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Sulfide-rich mine tailings usage for short-term support purposes: An experimental study on paste backfill barricades

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Abstract. Barricade failures generally occur at the early times of paste backfill when it is fresh in the stopes. The backfill strength increases and need for barricading pressure decreases as a result of the hydration reactions. In this study, paste backfill barricades of Cayeli copper mine were investigated to design cemented mineral processing plant tailings as barricade body concrete. Paste backfill in sub-level caving stopes of the mine needs to be barricaded for only four or five days. Therefore, short term strength and workability tests were applied on several cemented tailings material designs. Barricade failure mechanisms, important points of barricade designing and details of the new concrete material are explained in this work. According to the results obtained with this experimental study, the tailings were assessed to be used in concrete applied as temporary supports such as cemented paste backfill barricades.

Keywords: paste backfill; barricade support; shotcrete; mining; underground support; sub-level caving

1. Introduction

Paste backfill (PB) is a type of underground mine support which generally consists of mineral processing plant tailings mixed with cement and water. Typically, more than 90% of the solid content of PB is the tailings, and PB has much higher ratio of water to cement in comparison with widely applied concrete materials as a result of high water content need for convenient workability of the mix with fine tailings. Because fresh paste backfill is pumped to the underground stopes, its rheology is a critical factor for material transportation (Kesimal *et al*. 2004). In general, the slump test values of the fresh mix are desired to be between 7 and 7.5 inches. The fresh mix behaves like a non-newtonian fluid which flows by applying an external stress. Typical yield strength of fresh paste backfill is between 0.1 and 0.7 kPa (Yumlu 2008).

PB has advantages for disposing of the mine waste generated millions of tons per a month in the world. The increasing demand for metals appears to cause bigger natural problems in the future. Therefore, deposition of the mining wastes is becoming more important for protecting the environment. Within this scope, paste backfill is expected to be a standard application for many sub-level caving and cut-and-fill mines all over the world (Belem and Benzaazoua 2004).

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To keep the fresh backfill material in the stopes, barricades are set at the down-level gallery enterances. Backfill material stress starts to apply on barricade as it is filled from the up-level gallery. When PB has enough strength to be durable under its self-weight, barricades complete their mission. Therefore, barricades can be considered as a temporary support for fresh PB (Yumlu 2001, 2008, Karaoglu *et al*. 2011).

Lateral stress of backfill material is applied on the barricades. Because fresh PB behaves like a non-newtonian fluid which needs an external force to flow, the stress distribution can not be considered as completely hydrostatic. However, horizontal stresses are similar with the vertical stresses in fresh PB material (Karaoglu *et al*. 2011, Komurlu 2012). There are many application details to influence the barricade stresses: Filling rate, unit volume weight of PB, dimensions of the stope, height of fill material, drainage, temperature, filling step number, waiting time between filling steps (Li and Aubertin 2009a, 2009b, Belem and Benzaazoua 2004, Karaoglu *et al*. 2011, Gercek 2007, Mei *et al*. 2014, Orejarena and Fall 2011, Cakir 2014, Uzuner 2007).

In this study, Cayeli mine, a copper mine in Turkey was selected as a case study area. Actual filling rate and height of the first filling step in the mine are 0.43 m/hour and 7 meters, respectively. Therefore, the first step filling continues for 16 to 17 hours in the mine. According to in situ paste backfill stress measurements in the mine stopes, horizontal stress applying on the barricades typically varies from 130 kPa to 150 kPa, and vertical stress interval is between 150 kPa and 170 kPa at the end of the first filling step (Komurlu 2012). The second step is waited for 48 hours from the end of first step filling. Duration of the second step filling depends on the height of stope.

Barricades complete their mission in several days like 3-5 days, depending on the hydration of PB. There is no need for barricading PB when it is enough hydrated to be stable under its self-weight (Komurlu and Toptas 2012). Generally, first step PB with four days curing time has enough strength to be stable under the loads of both first and second steps PB in Cayeli mine stopes.

Cayeli copper mine's paste backfill barricades are concrete-steel composite flat fences. To prevent outward curved barricade setting, barricade area boundary is firstly drawn by reference lines. Second application is rebar bolt setting through the drawn lines. The rebar bolts have 20 mm diameter and ribbed surfaces. There is 0.8 meter distance between the rebar bolts with the length of 2.8 meters, which 1.8 meter part of them is inserted into drill-hole to attach barricade to the ground. As following step, wood and hardboards are set to create shotcrete applying surface that is 27 cm behind the reference line and rebar bolts.

Wood planks are set behind rebar bolts as shown in Fig. 1(a), and hardboards are nailed on wood planks. Steel reinforcement rebars with diameter of 28 mm and length of 4 meters are set to create meshes with 40 cm × 30 cm aperture. The reinforcement rebars are tied with the rebar bolts inserted into the ground (Fig. 1(b)). 1 m part of each reinforcement rebars overlays and intersects another reinforcement rebar's 1 meter part. Shotcrete passes through the steel reinforcement and adheres on the hardboards as shown in Fig. 1(d). Shotcrete total thickness is 0.3 meter, and 3 cm of this thickness covers the steel reinforcement rebars.

Barricades are set in three or four shifts in Cayeli mine. Dimensions of barricade are important for setting time and cost of barricades. The dimensions can change from 5 m × 4 m to 10 m × 5 m in the mine. Typically, 8 m × 5 m barricades are set with the material cost of 3500 $. The big part of this cost is payed for the steel rebars and shotcrete, which can be considered as 1200 $ for steel rebars and 1900 $ for shotcrete with the chemical additives of accelerator and plasticizer. Because PB filling starts one day later than the barricade setting, short curing time strength of concrete is important as the barricade material. Therefore, chemical additive of accelerator is crucial to be

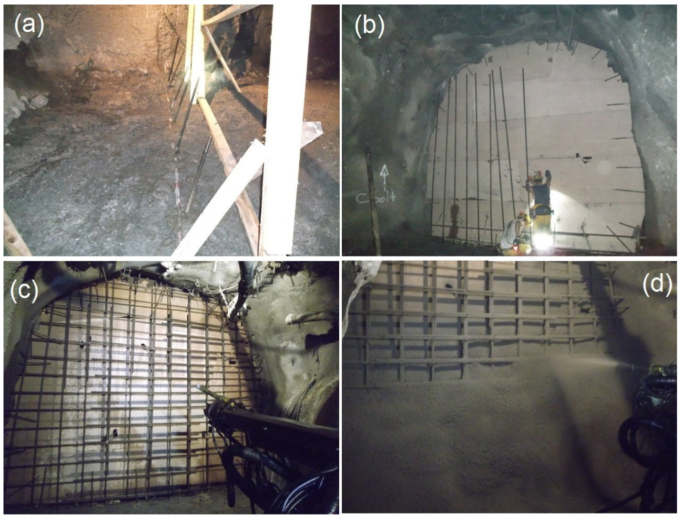

Fig. 1 (a) Wood plank behind rebar bolts; (b) Setting steel reinforcement rebars; (c) Barricade is ready for shotcrete; and (d) Shotcrete application of barricade

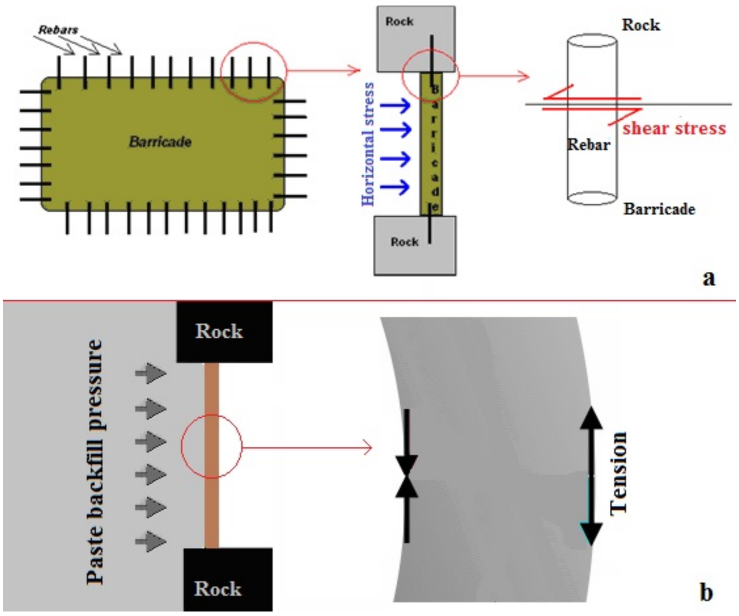

Fig. 2 (a) Failure of the attachment; (b) failure of the body

used in barricade concretes. Even if the barricades are removed after a week following the barricade setting, PB applied in the Cayeli mine has enough strength to be stable.

There are two main reasons for barricade failure. The first one is realized as a result of excessive stresses at the attachment of barricade to ground (rebar bolts and/or interface between the barricade body and wall). In this type of failure, barricade body is generally thrown to the gallery. Shear and tensile stresses occur in the attachment rebar bolts when lateral PB pressure applies on barricades (Fig. 2). In addition to strength of the bolt steel, its adherence with the injection in drill-hole is influential to prevent failure. From this point of view, rebar bolt surface ribs and injection quality are critical. On the other hand, barricade body concrete adhesion to the wall defines the attachment strength of barricades without the rebar bolts.

The other type of failure is barricade body failure. Lateral PB pressure induces flexural stresses in the flat barricade body (Ghazi 2011, Hughes 2008). To increase barricade body strength, arched (inward curved, concave) barricades can be set, which is exposed to compression by the backfill material pressure. Because concrete materials have quite higher compressive strength than their flexural strengths, concave body has important advantages. Much steel reinforcement in the flat body is needed to supply same strength with that of the concave barricade body without steel reinforcement (Hudson and Harrison 1997, Sinopoli 1998, Komurlu and Kesimal 2011). However, limited areas can prevent to set arched barricades. The concrete strength and arc body geometry define the concave barricade body performance. To be exposed a complete compression, the arched barricades must have convenient geometry with well curvature and enough ratio of indentation to span. Otherwise, tensile stresses can be induced in the body (Galambos 1998). For the flat and poorly arched barricades, the tensile strength of the concrete is critical in respect of barricade body stability. To increase the effectivity of the steel reinforcement in the barricade bodies, the adherence between reinforcement and concrete is critical in addition to the steel reinforcement usage details such as aperture between rebars and diameter of rebars.

In this study, tailings of mineral processing plant of the mine was aimed to use instead of the rock aggregate, as a part of barricade concrete. For this aim, strength and rheology tests were performed on several material designs with the tailings to be the candidate concrete of barricade. As a result of the affect of sulphur content, mine tailings is not considered as a shotcrete material. However, cemented sulphuric mine tailings is considerable to be used for the purposes of short term support needs such as barricading the backfill in stopes. Fine particle size of tailings is an advantage for passing through the steel reinforcement and decreasing the rebound problem which causes material loss (Arıoglu *et al*. 2008, Kolymbas 2005). In addition, adherence between the reinforcement rebars and concrete is expected to be better due to the decrease of voids in contact. As another reason for investigating the tailings as barricade concrete ingredient is mine waste management. Because of allowing to deposit more underground tailings, it is beneficial to use cemented tailings for the environmental protection.

2. Materials and methods

Two types of Cayeli copper mine tailings and their deslimed forms were investigated in this experimental study. Spec tailings, Bornite tailings and their deslimed (classified) forms were tested. Desliming to obtain classified material were carried out by using hydrocyclones in the mine. Important percentages of finer particles than 20 μm were deslimed for preparation of the classified tailings. For example, 44% of as-received (unclassified) Bornite tailings and 41% of as-received Spec tailings were finer than 20 μm, respectively. After desliming, 6% of C-Bornite (Classified Bornite) and 12% of C-Spec (Classified Spec) tailings became finer than 20 μm, respectively. Particle size distribution was analyzed by using laser particle size analyzer microsizer. Fig. 3 shows particle size distributions of Cayeli copper mine tailings used in this study.

More than 70% of both Bornite and Spec tailings (unclassified) had silt particle size (2-63 μm). Approximately, 10% of as-received tailings had clay particle size (< 2 μm). Silt particle size and

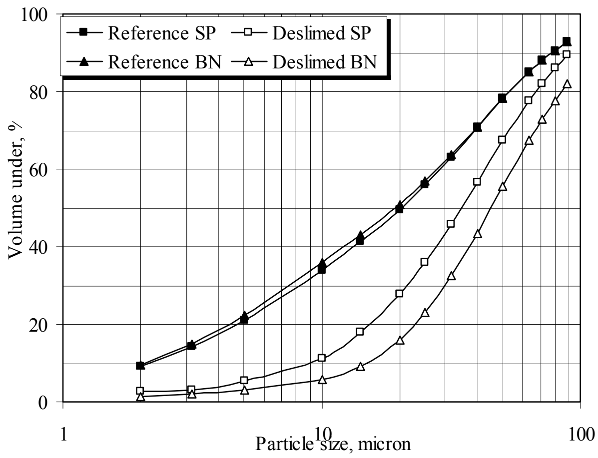

Fig. 3 Particle size distribution of Bornite (BN) and Spec (SP) tailings (Komurlu *et al.* 2013)

Table 1 Uniformity and curvature coefficients for the tailings

Type of Tailings	D_{10} (μm)	D_{30} (μm)	D_{60} (μm)	C_u	C_c
Bornite	2	7	26	13.0	0.94
Spec	2	8	26	13.0	1.23
C-Bornite	14	30	53	3.8	1.21
C-Spec	9	21	42	4.7	1.17

clay size percentages were respectively 75% and 3% for C-Spec (deslimed) tailings. 65% of C-Bornite had silt particle size, and 2% of C-Bornite had clay particle size. Some other details for particle size distribution analyses for the mine tailings, coefficient of curvature (Cc) and coefficient of uniformity (Cu) are given in Table 1 (D_{10}, D_{30} and D_{60} are 10%, 30% and 60% passing particle sizes, respectively).

Tailings material, cement, water and chemical additives (plasticizer and accelerator) were mixed and homogenized in a concrete mixer for 10 minutes. Before molding cemented tailings, workability of fresh materials were assessed with the slump test. The slump value of the paste mixtures was measured as between 18 cm and 20 cm, which is the most frequently used slump value interval of fresh material in both cemented paste backfill and shotcrete operations (Ghirian and Fall 2013, Komurlu and Kesimal 2011, Arioglu *et al.* 2008, Ercikdi *et al.* 2013).

As mentioned before, the aim of this material design study is suggesting new cemented tailings with high strength, which will be a candidate of shotcrete for temporary support applications like barricade bodies. Therefore, accelerator was used to obtain high strength results from the short term tests. Additionally, plasticizer was used in mixes to reduce water content without losing the workability performance. Amount of cement in unit volume and the ratio of cement to water were quite high for designed materials in comparison with cemented PB in stopes. Therefore, plasticizer usage was needed to have a proper workability.

Especially, accurate determination of tensile strength is crucially needed for investigation of new material designs as flat barricade body concrete. On the other hand, compressive strength mostly defines the arched barricade performance as long as it has a well-shaped body. The uniaxial compressive strength (UCS) test, three points flexural strength test, and Brazilian indirect tensile strength test were applied on various material designs. Because short term strength of barricade concrete is critical and PB is started to fill one day after barricade setting, strength tests were applied on the specimens with curing time of one day. As cemented backfill material cures in the stopes, only a couple of days are necessary for supplying barricade pressure. Maximum barricade support pressure is needed at the end of first filling step (typically after 0.5 day from filling start and 1.5 day from barricade setting).

Cubic samples with dimensions of 5 cm × 5 cm × 5 cm were prepared and used in the UCS test (Fig. 4). Classified (deslimed) tailings caused better workability values in comparison with as-received tailings. Because of the fine particle size of as-received (unclassified) tailings, excessive water content is needed to have a desirable workability. Conversely, classified (deslimed) material let to decrease the water content in mix. Among different material designs with tailings, the best strength results were obtained using C-spec type of tailings.

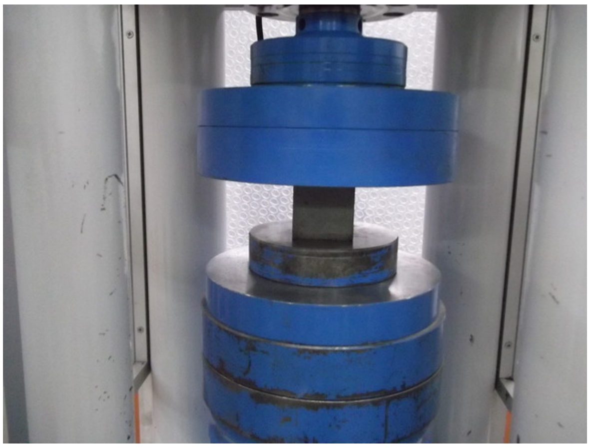

Fig. 4 UCS test applied on qubic specimens

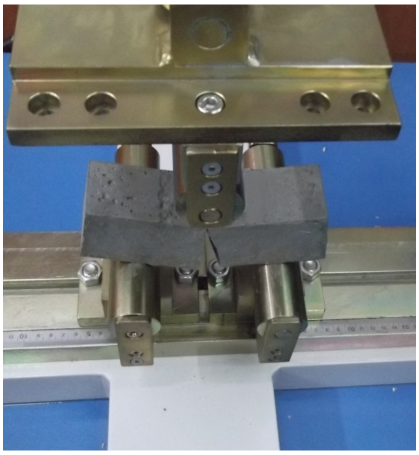

Fig. 5 Three point flexural strength test

Suggested cemented tailings material has 500 kg/m^3 ordinary portlant cement, water to cement ratio of 72.5% by weight, tailings material (c-spec) with amount of 1640 kg/m^3, plasticizer with amount of 4% of cement by weight, and freezer (accelerator) with amount of 5 % of cement by weight. Herein, it should be noted that the material cost of the suggested design with c-spec tailings can be considered as same with that of the barricade shotcrete with aggregate. Fresh and molded specimens were put on vibration table to remove air and increase homogeneity. Specimens were compacted by using tamping rods and their surfaces were flattened before putting on the vibration table.

Flexural strength test samples had dimensions of 18 cm × 5 cm × 5 cm (Fig. 5). The loading rate was selected as 0.2 kN/sec for both flexural and Brazilian indirect tensile strength tests whose results are informative for the performance of the new material design under tension. The Brazilian (splitting) tensile strength test specimens were casted into NX size diameter molds. As the ratio of thickness to diameter is suggested to be between 0.5 to 1.0 by ISRM (1978), splitting tensile strength test specimens were casted with the height from 4.5 cm to 5.5 cm. Splitting tensile strength of cemented tailings were measured by using two different load apparatus, which are the standard jaw suggested by ISRM (1978) and flat load platen (Fig. 6).

In addition to tensile strength test specimens, four cylindrical compressive strength test specimens were casted into the molds with the ratio of height to diameter of 2 by using same mix. As seen in Fig. 7, molded specimens (both tensile and compressive test specimens) were put on vibration table to remove air in fresh mix.

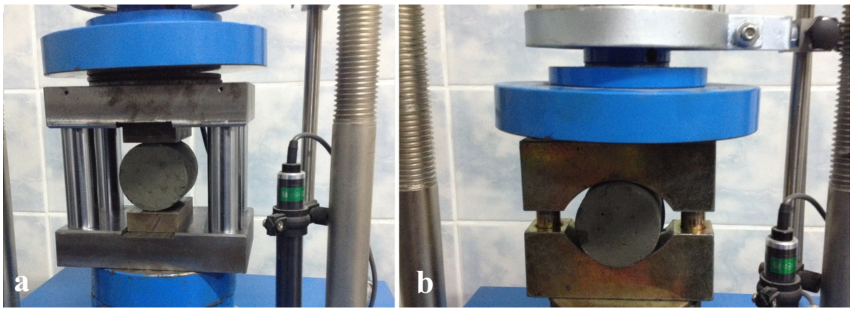

Fig. 6 Indirect tensile strength testing by using (a) jaw with flat contact; (b) standard jaw

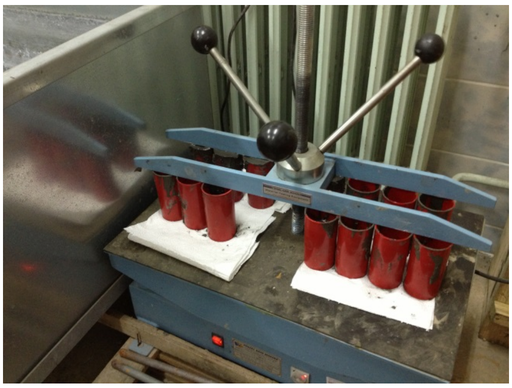

Fig. 7 UCS and Brazilian test specimens on the vibration table

Fig. 8 Uniaxial compressive strength test for cylindrical specimens

To compare with the new material design, actually used barricade shotcrete mix in the mine were prepared and casted into the molds also used for cemented-tailings specimens. The shotcrete mix contains 450 kg/m^3 cement, 1550 kg/m^3 aggregate, 225 kg/m^3 water, 10 kg/m^3 accelerator and 5 kg/m^3 plasticizer. Maximum particle size of aggregate is 8 mm in the mix, and more than 60% of the aggregate is under 4 mm. Before the slump testing, fresh concrete was mixed for 8 minutes in the concrete mixer. The slump value of fresh mix was measured as 20.5 cm. Specimen preparation were performed by following same procedures and same molds with those of the cemented-tailings specimens. Cylindrical UCS test specimens (diameter: NX size, height to diameter ratio: 2) and three point flexural strength test specimens (18 cm × 5 cm × 5 cm) were casted into the molds. Fresh concrete was compacted using tamping rods and put on vibration table to remove air. The loading rates (0.2 kN/s for flexural strength test and 1.0 kN/s for UCS test) were same for the cemented-tailings and shotcrete mixes.

Table 2 UCS (σ_c) and flexural strength (σ_f) test results for specimens (S.D. = standard deviation)

σ_c (MPa)	Specimen number	S.D. (MPa)	σ_f (MPa)	Specimen number	S.D. (MPa)
16.5	6	0.6	2.9	6	0.2

Table 3 Splitting tensile strength test results for standard ISRM (σ_{tB}) and flat jaws (σ_{tF})

Sample No.	σ_{tB} (MPa)	σ_{tF} (MPa)
1	2.54	2.15
2	2.25	1.99
3	2.34	2.11
4	2.11	2.26
5	2.37	1.96
Mean	2.32	2.09

Table 4 UCS test results for cylindrical specimens (S.D. = standard deviation)

Specimen number	σ_c (MPa)	S.D. (MPa)
4	14.4	0.4

Table 5 Results for shotcrete mix applied in the mine

σ_c (MPa)	Specimen number	S.D. (MPa)	σ_f (MPa)	Specimen number	S.D. (MPa)
15.4	6	1.2	2.3	6	0.2

3. Results

As given in Table 2, one day cured material's mean of uniaxial compressive strength (UCS) test results for cubic specimens was 16.5 MPa which can be accepted as very desirable compressive strength level for concrete with the curing time of just one day. Three point flexural strength test results for the 1 day cured concrete with c-spec tailings and standard deviations for obtained data are also given in Table 2. Results obtained from the splitting tensile strength test and UCS test of cylindrical specimens (Fig. 8) are respectively given in Table 3 and Table 4. The shotcrete mix UCS was a bit higher than the cemented tailings UCS. Contrarily, higher flexural strength test results than those of the shotcrete mix specimens were obtained from the cemented-tailings. Results of the tests performed on the shotcrete mix with aggregate and one day curing time are given in Table 5.

4. Conclusions

The new concrete material design allows depositing extra underground tailings. Therefore, it is beneficial to use cemented tailings for the environmental management. As a result of the desliming mineral processing plant tailings by using hydrocyclones, appropriate workability were obtained from the slump tests applied on the mixes with high cement contents. However, unclassified tailings is not economic to have good workability, because its fine particle content causes to need high amount of chemical additive use (Cihangir 2011, Kesimal *et al*. 2004, Komurlu 2012, Yılmaz *et al*. 2003).

The cemented sulfide-rich tailings are not suggested to use for long term support purposes. Because short term strength of the barricade concrete is critical, the affect of sulphide-rich mill tailings causing a long term strength loss of concrete is negligible (Yumlu 2001, Komurlu *et al*. 2014, Ercikdi *et al*. 2013, Ercikdi 2009, Komurlu and Kesimal 2014).

The uniaxial compressive strength and indirect tensile strength tests (three point flexural strength test and Brazilian test) were applied on the cemented mine tailings (classified tailings including %29 sulfur (S), %12 quartz (SiO_2), and aluminium oxide (Al_2O_3), hematite (Fe_2O_3), calcium oxide (CaO) and manganese oxide (MgO) with considerable amounts). Desirable results were obtained from the specimens with one day curing time. The laboratory study results were favourable for use of the cemented tailings as concrete material of both flat and arched barricade bodies. From the fine particle content of tailings, it is expected to have significant advantage of good surface adhesion and less rebound problem in comparison with the shotcrete including aggregate of crushed rock. In addition, the new material with fine particle content is convenient to have good adherence with steel reinforcement and suitable for applying on the meshes with narrow apertures (Kolymbas 2005, Arıoğlu *et al*. 2008, Hoek 2006). From this study which comprises the laboratory tests for design of alternative concrete material with the mill tailings, it can be inferred that the cemented tailings deserves to be investigated with further studies performed on sprayed material and its applicability as a mine support with the short service life times.

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