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Experimental investigation for the use of tailings as paste-fill material through design of experiment

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Abstract. In the mining industry, significant progress and increased mineral production cause waste disposal issues which is one of the crucial problems in mining operations. It leads to both environmental and economic issues. Particularly, wastes from the production of metallic sulfide ore cause serious environmental pollution. In the last three decades, waste has been stored in underground openings in a controlled manner as paste-fill. Paste-fill is created by waste, water, and chemical additives. In this paper, two types of wastes were chosen to investigate the usability of tailings as paste-fill material. A lead and zinc underground mine was selected as a research site located in Balikesir, Turkey. First of all, several tests were conducted to analyze the physical, chemical, and mineralogical characteristics of paste-fill materials. Then, one of the design of experiment methods was used to create different mixtures of paste-fill specimens by changing the binder ratio and water content as input variables for four curing times. Finally, the strength properties were obtained as output variables, and an optimum mixture of paste-fill was determined. The results show that the tailings can be used as paste-fill material to achieve environmental and economic benefits and provide a safe working environment.

Keywords: design of experiment; paste-fill; tailings, underground mining; waste disposal

1. Introduction

Huge amounts of tailings have been produced by ore-rock excavation to extract valuable minerals. The disposal of tailings may create some serious long-term environmental management and economic problems (Ercikdi *et al.* 2009). These tailings must be disposed effectively to avoid possible environmental problems such as leachate generation and acid mine drainage (Chen *et al.* 2014).

Most large-scale mines produce much more tailings than economic minerals (Niroshan *et al.* 2018). It is a preferred method to store tailings in the tailing dams on earth. However, this method may have environmental drawbacks and is a costly activity. Tailing dam failures are frequently seen and each catastrophic failure event concludes with an extensive damage to the environment. These cases also have resulted in the loss of human life (Owen *et al.* 2020). Moreover, the large underground openings were created to extract tones of materials during underground mining operations. The mine voids must be filled or supported effectively and economically before extracting the next mine stope to ensure the safety in underground (Niroshan *et al.* 2018).

Paste-fill is a common practice in underground mining operations (Emad *et al.* 2015) and various civil engineering projects (Gezgin and Cinicioglu 2019, Arefnia *et al.* 2020) particularly for waste disposal and ground stability. It is a mixture of dewatered mill tailings, chemical and natural binders and water (Ghirian and Fall 2015). Most of the operations, the paste-fill mixture consists of 3-8% portland cement as a binder and 70-85% tailings as solid content. At least 15% of the solid material size of the tailings must be ranging between -20 μm and 45 μm (Sivakugan *et al.* 2015). The water ratio in the mixture is important to transport the material to the underground openings and achieve the required strength with binders for ground stability (Ozturk *et al.* 2014). To prepare paste-fill, some types of equipment are necessary such as storage mechanism, dewatering equipment (cyclones and filter disks), weight belt, fluidization silo, mixer, binder silo, hopper and pump mechanism (pipeline and borehole). Moreover, the quality of paste-fill, which shows the adequate strength of the mixture, must be checked by a control system before transporting to the underground openings. Quality control is an important element for the paste-fill system because lack of this system might lead to some crucial problems such as paste-fill concentration, barricade and transportation problems. The skilled staff is also needed to have an intended operation (Ugurlu 2013).

Because of the need for high technology equipment such as thickener and storage mechanism, the capital cost of the paste-fill system might be more expensive than the other systems such as slurry and rock-fill. However, if the long-term is considered, paste-fill is cheaper because of the lower operating cost (Ugurlu 2013). In addition, many researchers have conducted several studies for reducing operating costs

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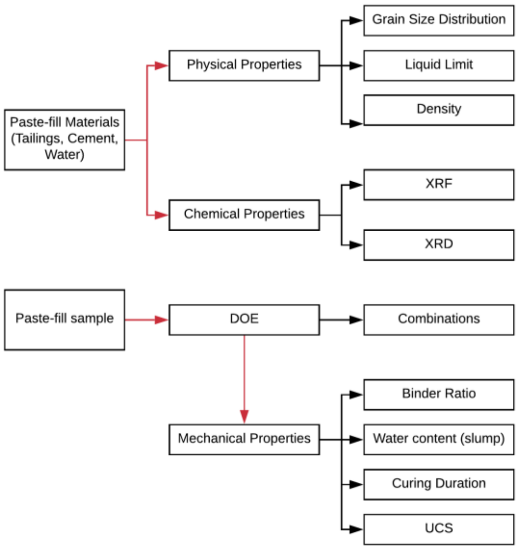


Fig. 1 Laboratory design steps for paste-fill application (modified from Ugurlu 2013)

(Ercikdi *et al.* 2009, Kesimal *et al.* 2005). The most vital part of the operating cost is binder usage. The previous researchers have focused on finding cheaper alternatives such as fly ash and geopolymers to achieve considerable savings and sustain paste-fill operation (Yilmaz *et al.* 2011).

In recent years, some researchers have focused on the mechanical performance of paste-fill. Ghirian and Fall (2015) developed an experimental setup to understand thermal, hydraulic, mechanical and chemical behavior of paste-fill at an early age (7 days). They also performed shear stress tests and uniaxial compressive strength (UCS) tests for mechanical performance. On the other hand, Niroshan *et al.* (2018) conducted USC tests to analyze long term (112 days) mechanical properties of paste-fill. Furthermore, Creber *et al.* (2017a) investigated the changes in paste-fill during distribution from the surface to a stope. They indicated that temperature is a significant factor for yield stress. Similarly, Creber *et al.* (2017b) analyzed paste-fill distribution system and performed wear rate measurement in order to predict the wear rate model in mine paste-fill distribution systems. Moreover, previous studies on paste-fill systems have also focus on curing temperature. Fang and Fall (2018) conducted an experimental study to determine the effect of temperature on shear and strength behavior of paste-fill. Therefore, transportation and strength are the two most significant elements of paste-fill applications. In addition to transportation and strength, Sadrossadat *et al.* (2020) constructed a model to predict the cost of paste-fill application based on cement percentage and solid content.

Design of experiment (DOE) can be defined as a collection of statistical and mathematical methods to analyze the relationship between input variables and output variables in order to optimize the process. It has been used for more than three decades in many areas such as chemistry (Kaminari *et al.*, 2005, Tumay Ozer and Gucer 2011), manufacturing (Murugara and Gunaraj 2005, Campatelli *et al.* 2014), mineral processing (Honaker 1998, Kokkilic *et al.* 2015) and mining engineering. More information about DOE can be found in (Ugurlu and Kumral 2020).

Some researchers investigated the effect of copper/zinc tailings on short and long term strength as paste-fill material in Turkish mines (Kesimal *et al.* 2005, Yilmaz *et al.* 2011). Although it is widely used due to the economic and environmental friendly supporting system in many countries such as Australia, Canada and the USA, very little information is available about the paste-fill made from the tailings of Turkish mines. Therefore, this paper aim to investigate the behavior of the tailings of Turkish mines as paste-fill material. A case study was conducted in an underground lead and zinc mine located in Balya Balikesir operated by Eczacibasi Group Esan. The mine has been operating since 2009 and it reaches nearly 1000 m depth and the annual production rate is approximately 1.7 million tons of lead and zinc production. The production depth and rate make the mine most important for the Turkish metal industry. The excavated ore from the underground mine hauls to processing plant constructed in the same area that also processes annually 1.7 million tons of ore. The concentrated ore is ready for the market while the tailings store in the tailing dam also close to the mine site. Cut and fill mining method performed in the mine, and the excavated production openings are filled by cemented backfill materials instead of paste-fill. In particular, the paper focused on the investigation of the characteristics of the materials which are the tailings, binders and water in order to prepare paste-fill specimens. The physical, chemical and mineralogical properties of the materials were determined. A DOE method was used to create different mixtures. The paste-fill specimens were created by changing the binder ratio and water content. The UCS test was performed on cylindrical paste-fill specimens cured for four curing times (7, 14, 28 and 56 days) to determine the mechanical behavior of the specimens. Finally, the optimum mixture was selected based on the strength properties such as UCS and modulus of elasticity.

2. Experimental procedure

The design steps for the paste-fill application are given in Fig. 1. All the laboratory experiments were conducted in

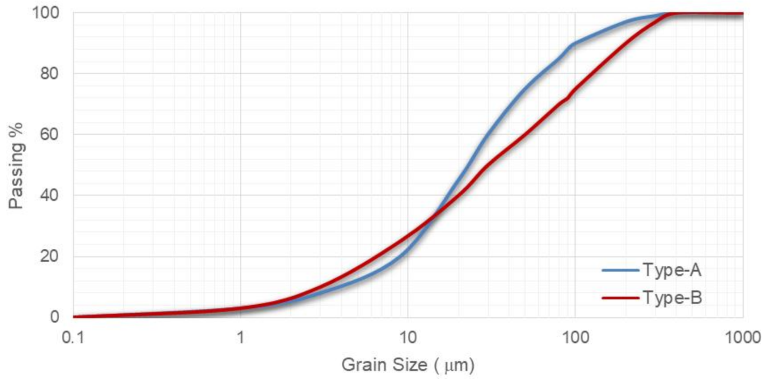


Fig. 2 Grain size distributions for Type A and Type B tailings (Ugurlu 2013)

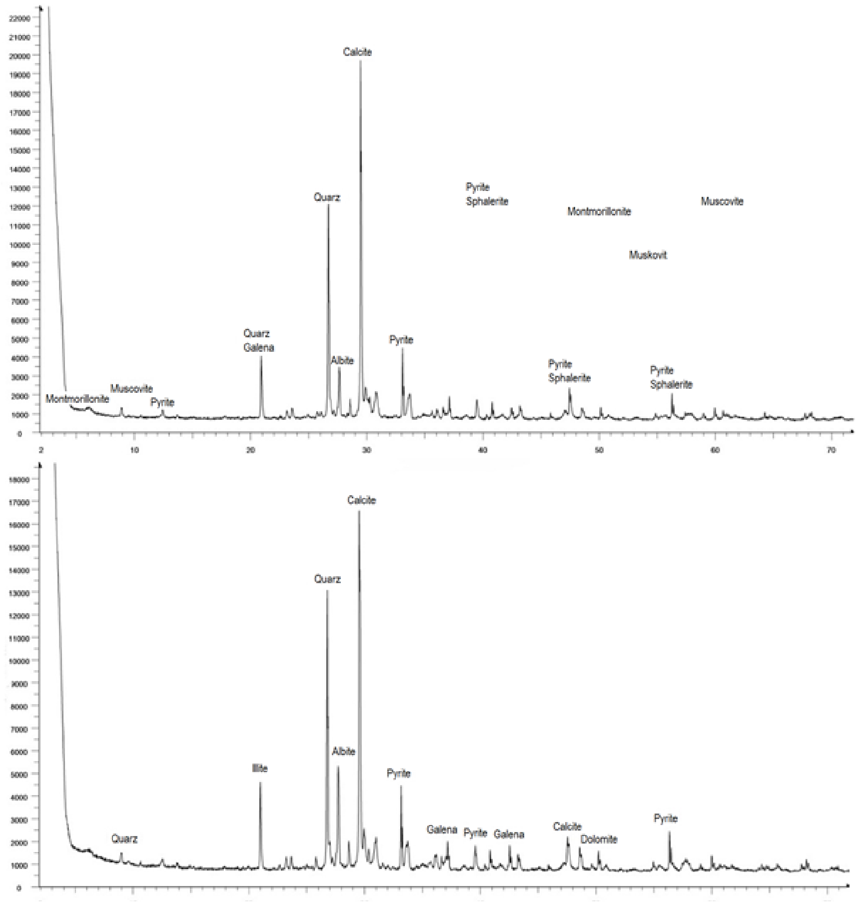


Fig. 3 XRD results of the tailings (Type A and B, respectively) by Bruker D8 Advance (Ugurlu 2013)

the laboratories of Istanbul Technical University (ITU).

The red arrows in Fig. 1 show the properties required for the paste-fill design and the black arrows show the outcomes.

2.1 Materials

The characteristic properties of tailings, water and binders (cement), which are the main components of paste-fill, were examined.

2.1.1 Characteristics of tailing materials

Tailings with different physical, chemical and mineralogical properties used in experiments were obtained from the underground mine. The initial moisture contents of the received tailings were in the range of 10-12%.

Grain size distributions of the tailings are given in Fig. 2 and Table 1 for two different tailing types that are defined as type-A and type-B in the study. The tailings were analyzed using a Malvern Mastersizer Hydro 2000 MU machine. The experiment was repeated 15 times in both wastes and the graphs were drawn by averaging the values.

The tailings A and B consist of around 40% of fine particles with sizes of less than 20µm which is significantly higher than 15%, generally accepted rule for paste-fill operations (Sivakugan *et al.* 2015). The tailings are classified as medium material size (35-60% ≤ 20µm) (Fall

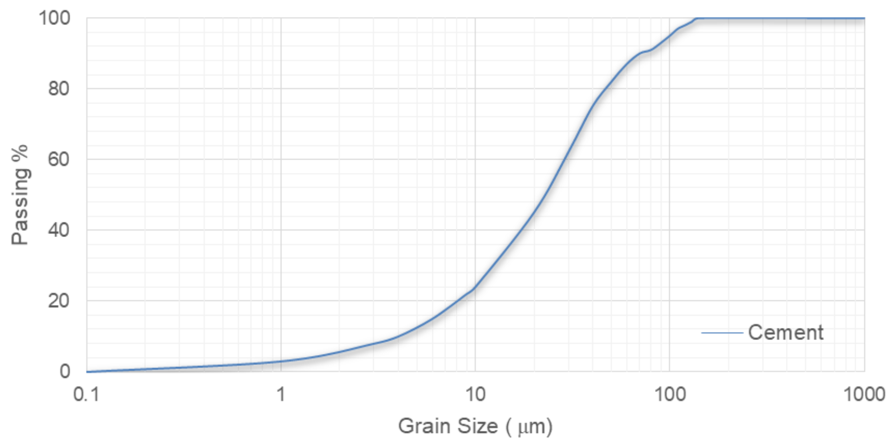


Fig. 4 Grain size distributions for the cement (Ugurlu 2013)

Table 1 Main physical properties of Type A and Type B tailings

Physical Properties	Type A	Type B
D_{10} (μm)	4.5	3.5
D_{30} (μm)	12.5	13.5
D_{50} (μm)	22.6	30.4
D_{60} (μm)	29.6	50.5
D_{90} (μm)	90.9	200.8
Uniformity (C_U)	6.57	4.3
Skewness (C_C)	1.17	1.03
Density (g/cm^3)	1.47	1.49
Classification	Non-plastic	Non-plastic

Table 2 Chemical composition from XRD and XRF analysis

Chemical Composition	Type A (%)	Type B (%)
SiO_2	33.11	38.27
Al_2O_3	6.88	6.30
Fe	7.13	9.10
CaO	24.85	24.28
MgO	2.82	3.64
TiO_2	0.26	0.24
Cr_2O_3	0.01	0.01
Na_2O	0.30	0.64
K_2O	2.32	2.31
MnO	0.48	0.52
P_2O_5	0.09	0.09
S	8.45	3.56
Ignition Loss	11.00	11.04

et al. 2005). The only difference between the two tailings is Type B waste contains more large-grained particles than Type A waste.

The uniformity coefficient (CU) and the curvature coefficient (CC) are calculated from Eqs (1)-(2), respectively. These coefficients help to classify the soil as well-graded or poorly-graded ones. For paste-fill material with a good size distribution, the CU should be between 4 and 7, and CC should be between 1 and 3 (Landriault 2001). The results show that both tailings have good size distributions (Table 1).

Table 3 Chemical composition of the cement from XRD and XRF analysis

Chemical Composition	(%)
SiO_2	17.05
Al_2O_3	4.14
Fe	2.88
CaO	63.36
MgO	1.29
TiO_2	0.21
Cr_2O_3	0.01
Na_2O	0.40
K_2O	1.11
MnO	0.04
P_2O_5	0.08
SO_3	10.12
Ignition Loss	4.69

Table 4 Properties of the mixing water

Definition	Site water 1 (ppm)	Site water 2 (ppm)	Lab water (ppm)
Si	< 10	< 10	< 10
Fe	< 5	< 5	< 5
Na	54.95	50.30	23.40
K	29.75	26.90	2.91
Ca	588.20	618.10	47.90
Mg	0.01	0.03	7.40
pH	11.40	10.80	7.90

$$C_U = \frac{D_{60}}{D_{30}} \tag{1}$$

$$C_C = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{2}$$

In the experiments carried out for the determination of density with a pycnometer, the average of 5 measurements was calculated and the density of the tailing was determined (Table 1). Using the density values obtained as a result of this pycnometer experiment, the amount of paste fill production required for filling the stopes (Ugurlu 2013) resulting from underground production was calculated.

In addition, Atterberg limit tests (liquid limit and plastic limit by Casagrande method) were conducted to define the limits of soil consistency for the classification of soils. Liquid and plastic limits of the received tailings indicate that there is no plasticity in both tailings (Table 1).

Moreover, the chemical structure of the tailings was analyzed by X-ray diffraction (XRD for compound analysis) and X-ray fluorescence (XRF for elemental analysis) analysis. These methods are used to determine the chemistry of a specimen. Combining the results of both XRF and XRD techniques allows for a better and more complete characterization of a given specimen. The chemical analysis of the tailings is given in Fig. 3 and Table 2.

According to the results, both tailings contain similar chemical compositions. A high percentage of calcite, quartz, pyrite and silicates were identified (Table 2).

2.1.2 Characteristics of binders

Portland cement CEM I 42.5 N was selected to use as a binder to prepare paste-fill specimens. The particle size distribution (grain size distributions) of the Portland cement is given in Fig. 4. The cement was analyzed by Malvern Mastersizer Hydro 2000 MU machine. The experiment was repeated 15 times and the graph was drawn by averaging the values.

The chemical composition of the portland cement is given in Table 3. It stands out that the silicium and calcium ratio in cement is high.

2.1.3 Characteristics of water

There are two different types of water in the mine site that can be used for paste-fill production. In addition, tap water was used in the laboratories at ITU to produce paste-fill specimens. Analysis of these three different water was done by “Perlik Elmer A Analyst 700” atomic absorption spectrophotometer and “WTW pH197_S” pH meter.

The results of the experiments to determine the properties of the mixing water are shown in Table 4. According to the data obtained as a result of the experiments, it has been observed that there will not be any negative effects on cement because the pH of the mixing water for all types is above 7 which is alkaline.

2.2 Design of experiment (DOE)

After analyzing the properties of the materials, paste-fill specimens were created based on different binder ratio and water content by one of the design of experiment (DOE) methods. DOE, also known as experimental design, is a systematic procedure that is carried out under controlled conditions in order to investigate the relationship between input and output factors. Statistically significant factors are determined by ANOVA (analysis of variance). Multiple input factors (independent variables) are considered and controlled simultaneously to ensure that the effects on the output responses (dependent variables) are causal and statistically significant (Montgomery 2009).

A central composite design, which is used to obtain the optimized paste-fill specimen, was selected as a DOE method to collect data from the mechanical tests. All possible combinations of the variables were investigated by

Table 5 Design patterns with coded variables for paste-fill specimens

Combinations	Binder Ratio (X_1)	Water Content (X_2)
1	-	-
2	-	0
3	-	+
4	0	-
5	0	0
6	0	+
7	+	-
8	+	0
9	+	+

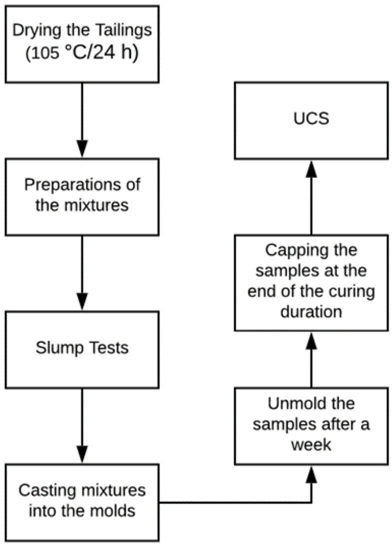


Fig. 5 The procedure of paste-fill specimen preparation (modified from (Ugurlu 2013))

Table 6 Paste-fill mixture combinations with different cement ratio and water content

Code	Tailing (%)	Binder (%)	Water (%)	Slump (inch)	Water/Cement	Solid Ratio (%)
A1 / B1	76.00	4.00	20.00	6.00	5.00	80.00
A2 / B2	75.25	4.00	20.75	7.00	5.19	79.25
A3 / B3	74.50	4.00	21.50	8.00	5.38	78.50
A4 / B4	74.00	6.00	20.00	6.00	3.33	80.00
A5 / B5	73.25	6.00	20.75	7.00	3.46	79.25
A6 / B6	72.50	6.00	21.50	8.00	3.58	78.50
A7 / B7	72.00	8.00	20.00	6.00	2.50	80.00
A8 / B8	71.25	8.00	20.75	7.00	2.59	79.25
A9 / B9	70.50	8.00	21.50	8.00	2.69	78.50

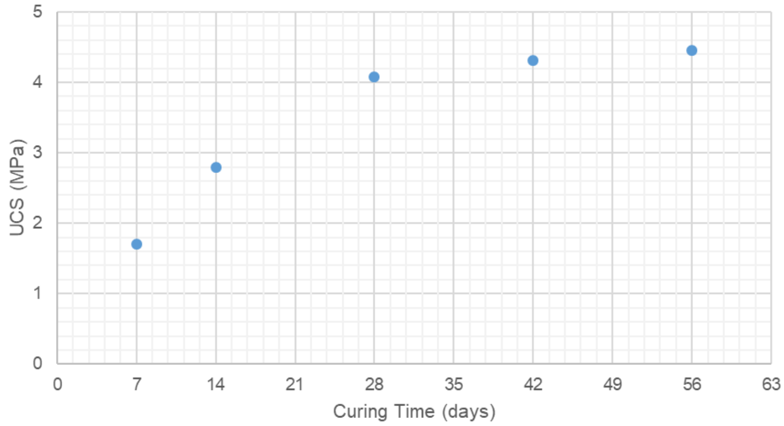


Fig. 6 The most optimized paste-fill mixture (Type B tailing, %8 binder, %20 water)

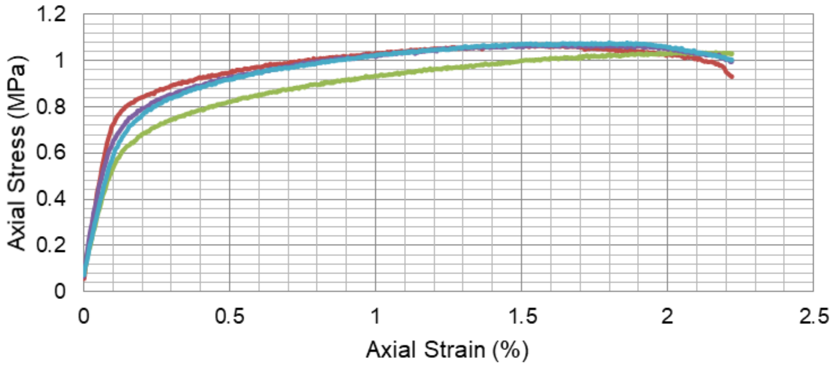


Fig. 7 An example of the stress-strain plot of the mechanical test

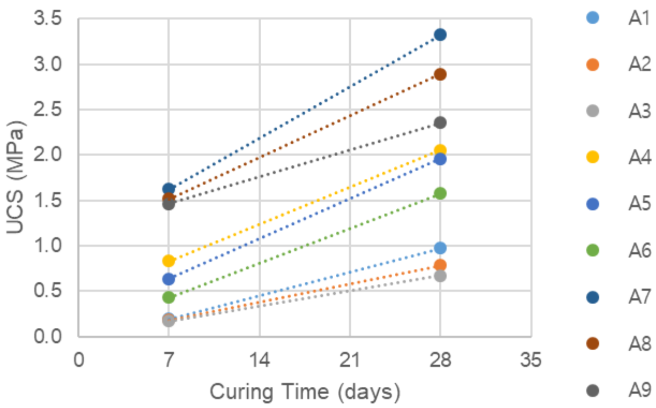


Fig. 8 The UCS of Type A specimens

the software called Minitab 17. The UCS tests and modulus of elasticity for different combinations were recorded. Minitab 17 software assisted for the experimental design, data analysis and data visualization of the study.

A face-centered central composite design (FCCCD) model was chosen to collect data from the laboratory experiments because it minimizes the cost of obtaining usable datasets and requires less time, effort and resources.

Table 5 shows the variables and their levels for all combinations. The binder ratio and the water content were selected as factors to monitor mechanical properties (UCS) of the paste-fill specimens, and the design patterns were chosen by FCCCD with two factors and three levels. The maximum binder ratio was selected as 8% and the minimum was 4%. Similarly, the maximum water content was selected as 21.5% and the minimum was 20%. The paste-fill production cost and the water amount which is necessary for pumping the paste-fill under the ground were taking into consideration in order to determine the experimental conditions. Five replications were applied to every combination for four curing times.

2.3 Fabrication of specimens

The procedure to prepare paste-fill specimens is given in Fig. 5.

There were differences in the moisture content of the tailings. Before the fabrication of the specimens, the tailings

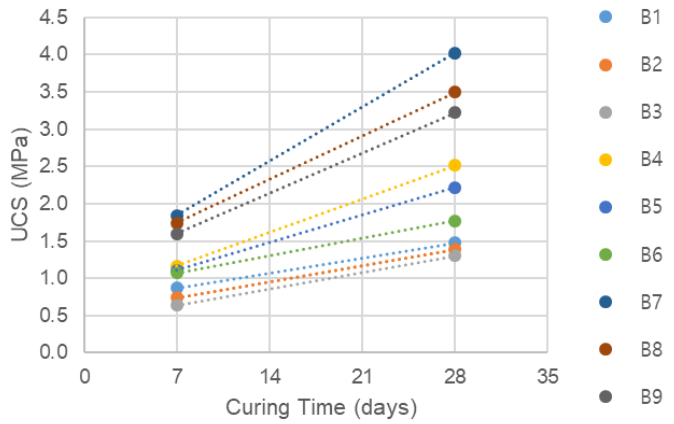


Fig. 9 The UCS of Type B specimens

were kept in the oven for 24 hours at 105°C. Then, all variables were calculated by Eqs (3)-(5) (Niroshan *et al.* 2018).

$$Binder\ \ content(\%) = \frac{Mass\ \ of\ \ binder}{{}^{\circ}Mass\ \ of\ \ solid\ \ material} \times 100 \quad (3)$$

$$Solid\ \ content(\%) = \frac{Mass\ \ of\ \ solid\ \ material}{{}^{\circ\circ}Mass\ \ of\ \ the\ \ specimen} \times 100 \quad (4)$$

$$Water\ \ content(\%) = \frac{Mass\ \ of\ \ water}{Mass\ \ of\ \ solid\ \ material} \times 100 \quad (5)$$

(°Mass of solid material = dry tailings + binder)
(°°Mass of the specimen = dry tailings + binder + water)

After the calculations, the tailing, cement, and water were mixed based on the results given in Table 6 by a mixer with the speed of 75 reps/min for 15 min to obtain a homogeneous paste. Each sample taken from the mixer was subjected to a standard conical slump test before casting the sample into the polyurethane cylindrical molds with 100 mm diameter and 200 mm length in order to determine the rheological properties of the paste-fill mixture.

After all, mixtures were prepared, cast into the molds, coded and placed to cure at room temperature because the temperatures in the mines may vary (Wu *et al.* 2020). 400 specimens were prepared to apply mechanical tests. Sulfur-graphite caps were made and applied on top of the specimens before the tests because the top surface of the specimens was not flat after removing from the mold.

2.4 Mechanical testing

Mechanical tests were performed on paste-fill specimens to investigate the applicability of paste-fill. Mechanical properties such as UCS and elasticity modulus were measured at the Rock Mechanics Laboratory at ITU by Solid Loading Device to optimize cement usage which is the most important factor in terms of economic concerns,

and water content which is the key factor for paste-fill transportation. During the tests, paste-fill samples were placed between two plates and loaded under a constant displacement rate of 0.5 mm/min. The required datasets were recorded every 2 secs. In addition, the deformation-strength graph of the mechanical test of each specimen was obtained by Test Work 4 FlexTest 40 data collector produced by MTS Company.

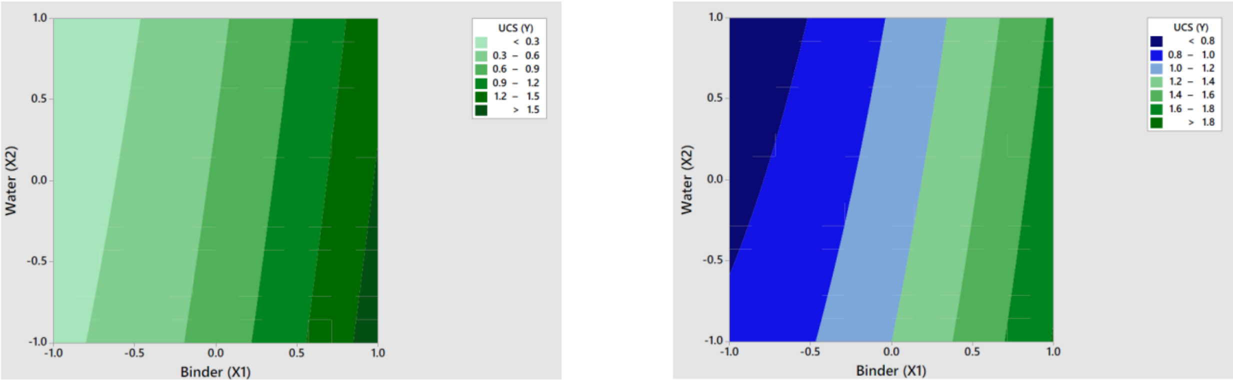
The required minimum strength must be more than 0.15 MPa for 7-day curing time and around 4 MPa for 28-day curing time to be used particularly as a basement of the upper production level (Grice 1998).

3. Results

After randomly conducting mechanical experiments based on FCCCD patterns, each dataset was analyzed to investigate the behavior of all possible combinations. The

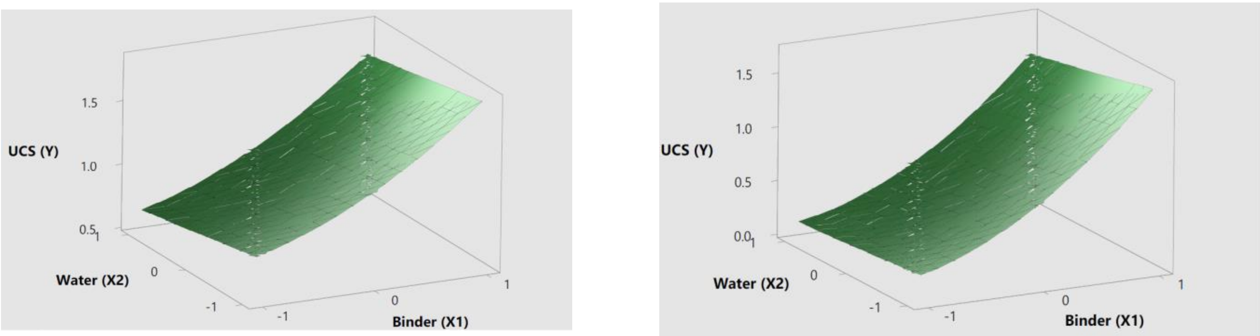
Table 7 ANOVA table of Type A and Type B tailings for 7-day curing time

Type A - Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	14.8453	2.9691	562.36	0
Linear	2	13.9804	6.9902	1324	0
Binder (X_1)	1	13.7228	13.7228	2599.2	0
Water (X_2)	1	0.2576	0.2576	48.79	0
Square	2	0.8296	0.4148	78.56	0
Binder (X_1)*Binder (X_1)	1	0.6923	0.6923	131.12	0
Water (X_2)*Water (X_2)	1	0.0007	0.0007	0.12	0.726
2-Way Interaction	1	0.0353	0.0353	6.68	0.012
Binder (X_1)*Water (X_2)	1	0.0353	0.0353	6.68	0.012
Type B - Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	5	7.61049	1.5221	876.09	0
Linear	2	7.34222	3.67111	2113.03	0
Binder (X_1)	1	7.0956	7.0956	4084.1	0
Water (X_2)	1	0.24661	0.24661	141.95	0
Square	2	0.26827	0.13413	77.2	0
Binder (X_1)*Binder (X_1)	1	0.22346	0.22346	128.62	0
Water (X_2)*Water (X_2)	1	0.00024	0.00024	0.14	0.709
2-Way Interaction	1	0	0	0	0.957
Binder (X_1)*Water (X_2)	1	0	0	0	0.957



(a) Type A (b) Type B

Fig. 10 The contour plot of Type A and Type B tailings for 7-day curing time



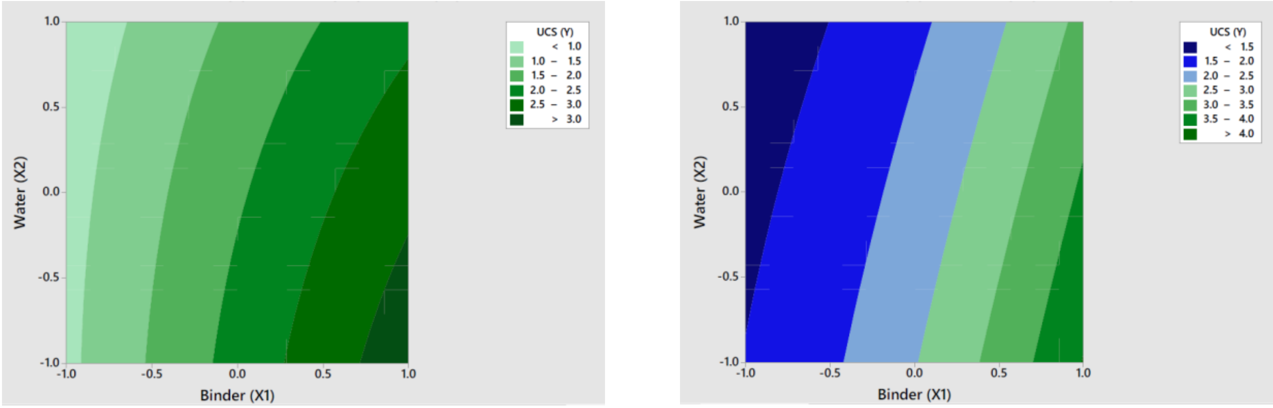
(a) Type A (b) Type B

Fig. 11 The surface plot of Type A and Type B tailings for 7-day curing time

Table 8 ANOVA table of Type A and Type B tailings for 28-day curing time

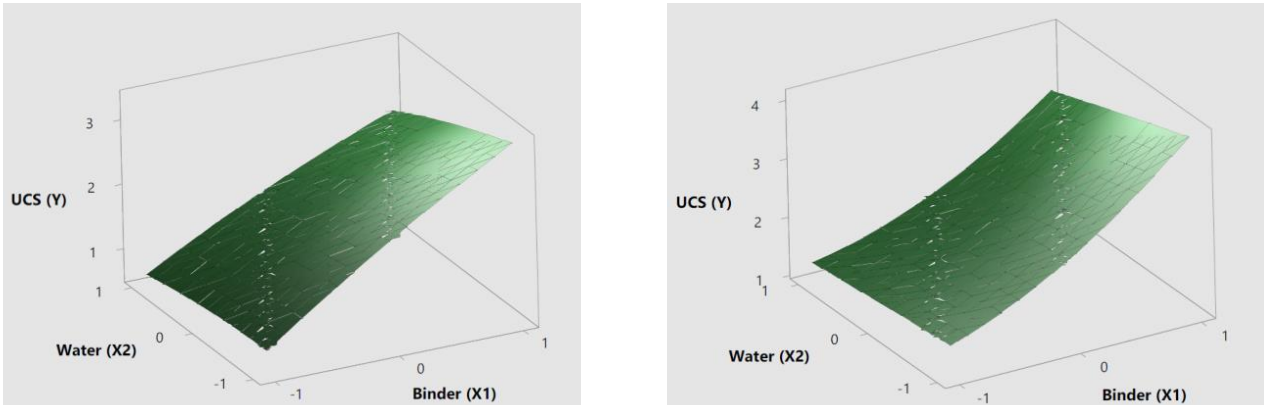
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	35.8422	7.1684	575.42	0
Linear	2	35.0601	17.53	1407.16	0
Binder (X_1)	1	32.5313	32.5313	2611.33	0
Water (X_2)	1	2.5288	2.5288	202.99	0
Square	2	0.2075	0.1038	8.33	0.001
Binder (X_1)*Binder (X_1)	1	0.099	0.099	7.95	0.007
Water (X_2)*Water (X_2)	1	0.0341	0.0341	2.74	0.103
2-Way Interaction	1	0.5746	0.5746	46.12	0
Binder (X_1)*Water (X_2)	1	0.5746	0.5746	46.12	0
Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	5	40.4369	8.0874	1198.57	0
Linear	2	38.5133	19.2566	2853.87	0
Binder (X_1)	1	36.0365	36.0365	5340.67	0
Water (X_2)	1	2.4768	2.4768	367.07	0
Square	2	1.4275	0.7138	105.78	0
Binder (X_1)*Binder (X_1)	1	1.2354	1.2354	183.09	0
Water (X_2)*Water (X_2)	1	0.0003	0.0003	0.05	0.825
2-Way Interaction	1	0.4961	0.4961	73.53	0
Binder (X_1)*Water (X_2)	1	0.4961	0.4961	73.53	0

most critical curing times for paste-fill specimens are 7-day and 28-day curing times (Grice 1998). Although over 0.15 MPa UCS for 7-day curing time was obtained for all mixtures, only one mixture had more than 4 MPa UCS for



(a) Type A (b) Type B

Fig. 12 The contour plot of type A and type B tailings for 28-day curing timeexponent 0.22



(a) Type A (b) Type B

Fig. 13 The surface plot of type A and type B tailings for 28-day curing time

28-day curing time. The mixture with Type B tailing, %8 binder ratio and %20 water content is the best mixture in terms of the highest strength (Fig. 6). The 42-day curing time is also added to see the behavior pattern of the UCS by time.

According to the data obtained during the mechanical tests, the specimens did not lose their strength completely after the moment of breaking and continued to take the load (Fig. 7). The figure shows the change in stress as strain increases for 4 samples which were represented by the lines.

In comparison with Type A and Type B tailings, a significant difference in terms of strength is demonstrated in Figs. 8 and 9, respectively.

Table 7 shows the ANOVA results of Type A and Type B tailings for 7-day curing time. Values that have more p values than 0.05 are not included in the regression equation. Eqs. (8) and (9) show mathematical models of the effect of input variables (cement ratio and water content) and their interactions on the output variable (UCS) for Type A and Type B tailings, respectively.

$$Y = 0.6312 + 0.6763X_1 - 0.0927X_2 + 0.2239X_1^2 - 0.0420X_1X_2 \tag{8}$$

$$Y = 1.1037 + 0.4863X_1 - 0.0907X_2 + 0.1272X_1^2 \tag{9}$$

The R-squared value, which shows the correlation between input variables and the output variable, is more than 90% for both tailings. Therefore, the quadratic model correlation is acceptable. Figs. 10 and 11 show the contour plot and the surface plot, respectively.

According to the regression equation and the plots, the binder ratio is in direct proportion to UCS, while the water content is in inverse proportion.

Similarly, Table 8 shows the results of the tests performed at the end of 28 days for both tailings. There is a dramatic increase in UCS values. The regression equations are given in Eqs. (10) and (11).

$$Y = 1.9365 + 1.0413X_1 - 0.2903X_2 - 0.0847X_1^2 - 0.1695X_1X_2 \tag{10}$$

$$Y = 2.1908 + 1.0960X_1 - 0.2873X_2 + 0.2991X_1^2 - 0.1575X_1X_2 \tag{11}$$

Figs. 12 and 13 show the contour plot and the surface plot, respectively. Contour plots show the change of UCS as a function of cement ratio and water content, and surface plots show a functional relationship between a designated dependent variable (UCS), and two independent variables (Cement ratio and water content). These plots help determining the optimum mixture to have the highest strength.

4. Discussion

The mechanical properties of the paste-fill specimens cured for four different curing time were measured using UCS tests. The effect of the paste-fill materials on the mechanical performance was examined using FCCCD to determine the optimum combination.

The cement ratio has a significant impact on the mechanical properties of the paste-fill specimens, whereas the water content has a slight impact. Increasing the cement ratio causes great changes in strength. However, the water content is an essential element to prepare paste-fill specimens and transport the mixture to the underground openings (Sivakugan *et al.* 2015). Hence, to determine the best mixing ratio is very important for mining activities and economics.

The cement ratio needs to be optimized to save millions of dollars in the mines (Yilmaz *et al.* 2011). The type of tailings and some natural additives such as fly ash, silica fume, and granulated blast furnace slag can be used as the partial replacement of the binders to reduce the use of cement (Ercikdi *et al.* 2009; Han *et al.* 2019). The mechanical tests reveal that, Type B tailing with less cement ratio achieved higher UCS than Type A tailings with more cement ratio. The reason behind this result is the grain size distribution. It is also observed in the experiments that the UCS increases rapidly from 7 days to 28 days and continues to increase slowly after 28 days. Thus, 7-day and 28-day curing times are crucial.

In this study, a minimum of 0.15 MPa strength was obtained in all specimens at the end of the 7-day curing time. 28-day UCS target of Kesimal *et al.* (2005) was achieved in 7 days with most of the specimens (0.7MPa ≤ UCS). Thus, both tailings can be used as paste-fill material. Moreover, Type B tailing with %8 cement ratio and %20 water content mixture, which was obtained more than 4 MPa UCS for 28-day curing time, can be used as a basement of the upper production level. Furthermore, during the mechanical tests, the specimens continued to take the load even after the moment of breaking. Hence, a safe working environment can be created under the ground using these tailings.

In the present study, the paste-fill mixtures were prepared without any flocculants. Xu *et al.* (2020) asserted that the flocculants have a negative impact on the strength properties of paste-fill, particularly after 7 days. On the other hand, Qi and Fourie (2019) reviewed the researches about flocculants used for the paste-fill applications. They did not indicate any correlation between flocculant usage and the strength of paste-fill. Thus, further research is needed to evaluate the effect of flocculants on the strength properties of paste-fill.

5. Conclusions

Even though the paste-fill system has some drawbacks such as high capital cost and skilled worker requirement, the advantages outweigh the disadvantages, particularly in the long-run. All tailings can be disposed of underground openings safely without causing environmental pollution. It also provides a safe working environment and decrease waste disposal cost. Moreover, the land requirement to store tailings can be dramatically reduced by paste-fill applications.

In this paper, two types of tailings, which have different grain size distributions, were investigated to applicability as paste-fill material with short-term and long-term mechanical properties. Paste-fill specimens were prepared by using different combinations of binder ratio and water content. Among the nine combinations carried out in the study, Type B tailing, 8% binder, 20% water specimen is the optimum mixture in terms of the highest strength. Furthermore, the experimental studies for physical, chemical, mineralogical and mechanical properties show that both tailings can be used as paste-fill material. However, the strength of Type B tailing is more than Type A tailing.

This study can be helpful for engineers and scientists working for decreasing the cost of waste disposal and creating a safe working environment.

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