MODELING AND SIMULATION OF PASTE BACKFILL PERFORMANCE PROPERTIES

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ABSTRACT: A methodological approach and response surface models were developed in this study to predict the performance properties of paste backfill and optimize its mixture. The predicted properties are the uniaxial compressive strength (UCS), the slump, solid concentration (solid percent) and cost (based on cement cost) of the backfill. Using a central composite experimental design, the effect of tailings grain size and density, binders content, W/C ratio on these properties was determined. Statistical analysis revealed a highly significant (P<0.001) effect of all these variables. Following identification of the significant variables, response surface equations have been developed to predict the above performance properties of the backfill. The models were experimentally validated. The programming of the developed equations led to the development of computer program, which will help mining engineers to create cost effective paste backfill. The results of this study represent a significant advance in research on paste backfill technology and will greatly benefit the mining industry.

RESUMÉ: Une méthode et des modèles mathématiques basés sur les techniques de surface réponse ont été développés dans cette étude pour prédire les propriétés des remblais miniers en pâte cimentés et optimiser leurs recettes de mélanges. Les propriétés sont: la résistance à la compression simple, la consistance (taux d’affaissement), la concentration en solide et le coût de la quantité de ciment utilisée. L’exécution d’un plan expérimental de type central composite a permis de mettre en évidence l’effet de la granulométrie du résidu, sa densité, de la teneur en liant, du rapport E/C sur lesdites propriétés. L’analyse statistique a mis en relief un effet très significatif (P <0.001) de toutes ces variables. Consécutive à cette analyse, des équations de surface réponse ont été développées. Celles-ci permettent la prédiction des propriétés des remblais. Les modèles développés ont été validés expérimentalement. La programmation des équations développées a permis de créer un outil d’aide à la confection de remblais économiques et effectifs. Les résultats de cette étude représentent une avancée significative dans la recherche sur les remblais en pâte et seront d’une grande utilité pour l’industrie minière.

1. INTRODUCTION

Paste backfill is well established in many mines in the world and significant cost savings and operational benefits have been realised, compared to other methods of fill. The application of paste fill could significantly reduce the cyclical nature of mining, improve ground conditions, speed up production and greatly reduce environmental costs related to tailings management on the surface (Hassani & Bois, 1992). However, paste backfill represents a relatively new technology in which several aspects (mechanical, chemical, physical, interactions between the components, etc.) are not yet completely understood. For example, many mining industries are confronted with failures risk of paste backfill due to the difficulty to predict its performances properties and to develop rational and practical design approach upon which operators can effectively manage backfill technology.

Hence, multi-disciplinary research programs are carried out at URSTM-UQAT by the above authors to develop a methodological approach and mathematical models for predicting the performance properties (strength, slump, bulk density, cost) of paste backfill. This paper presents the developed approach and mathematical model based on response surface method, which allows:
- to predict the physical and mechanical performance of the paste backfill in order to economize mining process and improve the safety in mining work;
- to analysis the effect of the interactions between the components of backfill on its properties;
- to estimate the cost of the produced paste backfill;
- to optimize the backfill mixture in order to reduce production cost of paste backfill.

2. METHODOLOGY

Figure 1 shows the developed methodological approach and the different work steps for predicting the performance properties of paste backfill and for optimizing its mixture. The methodology includes three main stages: experimental, modeling and optimization stage.

First experimental study was undertaken to identify and assess the effect of the physical and chemical properties of the main components (tailings, water, binder) of paste
backfill on its mechanical (strength) and physical (slump, bulk density) properties. The main results of this experimental investigation are given in Fall & Benzaazoua 2003-a and Benzaazoua et al. 2003. The analysis of the results of this experimental study has allowed to define the main parameters influencing the performance of paste backfill. It has been experimentally demonstrated that the mechanical and physical properties of paste backfill are most influenced by following parameters:

- the physical (grain size, density) and mineralogical properties (sulphide content, etc.) of the tailing materials;
- the type and the quantity of the used binders;
- the curing time;
- the quantity and chemistry (sulphate content) of the total mixing water (added water and remaining tailing pore water) of the paste backfill.

In the second stage, these identified parameters were used as basis data for the modeling. The latter allowed to predict the strength (uniaxial compressible strength), slump, cost of the used binder and bulk density of the paste backfill. The modeling is based on the techniques of response surface method (RSM). All fundamental aspects of RSM are detailed described in the works of Box & Wilson (1951), Box & Drapper (1987), Khuri & Cornell (1987) and Myers & Montgomery (1995).

Since the paste backfill produced by the backfill plant must satisfy the criteria of safety (satisfactory mechanical strength), technique, i.e transportability (slump ranging between 15 cm and 25 cm) and economic (low binder cost, profitability), an optimization of the paste backfill production is necessary. Therefore, in a third stage, an optimization of the paste backfill mixture was carried out. The modeling results were used as input data. This optimization consisted to maximize a function of desirability (Harrington 1965, Derringer and Suich 1980) which takes into account, simultaneously, of the important criteria for the mining company (safety of the workers, feasibility and profitability of the technique of paste backfill). The analysis and programming of the equations developed in the modeling led to the development of computer program which will help mining engineers to create cost-effective paste backfill.

Globally, two main types of models were developed in this study. Models for predicting the performance of paste backfill not confronted with sulphate attack (most frequent case) and other models for backfill confronted with sulphate attack. The first type of models will be presented in this paper. The second type of models is presented elsewhere (Fall & Benzaazoua, 2003-b). This paper will be also focussed on the results of modeling and optimization study. The results of the experimental study are detailed described in the works of Benzaazoua et al. 2003, Fall & Benzaazoua 2003a.

Figure 1. Developed approach for modeling the performance properties of paste backfill and optimizing its mixtures *Labo: experimental stage

3. MATERIEL, SPECIMEN PREPARATION AND TESTING

3.1 Material used

The used material included binder reagents, tailings and water.

Binder reagents: Type I Portland cement (PC I) and blast furnace slag (Slag) were used. The two cement reagents were blended in the ratio 20/80. PC I and Slag, and this ratio are often used by the mining industry in eastern Canada for paste backfill mixtures.

Tailings: Tailings material from polymetallic mines located in eastern Canada were used as aggregates. The tailings contain about 16 % sulphide. The sulphide minerals are mainly represented by pyrite. The separation of the tailing materials by hydrocyclone has allowed to create several grain size classes from fine to coarse tailing. The particle-size distribution curve (figure 2) shows the range of particle sizes present in the tailings samples and the type of distribution of these particles. This distribution covers a wide range of possible particle size distribution of tailings from Canadian mines. The relative mass proportions of fines F (particle size < 20 µm) present in the tailing were used to identify differences among the used tailings.

Water: tap water with low sulfate content, and mine process waters with high sulfate content were used.

Figure 2. Grain size distribution of the used tailings
3.2 Preparation of test specimen

The samples of tailing materials were received in barrels. The tailings were then separated in different grain size classes by hydrocyclone. After that, the barrels were homogenized. In order to produce paste backfill mixtures, the tailing materials, cement and water were mixed and homogenized in a mixer with double spiral. The produced paste backfill mixtures were poured into curing cylinders, 10 cm in diameter and 20 cm high. The poured specimens were sealed and cured in a humidity chamber maintained at approximately 70% humidity (similar humidity conditions in the underground mines) for periods of 28 days.

3.3 Testing of specimens

The following properties were then determined on paste backfill specimens:
- compressive strength up to 28 days after curing at 23 ± 2°C according ASTM standards using a computer-controlled mechanical press (MTS 10/GL). The compressive strength testing allowed the determination of the uniaxial compressive strength (UCS) of the tested samples, which corresponds to the maximum stress observed during the test. The UCS is used in the practice to judge the stability of the underground backfill or backfill failure risk;
- cost of each specimen. It is based on evaluation of the cost of the quantity of used binder. The latter was calculated from the mix proportions using costs for each binder reagent (binder cost applied at the eastern Canadian market, Benzazoua et al. 2002). The binder can represent up to 75 % of the paste backfill production cost (Grice, 1998);
- slump of the fresh paste backfill mixtures. The latter was measured by slump test according to ASTM C 143-90. The Determination of slump has allowed characterizing the paste backfill’s consistency that can be related to its transportability;
- solid concentration or solid percent (%). The latter is the ratio of the solids (tailings and binder) in a mix to the weight of the total mix (water and solids).

4. MODELLING

The formulation and development of the mathematical models (material models) is first based on the results of the performed experimental design. These experiments were undertaken, using a central composite design. The experimental results were then subjected to regression analysis to obtain the parameters of the mathematical models for the dependent variables (UCS, Slump, Solid percent, Cost).

4.1 Performed experimental design

A rotatable orthogonal central composite design (Khuri and Cornell 1987, Myers and Montgomery1995) has been used for developing the material models for the paste backfill. The four following factors (independent variables) were chosen to describe the system "paste backfill":

\[ X_1 = \% \text{ cement}; \] it represents the type and the quantity of used cement;
\[ X_2 = \text{W/C}; \] the weight ratio of the quantity of used water and cement;
\[ X_3 = \% \text{ Fine (F)}; \] the mass proportion of fine particules (<20 µm) in the tailings; it well represents the grain size of the used tailings material.
\[ X_4 = \rho_t \text{ (g/cm}^3\text{)}; \] the density of the tailings.

The sulfate concentration of the total mixing waters (tailing pore water and added water) was maintained constant (<500 ppm). The measured responses (independent variables) were the uniaxiale compressible strength of the paste backfill after 28 days curing time (UCS 28-days), slump, %Solid and the cost of the quantity of used cement. Figure 3 shows a schematic representation of the developed models.

![Figure 3. Schematic presentation of the developed models](image_url)

Cost in $/t (Can $/ tonne solid); Slump in cm; %S: solid percent; UCS in kPa.

The experiments were run in a random order. Five levels of variables were used in the experimental design. Based on the results of the experimental stage (Fall & Benzaazoua, 2003) and on economical reasons (binders cost), the ranges of these four factors were determined as given in table 1. Indeed, a binder proportion higher than 7% is not economical feasible in the mining industry in Canada. To simplify the calculation and avoid numerical error in the computer calculation, the variables \( X_1, X_2, X_3, X_4 \) are transformed to dimensionless variables \( x_1, x_2, x_3, x_4 \) (coded values). The experimental design consisted of 16 factorial points, 8 axial or star points (two axial points on the axis of each design at a distance of ±2.0 coded units from the design center; 1 factor been level -2.0 or +2.0, while others are maintained at zero level), and 6 central points for replications (to evaluate the experimental error). The variables and their levels, both coded and actual units, selected for this study are shown in Table 1. The correspondence between the coded and actual values can be obtained using the equation (1)

\[ x = \frac{X - X_0}{\Delta X} \]
where \( x \) is the coded value, \( X \) is the corresponding actual value, \( X_0 \) is the actual value in the center of the domain, and \( \Delta X \) is the increment of \( X \) corresponding to 1 unit of \( x \).

Table 1. Experimental range definition

<table>
<thead>
<tr>
<th>Variables ((X_i))</th>
<th>Codes (x_i)</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>% cement</td>
<td>(X_1)</td>
<td>0.8</td>
<td>2.8</td>
<td>4.8</td>
<td>6.8</td>
<td>8.8</td>
</tr>
<tr>
<td>W/C</td>
<td>(X_2)</td>
<td>6.2</td>
<td>7.0</td>
<td>7.8</td>
<td>8.5</td>
<td>9.3</td>
</tr>
<tr>
<td>% Fine (F)</td>
<td>(X_3)</td>
<td>10</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>(\rho) (g/cm³)</td>
<td>(X_4)</td>
<td>-</td>
<td>3.38</td>
<td>3.44</td>
<td>3.5</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2 Results and discussions

4.2.1 Model development and analysis

Quadratic response surface models were constructed. The below 2nd order polynomial (equation 2) was used to develop predictive models for the strength (UCS28 days), the slump, the solid percent and the cost of the paste backfill. Because the UCS, slump and cost of the paste backfill vary over several orders of magnitude for the conditions considered in this study, the log of UCS, of slump and of cost were used. The polynomial has this form:

\[
Y_m = b_0 + \sum_{i=1}^{4} b_i x_i + \sum_{i=1}^{4} b_{ii} x_i^2 + \sum_{i=1}^{4} \sum_{j>i} b_{ij} x_i x_j + e \tag{2}
\]

where, \( Y_m \) (\( Y_1 = \ln \text{UCS28 days} \) for the strength, \( Y_2 = \ln \text{Slump} \) for the slump, \( Y_3 = \ln \text{Cost} \) for the cost, \( Y_4 = \% \text{Solid} \) for the solid percent) are the predicted responses, \( b_0 \) is the intercept, \( b_i \) are constant regressions coefficients for the linear terms, \( b_{ii} \) are constant regressions coefficients for the pure quadratic terms; \( b_{ij} \) are constant regressions coefficients for the cross-product terms. The \( x \) variables represent the normalized values of each of the input variables which affect the responses; the cross-term \( x_i x_j \) represent two-parameter interactions and square terms \( x_i^2 \) represent second order non-linearity. The interaction-terms \( x_i x_j \) and the quadratic terms \( x_i^2 \) account for curvature in the response surface. This curvature is frequently present when a response is at or close to maximum or minimum. And finally, \( e \) is associated random error; it represents the combined effects of variables not included in the models.

The equation 2 was used to fit the data of the experimental design. All data were analyzed using standard statistical software which estimates average effects, statistical significance, and regression coefficients for all variables and their interactions. T-tests were conducted to identify the most important \( b \) terms to include in the developed equations. Thus, square and interactions term which were below 95% confidence level were discarded from the models through stepwise regression. This has allowed the development of four predictive models (\( \ln \text{UCS28 days} \), \( \ln \text{Slump} \), \( \ln \text{Cost} \), \%Solid). Analysis of lack-of-fit was then performed to assess the adequacy of the models to represent the experimental data.

Some results of the regression analysis are summarized in Tables 2 and 3. Table 2 shows the results of the analysis of variance, while the coefficients of the determination of the models are given in table 3. The results of regression analysis clearly highlighted that quadratic function material models of paste backfill can give reliable predictions for the strength, the slump, the cost and solid percent. The models show high F-value (table 2). The coefficients of determination (table 3) are for all models very high (>0.97). It means that more than 97% of the variations of the \( \ln \text{UCS} \), \( \ln \text{Slump} \), \( \ln \text{Cost} \) and solid percent are caused by the variations of the input variables \( x_1, x_2, x_3, x_4 \) (%cement, W/C, %Fine and \( \rho \)).

Table 2. Results of the analyse of variance of the different models (table ANOVA)

<table>
<thead>
<tr>
<th>Models</th>
<th>Source</th>
<th>DF*</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F</th>
<th>Prob&gt;P</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ln \text{UCS28 days})</td>
<td>Model</td>
<td>7</td>
<td>4.36</td>
<td>0.484</td>
<td>65.03</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>20</td>
<td>0.14</td>
<td>0.007</td>
<td>3.83</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>27</td>
<td>4.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\ln \text{Slump})</td>
<td>Model</td>
<td>8</td>
<td>3.71</td>
<td>0.53</td>
<td>85.48</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>11</td>
<td>0.12</td>
<td>0.01</td>
<td>3.83</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>19</td>
<td>3.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\ln \text{Cost})</td>
<td>Model</td>
<td>14</td>
<td>2.95</td>
<td>0.21</td>
<td>11411</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>26</td>
<td>0.00031</td>
<td>0.0018</td>
<td>3.83</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>31</td>
<td>3.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Solid</td>
<td>Model</td>
<td>5</td>
<td>1364.1</td>
<td>272.8</td>
<td>96.2</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>26</td>
<td>73.7</td>
<td>2.8</td>
<td>3.83</td>
<td>&gt;0.001</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>31</td>
<td>1437.8</td>
<td></td>
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</tbody>
</table>

*DF: degree of freedom

<table>
<thead>
<tr>
<th>Models</th>
<th>(\ln \text{UCS28 days})</th>
<th>(\ln \text{Slump})</th>
<th>(\ln \text{Cost})</th>
<th>% Solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r^2)</td>
<td>0.96</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>(r)</td>
<td>0.95</td>
<td>0.96</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

\(r^2\): coefficient of determination; \(r\): adjusted coefficient of determination

The results of the analysis of variance have also demonstrated that:

- the factors significantly influencing the strength (UCS 28 days) of the paste backfill are %cement, the W/C ratio, the tailings grain size (%fines) and the tailings density. The interactions between cement and W/C, W/C and density, also play a significant role in the backfill hardening process (\(P<0.01\)). The quadratic term \( x_1^2 \), \( x_2^2 \) and \( x_3^2 \) are also statistical significant (\(P<0.01\)). The non-negligible effect of the interactions between the model parameters demonstrates the non-additive nature of the relation describing the 28-day strength development of paste backfill.

- the factors %cement, %Fine and density significantly affect the slump of the paste backfill (\(P<0.0001\)). The interactions between the cement or density and the tailings grain size are statistical significant (\(P<0.02\)). %Fine and \( \rho \) strongly interact synergistically for higher...
slump. The square terms $x_1^2$ and $x_3^2$ also plays a non negligible role ($P<0.03$).
- The cost of the paste backfill, as expected, essentially depends on the quantity of used cement, the tailings grain size and density ($P<0.001$). The interaction between cement ($x_1$) and tailings density ($x_4$) is strongly significant at $P < 0.05$. There is an antagonistic effect between the cement and the tailings density. This means, increasing the tailings density has a negative effect on the cost of paste backfill and leads to higher binder consumption.
- The solid percent is essentially controlled by the variables cement, W/C, % Fines, $\rho_t$. The square term $x_1^2$ is also statistical significant.

The results of the analysis of lack-of-fit have shown that it is not significant. Thus, the developed models are adequate to represent the true relationships.

4.2.2 Simulations

The developed predictive models were applied to simulate the effects of the model parameters (%cement, W/C, tailings grain size and density) on the performance properties of the paste backfill.

Figure 4 illustrates the effects of binder proportion, W/C, tailings grain size and density on lnUCS 28 days. As expected, increasing the amount of cement leads to higher paste backfill strength. The higher the ratio W/C at any given binder proportion or tailing grain size, the lower the strength at 28 days becomes (Figure 5). This decreasing of backfill strength with increasing of the W/C ratio is mainly caused by the subsequent increasing in overall porosity due to the once water-filled voids (Amaraunga & Yaschyshyn, 1997).

![Figure 6. Evolution of UCS 28 days of the paste backfill for different binder contents related to the grain size of the tailing (W/C = 7; $\rho_t$ = 3.459)](image)

Figure 4 and 8 demonstrate that the tailings density plays an important role in the backfill strength development. The log of the UCS 28 days decreases with the increase of tailings density as far as a density equal to 3.45 g/cm³ (figure 8). After this value, the log of UCS increases with the tailings density. This increasing of UCS with the tailings density is due to higher binder consumption in volume (Benzaazoua et al, 2003). However, the higher tailings density, the more expensive is the cost production of the paste backfill (Figures 9 and 10).

![Figure 7. Effect of tailings grain size on UCS 28 days of the paste backfill for different binder contents (W/C = 7; $\rho_t$ = 3.459)](image)
The effects of cement content, W/C, tailings grain size and density on the cost (cement cost) of the paste backfill are clearly shown in Figure 10. The cost of the backfill is mainly controlled by the cement content. However the tailings grain size and density has non-negligible influence on the cost (Figure 9).

The effect of the binder proportion, the tailings grain size and density on the slump of the paste backfill is presented in Figure 11. As expected, higher binder proportions confer the paste backfill higher slumps. However, the slump decreases as the tailing density increases. The fineness of the used tailing has also effect on the backfill slump.

Table 4. Selected results from verification trials

<table>
<thead>
<tr>
<th>Cem. (%)</th>
<th>W/C</th>
<th>% Fi.</th>
<th>P(t) (g/cm³)</th>
<th>Expe value</th>
<th>Pred value</th>
<th>Err. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>8.5</td>
<td>35/65</td>
<td>3.4981</td>
<td>1108</td>
<td>1033</td>
<td>6.7</td>
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<td>6.6</td>
<td>8.5</td>
<td>35/65</td>
<td>3.4981</td>
<td>2000</td>
<td>1999</td>
<td>0.0</td>
</tr>
<tr>
<td>6.8</td>
<td>8.5</td>
<td>65/35</td>
<td>3.4271</td>
<td>910</td>
<td>1008</td>
<td>10.7</td>
</tr>
<tr>
<td>2.8</td>
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<td>1240</td>
<td>2.8</td>
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<tr>
<td>2.8</td>
<td>10</td>
<td>65/35</td>
<td>3.4271</td>
<td>486</td>
<td>446</td>
<td>8.2</td>
</tr>
<tr>
<td>6.8</td>
<td>10</td>
<td>65/35</td>
<td>3.4271</td>
<td>602</td>
<td>627</td>
<td>4.2</td>
</tr>
<tr>
<td>4.8</td>
<td>9.3</td>
<td>50/50</td>
<td>3.4481</td>
<td>863</td>
<td>997</td>
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<td>4.8</td>
<td>9.3</td>
<td>24/76</td>
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<td>1184</td>
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<td>4.8</td>
<td>9.3</td>
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<td>3.4481</td>
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average error: 8%

<table>
<thead>
<tr>
<th>UCS 28 days (kPa)</th>
<th>Cem. (%)</th>
<th>W/C</th>
<th>% Fi.</th>
<th>P(t) (g/cm³)</th>
<th>Expe value</th>
<th>Pred value</th>
<th>Err. (%)</th>
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<tbody>
<tr>
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<tr>
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<td>6.4</td>
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<td>3.4981</td>
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<td>3.4981</td>
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<td>27.3</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>10</td>
<td>35/65</td>
<td>3.4981</td>
<td>15.0</td>
<td>14.3</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>8.5</td>
<td>65/35</td>
<td>3.4271</td>
<td>10.0</td>
<td>10.5</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>10.6</td>
<td>50/50</td>
<td>3.4481</td>
<td>29.0</td>
<td>28.3</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>9.25</td>
<td>50/50</td>
<td>3.4481</td>
<td>28.0</td>
<td>27.0</td>
<td>7.2</td>
<td></td>
</tr>
</tbody>
</table>

average error: 9%
In order to find the optimum backfill mixes, the principle of multi-criteria optimization (Derringer and Suich, 1980) was used. The latter is based on the desirability function first developed by Harrington (1965). The desirability approach combines the multiple responses into a single function and try to find the optimal mix. First, a desirability function \( d_i \) has to be determined for each response \( Y_i \) (\( \text{inUCS, Inslump, Incost, } \%\text{solid} \)). The desirability \( d_i \) may range from zero to one. A desirability of zero indicates least desirable value of \( Y_i \); this represents a property level that expected to render the product (paste backfill) unacceptable for use. A desirability of one indicates most desirable or ideal value of \( Y_i \). The individual desirabilities \( d_i \) are then combined using the geometric mean, which gives the overall desirability \( D \). The overall desirability function is defined by

\[
D = \left( \prod_{i=1}^{q} d_i^{r_i} \right)^{\frac{1}{r_i}}
\]

where \( d_i \) are individual desirability, \( r_i \) is a value between one and five reflecting the relative importance of response \( Y_i \).

For example, if \( Y_i \) is specified to be in some target range \( (L_i, U_i) \), with target value \( T_i \), then \( d_i \), the desirability corresponding to \( Y_i \) is defined by

\[
d_i = 0, \quad Y_i < L_i, \quad d_i = (Y_i - L_i)^a, \quad L_i \leq Y_i \leq T_i \quad d_i = (T_i - Y_i)^b, \quad T_i \leq Y_i \leq U_i \quad d_i = 0, \quad Y_i > U_i,
\]

where \( a \) and \( b \) determining how important it is to hit the target value. For example, for 28-day strength, the desirability value is 0 below 700 kPa (risk of backfill failure) and 1 above 1000 kPa (ideal strength).

However, if we want to minimize a response \( Y_i \), then \( d_i \), the desirability corresponding to \( Y_i \) is defined by

\[
d_i = 1, \quad Y_i > T_i, \quad d_i = (U_i - Y_i)^b, \quad T_i \leq Y_i \leq U_i
\]
\[ d_i = 0, \quad Y_i > U_i, \] \hspace{1cm} (10)

For example the cost is to be minimized, the desirability value is 1 below 2.5 % binder content and 0 above 5.5% binder content (backfill too expensive).

The optimum paste backfill mix was considered here as that mix which offers the mine workers safe workplace (700 <28-day strength<1000, Hassani and Bois 1992), has a technical acceptable consistence (15 cm<slump>25 cm), has a high solid concentration (70<%solid<85) and minimizes cost (binder cost). Table 5 shows the optimized responses and their desired ranges.

Table 5. Optimized Responses and their desired ranges

<table>
<thead>
<tr>
<th>Responses</th>
<th>Desired range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCS 28 days (kPa)</td>
<td>700 &lt; Y₂ &gt; 1000</td>
</tr>
<tr>
<td>Slump (cm)</td>
<td>15 &lt; Y₃ &gt; 25</td>
</tr>
<tr>
<td>Cost ($/t*)</td>
<td>Y₄ &lt; 6</td>
</tr>
<tr>
<td>% Solid</td>
<td>70 &lt; Y₅ &gt; 85</td>
</tr>
<tr>
<td>% can $/tonne solid</td>
<td></td>
</tr>
</tbody>
</table>

Assuming equal important \((r_1 = r_2 = r_3 = r_4 = r_5)\) for the four paste backfill properties \((Y_1 = UCS, Y_2 = Slump, Y_3 = Cost, Y_4 = %Solid)\), overall desirability has been calculated and desirability plots were constructed as a function of the paste backfill components (%cement, W/C, %Fine, ρₜ) using equation (3). Figure 13 shows the overall desirability function \((D)\) of the paste backfill plotted against the cement content, the ratio W/C, the tailings grain size and density (only tailings density between 3.36 and 3.50 g/cm³ has been considered in this optimization).

Some desirabilities are relatively high, and some are near zero. It is important to remember that, by definition, if a D value is greater than zero, the backfill mix is acceptable.

In figure 13, it is clear the quality of the paste backfill is mostly controlled by the cement content, the tailings grain size and density. Figure 13 clearly indicates that, for the given desirability curves and weight assignments, the optimum mix is composed by 3.8 % binder content, W/C = 7, %Fine = 50%, ρₜ=3.46 cm³/g. However, a binder content of 3%, W/C =7, %Fine = 50%, ρₜ=3.46 cm³/g will also enable the backfill mix to satisfy all performances criteria mentioned above.

Figure 13. The overall desirability of the paste backfill

6. CONCLUSION

This study has demonstrated that the paste backfill can be defined as “mixture systems”. It was shown that a material model based on surface response method, particularly on quadratic functions formed a suitable basis for the prediction of mechanical, physical, economical and rheological performance properties of paste backfill and the optimization of its production. The developed models have allowed to obtain valuable results regarding the relationship between the physical and chemical properties of the components of the paste backfill and its performance, the prediction of its strength. The results of this modelling are in perfect concordance with the results of the experimental studies carried out in this work (Fall & Benzaazoua 2003-a) and by several authors (Lamos & Clark 1989, Landriault 1995, Naylor et al. 1997, Archibald et al. 1998, Ouellet et al. 1998; Bernier et al. 1999, Benzaazoua et al. 2000, etc.). The performed optimization has simultaneous taken into account several paste backfill properties including transportability (slump), strength development (security of mine workers) and cost (profitability of the paste backfill technology) and also allowed the development of cost-effective backfill mixes. The results of this research represent a significant advance in paste backfill technology and will greatly contribute to better understanding the behaviours of paste backfill. However, additional researches will be necessary in order to improve the accuracy of the developed response surface models, to develop predictive models for long term strength (UCS 90-days), to take account of the effect of changing mineralogical characteristics of the tailing material on paste backfill performance and to widen the field of validation of the developed models. Additional validation tests have also to be performed. All these problems couldn’t be studied in the available time. However, researches on these problems and on in situ-application of the developed models are actually carrying out at URSTM-UQAT.

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REFERENCES


