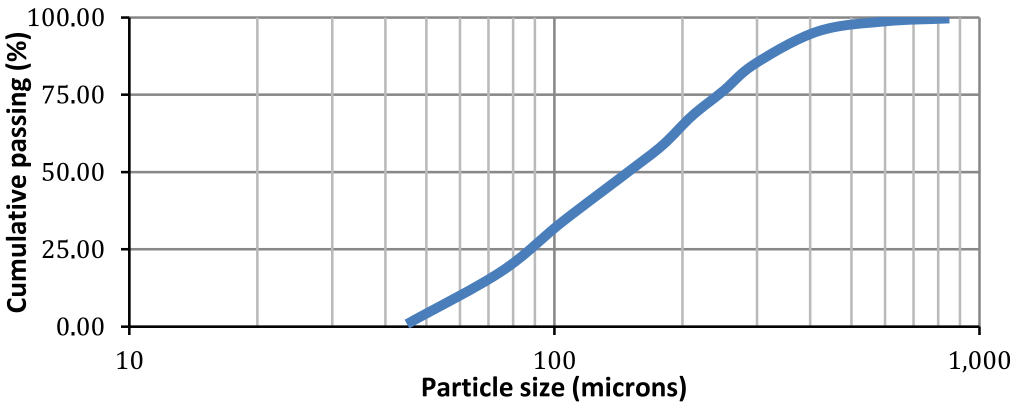


**Figure 1 Particle size distribution of copper tailings**

### 2.1.2 *Binder*

The use of binder is the most costly component of backfill material, as it represents 75% of the total backfill costs (Hassani & Archibald 1998). General use normal Portland cement, provided by Lafarge Canada, and which has a specific gravity of 3.15 g/cm$^3$, was used as the binder since it is used in most Canadian mines. However, other binders, such as slag, fly ash or a blend of different binders are also being considered for further investigation.

### 2.1.3 *Foaming agent and foam generator*

It was essential in this research to use both a high quality foaming agent and an aerator machine to ensure foam consistency. Based on previous experimental investigations, inconsistent foam yields samples with different physical and mechanical properties, despite having the same mixture design (Marquez & Hassani 2010). These problems were resolved by using the Stable Air® system, which uses Stable Air admixture (complies with ASTM C260 standard) and the Stable Air M100 aerator (ASTM International 2010). The foaming agent is a liquid air-entraining admixture consisting of a unique blend of synthetic materials (Cellular Concrete Technologies, Inc. 2013). Admixture is diluted with water to a ratio of 1:120, combined with compressed air, and processed through a patented foam generator in order to output Stable Air foam with a consistent density of 69 kg/m$^3$ (Figure 2).

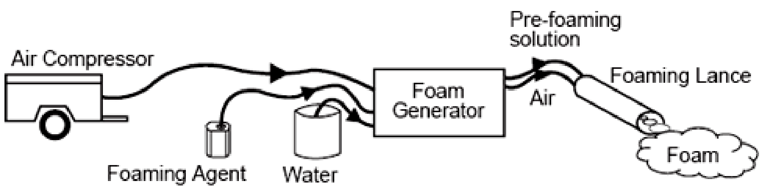


**Figure 2 Foam making process (Glocal ChemVentures Pvt. Ltd. 2013)**

### 2.1.4 *Sample preparation and curing*

FMF samples were prepared using cylindrical, polyvinyl moulds. The moulds' dimensions were 10 cm high with an internal diameter of 5 cm (Figure 3) in accordance with the International Society for Rock Mechanics' suggested methods (Brown 1981). Samples were cured for 28 days inside a curing chamber, where the relative humidity was kept constant at 85% ± 2%, and temperature was controlled at 25°C ± 2°C to simulate underground conditions. Furthermore, grinding was used to flatten the surface of the samples, in order to make them suitable for the UCS test.

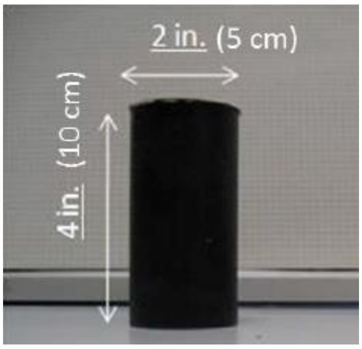


**Figure 3** **PVC mould and its internal dimensions**

## 2.2 Methodology

### 2.2.1 *Experimental design*

FMF samples were prepared under three different levels of binder dosage, pulp density, and amount of air entrained (Table 1). Moreover, binder dosage and pulp density were calculated in a mass basis, as shown in Equations (1) and (2). However, the amount of entrained air used in the mixtures was measured in a volume basis, but can be converted to mass basis by knowing the target backfill volume and foam density (Equation (3)).

**Table 1** **Levels of factors tested**

| Factor | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Binder dosage (%) | 10 | 15 | 20 |
| Pulp density (%) | 75 | 77 | 79 |
| Air volume (%) | 10 | 20 | 30 |

$$\text{Binder dosage (\%)} = [M_{binder} / (M_{binder} + M_{tailings})] \times 100 \quad (1)$$

$$\text{Pulp density (\%)} = [(M_{binder} + M_{tailing}) / (M_{binder} + M_{tailings} + M_{water})] \times 100 \quad (2)$$

$$\text{Mass of foam (kg)} = \text{target vol.} \times \text{air \%} \times \text{foam density} \quad (3)$$

Where:

$M_{binder}$ = mass of cement (kg).

$M_{tailings}$ = mass of tailings (kg).

$M_{water}$ = mass of water (kg).

Furthermore, face centred central composite design (FCD), a type of RSM design, was adopted to analyse and optimise the experimental results, as well as to develop a predictive model through a statistically designed experiment (Anderson & Whitcomb 2005). This design can be expressed as a cube in which a mixtures' design represents the coordinates of the points in the vertices, the centre of each face, and an axial point in the centre of the design space (Figure 4). The total numbers of runs was 15 and Table 2 shows the mixture characteristics of the FMF samples that were prepared. The response analysed the UCS values after 28 days of curing. DOE PRO® software (SigmaZone 2013) was used to analyse the results. The software calculates the main effect of each factor, and finds which factor has the biggest influence on the UCS values. Furthermore, this software can detect interactions between these factors, if there are any. Finally, mercury intrusion porosimetry (MIP) was conducted to investigate the microstructural properties for two selected samples.

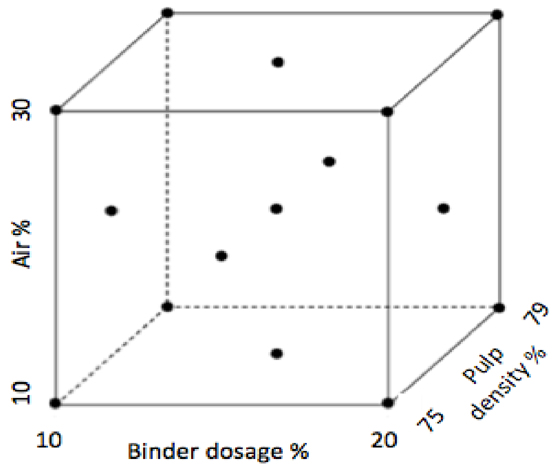


**Figure 4 FCD cube for the three variables studied**

**Table 2 Mixture characteristics of 15 FMF samples**

| Mixture # | Binder dosage (%) | Pulp density (%) | Air volume (%) |
|---|---|---|---|
| 1 | 15 | 79 | 20 |
| 2 | 15 | 77 | 20 |
| 3 | 20 | 77 | 20 |
| 4 | 20 | 75 | 10 |
| 5 | 10 | 77 | 20 |
| 6 | 15 | 77 | 10 |
| 7 | 15 | 75 | 20 |
| 8 | 10 | 75 | 30 |
| 9 | 20 | 75 | 30 |
| 10 | 10 | 79 | 10 |
| 11 | 15 | 77 | 30 |

### 2.2.2 UCS test

UCS tests were conducted in accordance with ASTM D2166-91 (ASTM International 2006b) on three FMF samples after 28 days of curing, and the overall average was taken. The tests were conducted immediately after removing the samples from the humidity chamber.

## 3 Results

Table 3 shows the UCS values for the FMF samples after 28 days of curing. Moreover, air bubble arrangements for each mixture design have also been noted, and will be further discussed in the next section.

**Table 3 Experimental results**

| Mixture | UCS (MPa) | Air bubble arrangements |
|---|---|---|
| 15/79/20 | 4.03 | Large |
| 15/77/20 | 3.13 | Homogeneous |
| 20/77/20 | 5.89 | Homogeneous |
| 20/75/10 | 6.45 | Segregated sample |
| 10/77/20 | 1.76 | Homogeneous |
| 15/77/10 | 4.82 | Homogeneous |
| 15/75/20 | 3.81 | Segregated sample |
| 10/75/30 | 0.88 | Segregated sample |
| 20/75/30 | 3.51 | Segregated sample |
| 10/79/10 | 2.72 | Large |
| 15/77/30 | 2.58 | Homogeneous |
| 20/79/30 | 5.1 | Large |
| 20/79/10 | 7.4 | Large |
| 10/79/30 | 1.43 | Large |
| 10/75/10 | 2.47 | Segregated sample |

# 4 Discussion

## 4.1 Observation

FMF samples exhibited three different air bubble arrangements: foam segregation, homogenous micro-air bubbles, and large air bubbles (Figure 5). Samples with foam segregation indicate that the mixture has an excess amount of water, causing foam to float on the surface. Samples with homogenous air bubbles show that the samples had the optimal pulp density before adding the foam, since neither segregation nor large air bubbles were observed. Finally, samples with large air bubbles indicate that the mixture is too stiff, causing air loss and low compaction. In this research pulp density was found to be the principal factor in bubble arrangement; 75% pulp density was found to result in segregation, 77% in homogenous bubbles and 79% in large bubbles. Therefore, the optimal pulp density before adding the foam should be determined in order to cause neither air segregation nor breakage.

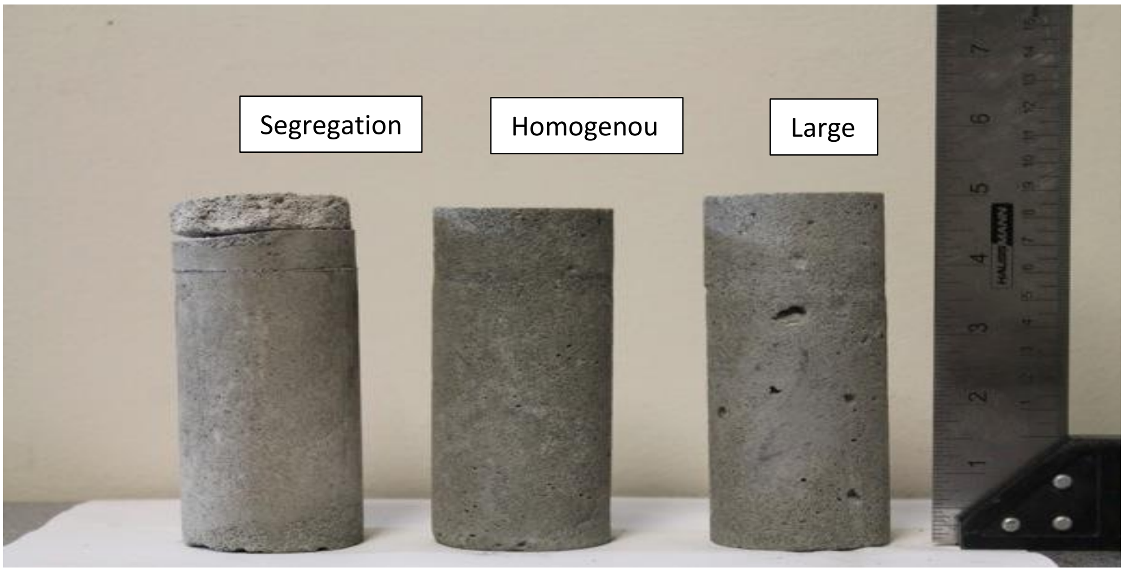


**Figure 5 Air bubble arrangements observed in the FMF samples**

### 4.2 FMF UCS

The relative effects of the investigated factors themselves and the interaction between them in terms of FMF compressive strength can be graphically represented in ordered horizontal bars by a Pareto chart (Figure 6). The chart clearly shows that the main factors responsible for strength development on FMF compressive strength, in order, are binder dosage, amount of air entrained, and pulp density. Furthermore, the interaction terms AC, AB, BB, BC, CC, AA and ABC were found to have a p-value >0.05 and therefore they can be considered to be statistically insignificant.

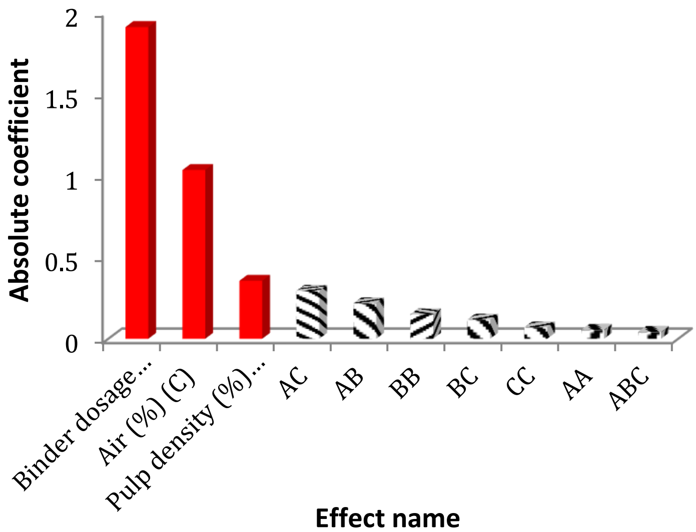


**Figure 6 Pareto chart of relative effects on FMF compressive strength**

An empirical model was developed after analysing the data with DOE PRO® software (Equation (4)). Based on this model, all 15 measured UCS values were plotted against predicted values in the residual plot shown in Figure 7. The experimental and predicted data can be fitted in a straight line with $R^2$ value of 0.96258.

$$USC\ (MPa) = -13.692 + 0.3818 \times \text{binder dosage} - 0.1036 \times \text{air} + 0.178 \times \text{pulp density} \tag{4}$$

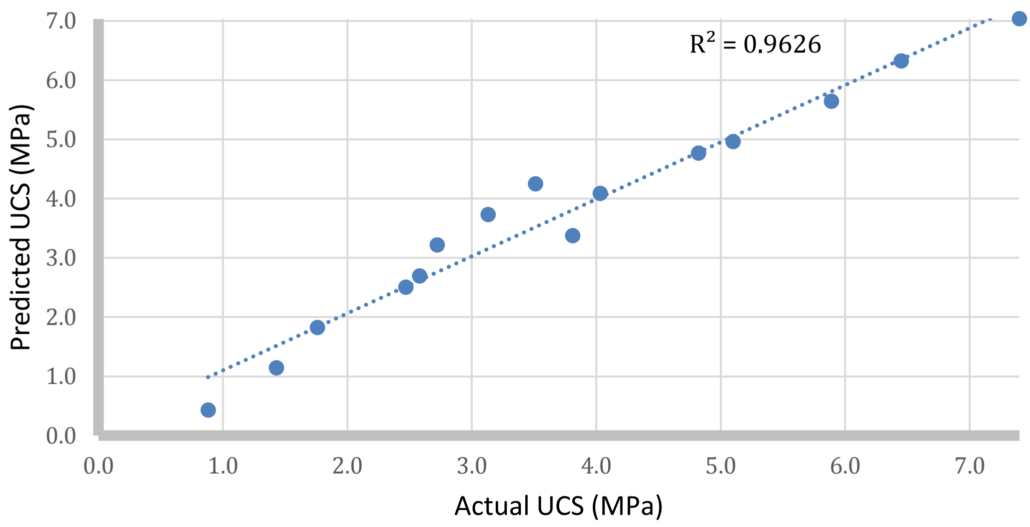


**Figure 7 Residual plot of measured and predicted results**

#### *4.2.1 Effect of air volume on FMF UCS*

The predictive model developed shows high residual values at 75% pulp density with compare to 77% and 79% pulp densities (Figure 7). This can explain the behaviour of segregated samples since air was not incorporated in the mixture and did not contribute to a decrease in strength. For example, in mixtures 15/77/20 and 15/75/20, measured UCS values were 3.13 and 3.81 MPa, respectively. This can also be observed in the marginal mean plot in Figure 8, where the average UCS value at each pulp density is calculated when the amount of air entrained was 10, 20 and 30%. Moreover, air bubbles were partially destroyed at a 79% pulp density, thus achieving the lowest marginal decrease in UCS. At a 77% pulp density, on the other hand, air bubbles were incorporated properly in the mixture, and samples with homogenous air bubbles were attained. Therefore, only samples with 77-79% pulp densities will be considered for FMF samples. Finally, at 77 and 79% pulp densities, UCS decreases linearly by 0.09 MPa and 0.112 MPa for each 1% increase in the amount of air added.

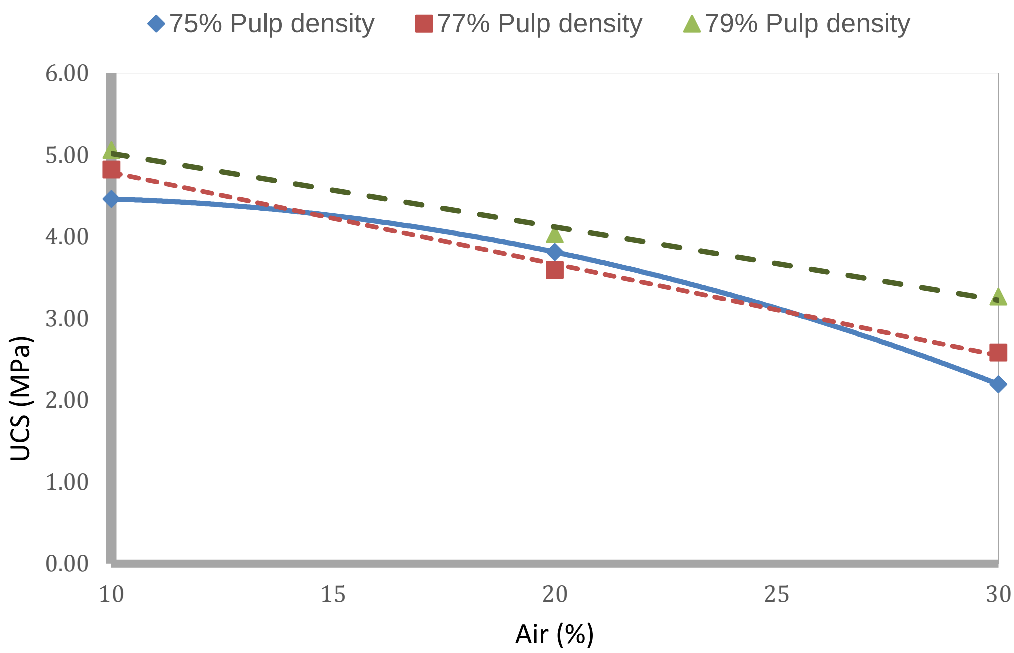


**Figure 8 Effect of air volume on FMF UCS**

#### 4.2.2 *Effect of binder dosage on FMF UCS*

The effect of binder dosage can be similarly obtained from the marginal plot shown in Figure 9. For example, at a 77% pulp density, UCS increases linearly by 0.42 MPa for each 1% increase in binder dosage; 79% is similar.

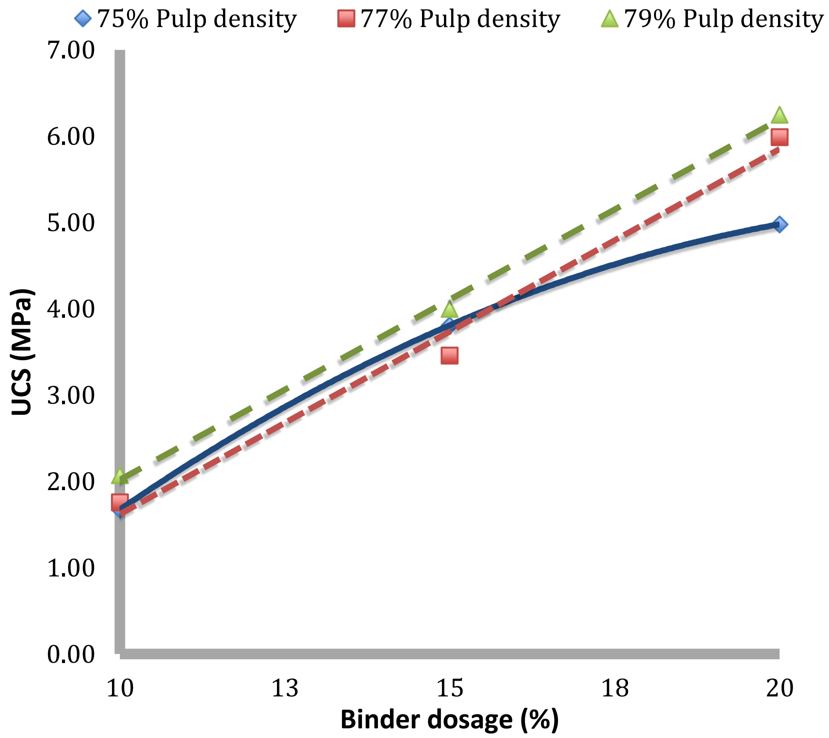


**Figure 9 Effect of binder dosage on FMF UCS**

### 4.3 FMF microstructural properties

In order to investigate the microstructural properties of FMF and its influence upon UCS results, MIP was conducted on two selected samples cured for 28 days, one of which has 10% air while the other one has 30% air. Binder dosage and pulp density were kept constant at 10 and 79%, respectively.

Figure 10 shows the differential pore size distribution of the FMF samples, where the size of pores can range between 200 and 0.006 µm. In both cases, most of the pores are in the 1-10 micron range; the higher air sample contains a notable increase of pores in this range. The total porosity of FMF samples at 10% air and 30% air were 29.35% and 34.42%, respectively (Figure 11). This explains the higher UCS value obtained from the sample with 10% air at 2.72 MPa, in comparison to the sample with 30% air at 1.43 MPa.

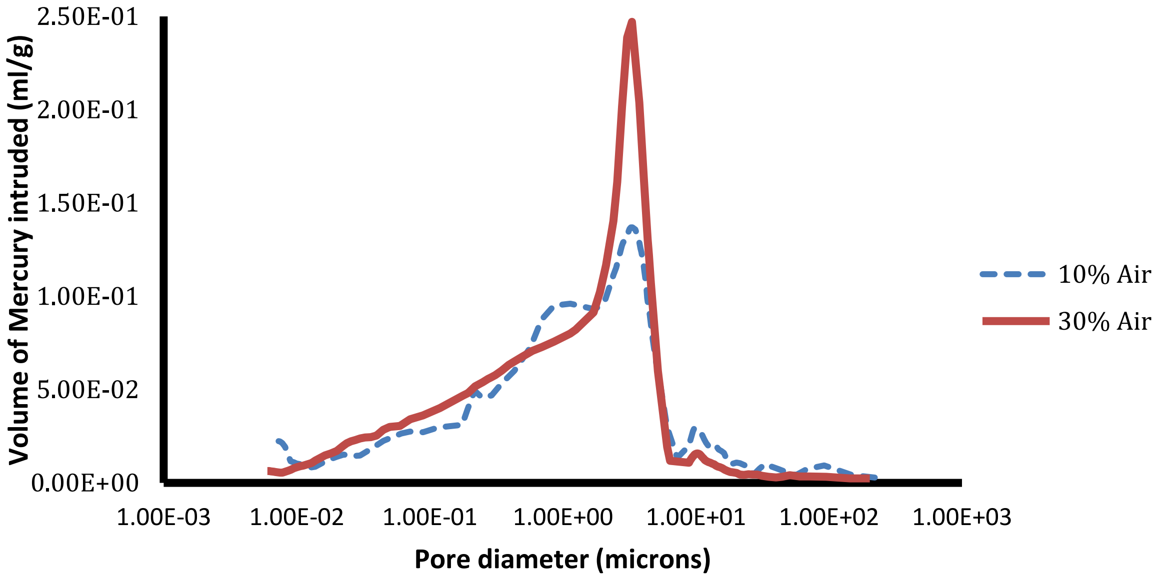


**Figure 10 Differential pore size distribution of FMF samples**

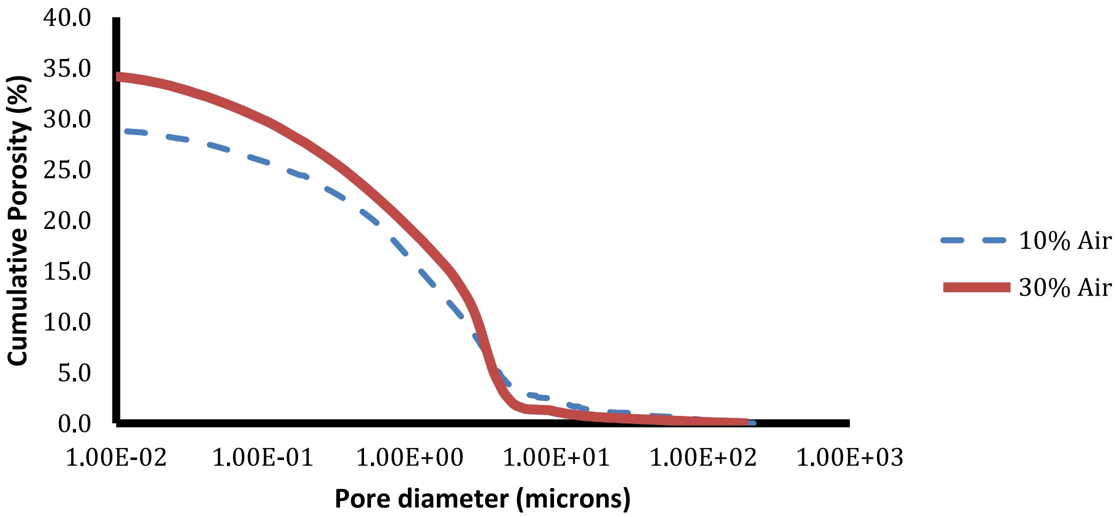


**Figure 11 Pore size distribution FMF samples**

## 4.4 Optimisation

The study aims to produce the first reference FMF sample with a UCS value of 1 MPa after 28 days of curing. Figure 12 shows the response surface obtained at a 10% binder dosage, since the objective is to minimise the use of binders due to their high cost. Figure 13 shows the top view of the response surface. Since 77% was selected as the optimal pulp density, then a 28% volume of air is required to achieve 1 MPa.

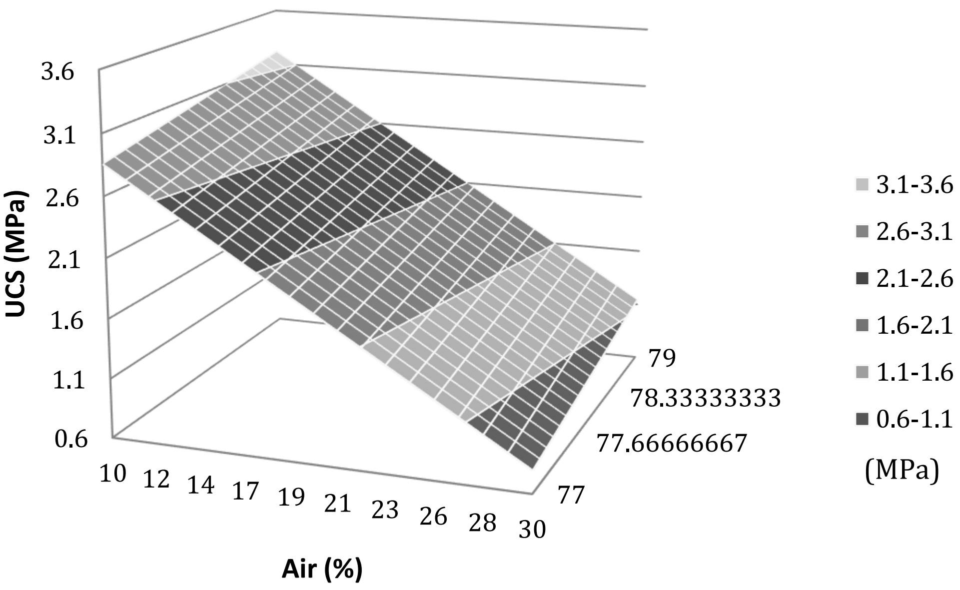


**Figure 12 Response surface for FMF UCS at 10% binder dosage**

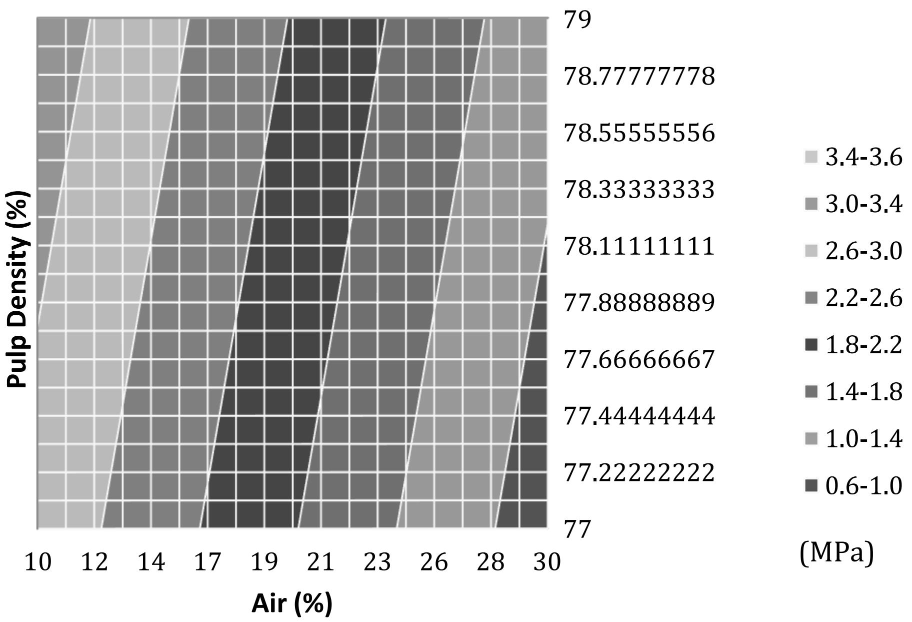


**Figure 13 Top view of the response surface in Figure 12**

# 5 Conclusion

An empirical model using RSM were developed in order to investigate the properties of FMF. It was found that pulp density is a very critical factor, since it highly influences air bubble arrangements, and therefore it should be optimised before foam is added. It was also demonstrated that microstructural properties influence UCS values, particularly when the amount of air in the samples is increased. Finally, in order to produce the first FMF reference sample of 1 MPa after 28 days of curing, the binder dosage, pulp density, and the amount of air entrained should be 10, 77 and 28%, respectively.

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