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Co-Disposal of Coal Ash with Mine Tailings in Surface Paste Disposal Practices: A Gold Mining Case Study

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***Abstract*—**The present paper describes the study of paste tailings prepared in laboratory using gold tailings, produced in a Finnish gold mine with the incorporation of coal ash. Natural leaching tests were conducted with the original materials (tailings, fly and bottom ashes) and also with paste mixtures that were prepared with different percentages of tailings and ashes. After leaching, the solid wastes were physically and chemically characterized and the results were compared to those selected as blank – the unleached samples. The tailings and the coal ash, as well as the prepared mixtures, were characterized, in addition to the textural parameters, by the following measurements: grain size distribution, chemical composition and pH. Mixtures were also tested in order to characterize their mechanical behavior by measuring the flexural strength, the compressive strength and the consistency. The original tailing samples presented an alkaline pH because during their processing they were previously submitted to pressure oxidation with destruction of the sulfides. Therefore, it was not possible to ascertain the effect of the coal ashes in the acid mine drainage. However, it was possible to verify that the paste reactivity was affected mostly by the bottom ash and that the tailings blended with bottom ash present lower mechanical strength than when blended with a combination of fly and bottom ash. Surface paste disposal offer an attractive alternative to traditional methods in addition to the environmental benefits of incorporating large-volume wastes (e.g. bottom ash). However, a comprehensive characterization of the paste mixtures is crucial to optimize paste design in order to enhance engineer and environmental properties.

***Keywords*—**Coal ash, gold tailings, paste, surface disposal.

I. Introduction

Mining operations produce large quantities of wastes during the extraction and mineral processing stages. These mining wastes consist of ground rock and process effluents (tailings) which are, in many cases, disposed in stockpiles and tailings dams where the major safety and environmental risks are related either to the structural stability or to the releases of acid rock drainage. The management of these waste storage impoundments, generally known as waste storage facilities, presents significant environmental, safety and engineering challenges. The collapse of a storage waste facility usually implies environmental and socio-economic consequences, extremely difficult and costly to address through remedial measures and, above all, a significant loss of life. Significant accidents have occurred in the last 50 years involving waste storage facilities: Aberfan (Wales, 1966), Stava (Italy, 1985), Aznalcóllar (Spain, 1998), Baia Mare and Baia Borsa (Romania, 2000) and very recently in Brazil (Minas Gerais, 2015). Wastes from the mining industry have therefore to be properly managed to ensure, at least, a long-term stability and to prevent the generation or release of acid leachates [1], [2].

In the last decades, the development of alternative tailings management options, such as the use of paste fill technology as a surface tailings management method, have received much attention and gradually became a very attractive option to conventional tailings and mine waste management. The benefits of surface paste disposal cover a wide range of environmental and engineering issues. In addition, surface paste disposal method can be designed to manage co-disposal both with mining wastes and wastes or by-products from other industries such as coal ash. This, in particular, has the additional advantage of avoiding the disposal of coal ash, besides the potential to promote the neutralization of the acid mine drainage commonly generated in many mine tailings. The origin and the environmental impacts of acid mine drainage has been well documented in the literature [3]-[8].

The generic benefits from surface paste disposal come from: i) improved tailings geotechnical properties; ii) small amount of free water at the paste surface; iii) homogeneity of paste tailings (less particles segregation); iv) increased strength; v) acid neutralization potential and contaminants stabilization capability due to addition of alkaline binders [9]-[13].

Paste tailings generally consists of mine tailings and water, prepared from dilute slurries of tailings by dewatering using conventional thickening or filtering systems [13], [14]. It forms a high density non-segregating mixture containing 70-85% solids by total mass and enough fines (at least 15% less than 20 μm) to prevent settlement and particle segregation when transported for disposal. The preparation of paste can include the use of additives in order to enhance the beneficial properties of the paste. In particular, coal ash (fly ash, bottom ash or a combination of both) may be used as a binder.

Coal ash has cementitious properties as well as pozzolanic properties and is capable of reducing the acid potential of tailings due to the high calcium content [15]. Nevertheless, coal ash composition's is highly dependent upon the type of coal burned and the combustion process itself, but, in general, coal ash is mainly composed of oxides of silica, aluminum,

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iron, calcium, magnesium and sulfur. Fly ashes are fine-grained particles ranging from 1 to 150 microns in diameter while bottom ashes are coarser, ranging from approximately 0.1 to 50 mm in diameter [13].

A small amount of bottom ash may be used by other industries but the discarded part as well as the boiler slag are either landfilled or sluiced to storage lagoons. The great majority of the fly ash produced is effectively used in other industries such as construction-related and road applications. Also, the addition of fly ash to mining wastes has been studied as a technique to prevent acid mine drainage [16]-[18] as well as an attempt to improve engineering properties such as strength and stiffness in paste surface disposal [13], [19]-[22]. However, the usage of bottom ash or slag with the same purpose is not so well documented in the literature and these represent the major amount of coal combustion by-products that are mostly landfilled. In addition, the usage of by-products for environmental applications, which is driven by both economic and environmental considerations, contributes to the development of a sustainable strategy in wastes management [22], [23].

In the present study, the effectiveness of adding coal ash to mine tailings for its behavioral characteristics and its ability to make paste was evaluated. In this way, the co-disposal of mining tailings paste with coal ash was investigated as a sustainable disposal strategy.

II. Materials and Experimental Methods

A. Materials

The original materials used in this study were paste mining tailings and coal ash (fly ash and bottom ash). The paste tailings materials were collected from a gold mine, located in Finland. Currently, the tailings from the leaching process are disposed on surface ponds after neutralization.

The bottom ash was collected directly from the bottom of the furnace of a Portuguese thermal coal-fired power plant. The fly ash had its origin in the same coal-fired power plant but from the collecting filtering system. Usually, the bottom ash from this plant has no economic output and is disposed in the nearby landfill owned by the plant. On the contrary, most of the coal fly ash allows special properties and features which are very attractive to cement and concrete industry.

B. Experimental Methods

1. Preliminary Experimental Works

The tailings paste sample was previously disaggregated in order to represent the original tailings (OT) from the mining operations. As the bottom ash have a coarser particle size it is necessary to grind this material. The fraction above 0.425 mm was grind, first in a roll mil and then in a rings mill. The resulting material is identified as bottom ash (BA) in the next sections.

The experimental stage comprised a previous characterization of all materials for particle size, chemical composition, pH, density, moisture and porosity. All materials were dried to constant mass at 110 ± 5 ºC for a minimum period of 16 h.

The pH was determined in an aqueous solution by two different methods, with distilled water in a 1:1 solid-liquid ratio and with 0.01 M $CaCl_2$ in a 1:2 solid-liquid solution ratio [24].

Slump testing (slump vs. solids content) was carried out for tailings to determine the best solids content (wt % solids) to be adopted for the paste preparation (Table I). The slump test followed the procedures given in the ASTM C143 standard. After this, a series of slump test were performed to evaluate the consistency of the prepared mixtures.

TABLE I
Solids Content (wt % solids) in Tailings Slump Tests

Tailings	Test 1	Test 2	Test 3
Mass (g)	2000	2000	2000
Water (mL)	439	815	660
Wt % Solid	82	71	77

2. Paste Tailings and Coal Ash Mixtures

Four mixtures of mine tailings and coal ash were prepared with different percentages of tailings, fly ash and bottom ash. The paste was molded by adding tap water, according to a solids content of 77 % (best slump result). The composition of each mixture is presented in Table II.

TABLE II
Composition of the Prepared Mixtures

Materials	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Tailings (g)	1600	1800	1600	1800
Fly ash (g)	133	66	0	0
Bottom ash (g)	266	133	400	200

The chemical composition was determined using X-ray florescence spectrometry (XRF).

The original tailings and the prepared mixtures were tested for flexural strength (ASTM C348), compressive strength (ASTM C109) and consistency (ASTM C143) in order to study the behavior of the prepared paste tailings (with and without coal ash). To produce the specimens to be tested, the mixtures were cast into three-gang prism molds, each 40 x 40 x 160 according to ASTM C348. The flexural tests were carried out in duplicate, on a total of 10 prismatic specimens', from each one of the mixtures and from the paste prepared only with tailings for a solids percentage of 77 %. One point load was applied according to ASTM C348. The compressive strength tests were conducted using 20 specimens obtained after the flexural strength test at a loading speed of 1 mm/min. The average values obtained for the flexural strength and the average values obtained for compressive strength represent the value of the respective mechanical test.

The slump tests provide a way to characterize the material's consistency which is important to relate to its transportability. The slump test method is widely standardized throughout the world (ASTM C143 standard in the United States and EN 12350-2 standard in Europe). In practice, the slump height and the spreading of the material are determined. The slump height is given by the difference between the initial and the final heights of the paste after the truncated cone is removed. A cone of 150 mm was used in the performed tests.

Natural leaching tests were conducted on the original materials (tailings, fly ash and bottom ash) as well as on the prepared mixtures. The leaching process was simulated with distilled water in batch cells with a constant stirring for a maximum period of 24 hours. The tests were stopped at each 1, 3, 12 and 24 h to measure the pH, dissolved oxygen, salinity, total dissolved solids, conductivity and temperature. The leached solid samples were characterized and the results were compared to those selected as blank – the unleached samples. The standard method DIN 38414-S4 was followed to set up the experimental phase in the laboratory.

The acid generation capacity was also tested through one of the possible acid generation prediction methods: the acid/base account (ABA) method. The procedure involves a laboratory static test that compares the maximum acid production potential (AP) of a sample with its maximum neutralization potential (NP). The acid-base accounting method was conducted only on the original materials (tailings and ashes).

III. Results and Discussion

A. Preliminary Characterization of the Materials

1. Original Tailings and Mixtures Solution's pH

The results for the pH solutions of the original materials and the prepared mixtures, obtained by the two methods used, is presented in Fig. 1. The difference of the results between the two methods can be neglected.

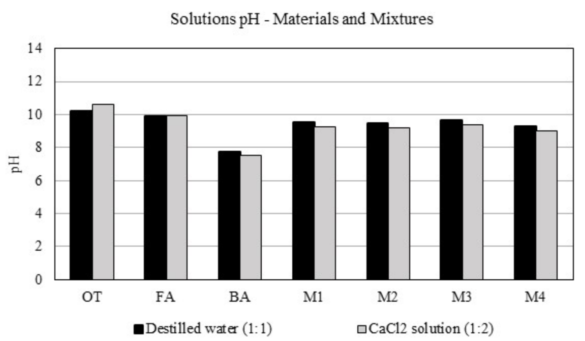

Fig. 1 Solutions pH of original materials and prepared mixtures

The pH of the original materials (OT, FA and BA) ranges between neutral and alkaline values. In particular, the original tailings samples present an alkaline pH related to the fact that during the processing stage these were previously submitted to pressure oxidation with destruction of the sulfides.

For the prepared mixtures it was possible to observe that the addition of coal ashes allowed a more stable pH within the range of pH's values of the original tailings and bottom ash.

2. Density, Moisture and Porosity

For coal ashes samples the bulk density ranged from 0.935 to 1.111 g/cm^3, the particles density ranged from 0.960 to 1.327 g/cm^3, the (gravimetric) moisture content varied from 2.74 to 4.17% and the porosity ranged from 2.60% (FA) to 18.52% (BA).

For the OT the bulk density was 1.014 g/cm^3, the particles density was 0.852 g/cm^3, the (gravimetric) moisture content was 37.61% and the porosity was 13.51%.

Concerning the prepared mixtures (M1, M2, M3 and M4), the addition of coal ashes to the original tailings increased the porosity of the mixtures (range between 14.67 and 22.00%) but decreased the moisture content (range between 27.20 and 31.60%) while the density remained approximately the same.

3. Particle Size Distribution

The particle size distribution of both the materials (OT, FA, BA) and the obtained mixtures were determined. The results are presented in Figs. 2 and 3, respectively.

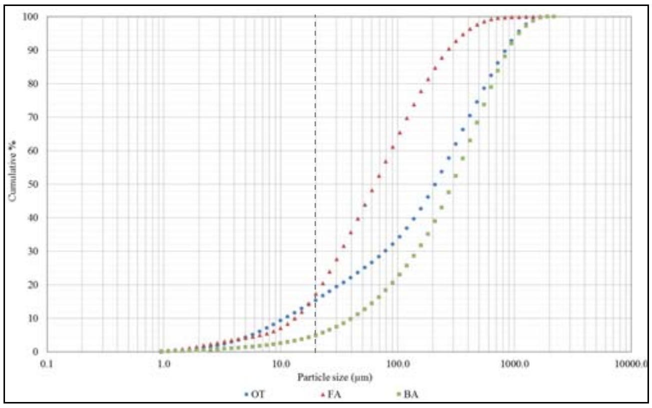

Fig. 2 Particle size distribution of the materials

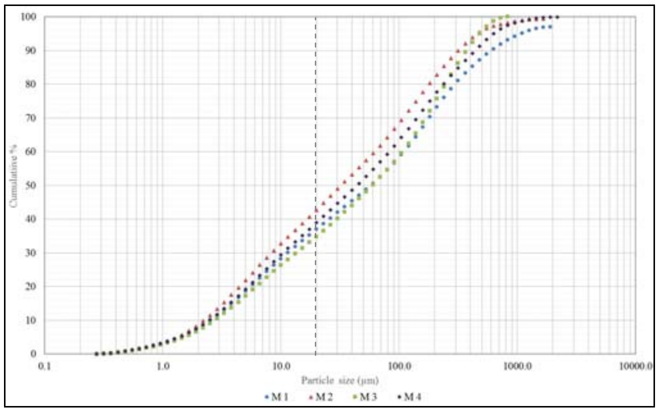

Fig. 3 Particle size distribution of the prepared mixtures

In what concerns to the particle size distribution, both the OT and FA satisfy the minimum fine particle content for a stable paste production. However, BA alone does not accomplish the required minimum.

For the prepared mixtures, the particle size distribution is similar for all ash percentages and all mixtures satisfy the minimum fine particle content for paste production. The mixture of fly and bottom ash showed good results but the mixture using only bottom ash has a particle size distribution with higher percentage in the coarse size range. It is known that finer particles are more reactive than coarser particles which are generally rich in unburned carbon [25]-[27].

4. Elemental Composition

The chemical element composition for tailings, fly ash and bottom ash is presented in Fig. 4.

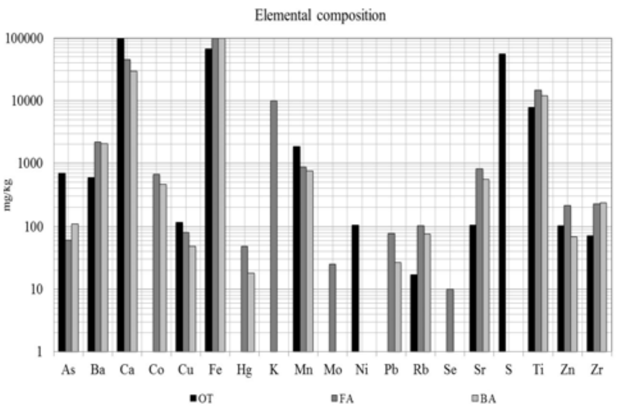

Fig. 4 Chemical element composition of the studied materials

The tailings primarily consist of Ca and Fe but they also contain significant concentrations of heavy metals such as Ni, Ti, Mn, and Zn as well as S. The high concentration of Ca is a result of both the carbonate mineralization present in the tailings stream and liming, which is added to the acidic water and to the sulphur flotation tailings before disposal onto the tailing facility [28]. The high concentrations of S result from the sulphide mineral weathering (oxidation) process which may lead to the generation of AMD.

Fly and bottom ashes have similar elemental composition with the exceptions for K, Mo, and Se once these elements are present only in FA. The major composition of both type of ashes are Ca and Fe containing also significant concentrations of heavy metals such as Co, Hg and Pb but not present in the tailings. Therefore, the presence of Co, Hg and Pb should be looked into when considering to incorporate the coal ashes into the tailings. The presence of Ca provides a beneficial effect to control and mitigate the generation of AMD from the tailings as well as to enhance the stability of tailings.

The element composition of the prepared mixtures is presented in Fig. 5.

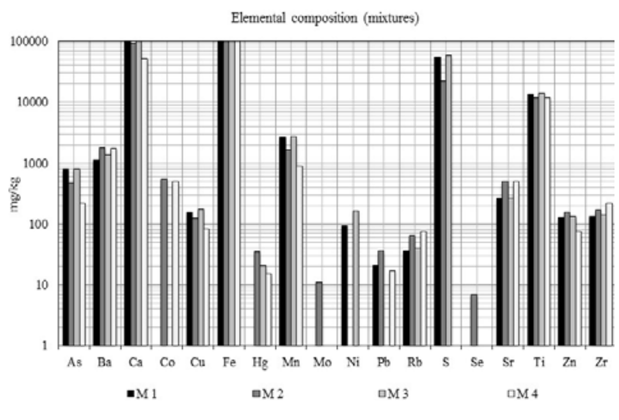

Fig. 5 Chemical element composition of the prepared mixtures

In both cases (materials and mixtures) there are common elements, as expected, in particular for the elements with higher concentration such as Ca, Fe and Ti, and as well as for other elements such as As, Ba, Cu, Mn, Rb, Sr, Zn and Zr. However, there are still some remarks that should be pointed out. Some elements are present only in the mixture M2 (Mo and Se) although they make part of the fly ash composition and therefore they should also be present in the mixture M1. The mixtures M2 and M4 are the only ones with Co, although this element is present in both fly and bottom ash and therefore it should be present in all mixtures. The same is verified for Hg which was not detected in mixture M1, for S which concentration is very high in the tailings but was not detected in mixture M4 and for Ni present in the tailings but not in the mixtures M1 and M4.

5. Natural Leaching Tests

The natural leaching tests were carried out as short-term extraction tests (24-hour batch extraction tests using distilled water). These tests provide information on the short term metal leaching potential although in natural conditions (under the influence of atmospheric conditions and the presence of microorganisms) there are several physical, chemical and biological processes that are not possible to reproduce in batch laboratory tests.

The pH of the leachate solution as a function of weathering (leaching) time (hours) is presented in Fig. 6.

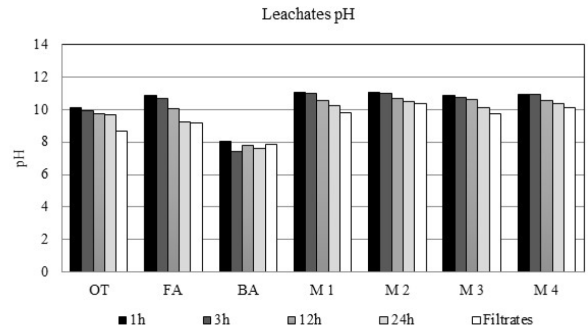

Fig. 6 Variation of pH during the natural leaching tests

Based on the obtained results it is possible to observe a decrease on pH values for all materials and mixtures within the alkalinity range, with the exception of the bottom ashes, which are slightly neutral presenting the lowest pH values (7.4-8.0).

The pH of the effluent from fly ash natural leaching test is generally higher than that of the control test, containing mine tailings only, indicating that addition of fly ash has contributed with some long-term alkalinity to the system.

The measured values for salinity during the leaching test are presented in Fig. 7.

The dynamics of salinity in tailings is very important in case of future revegetation of the disposed tailings. High salinity values are one of major constrains to revegetation in many tailings impoundments [29]-[31]. In this study, while the salinity increases in the leachate of the OT, the leachates' mixtures show a continuous decrease over time. These behaviors should be analyzed in a longer term.

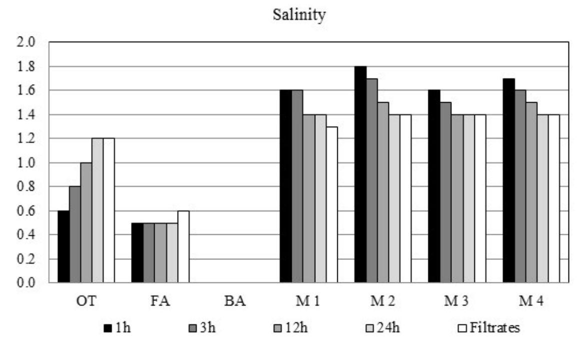

Fig. 7 Variation of salinity during the natural leaching tests

The results obtained for electrical conductivity during the leaching tests are presented in Fig. 8.

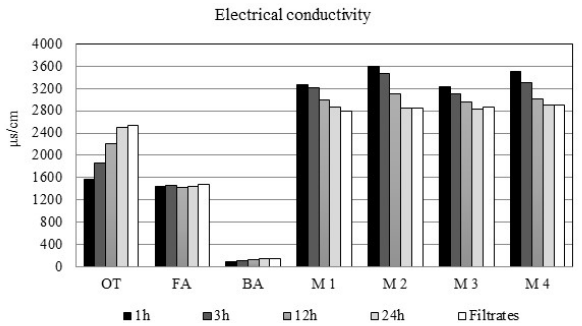

Fig. 8 Variation of electrical conductivity during the leaching tests

In the early hours of the leaching test, both electrical conductivity and salinity from all samples show a similar behavior. For the mixtures, the values decreased over time and it is expected that these values stabilize after a certain period of time. This is probably due to the dissolution of readily soluble salts present in the coal ashes and tailings materials.

For the OT, the behavior was the reverse, with the increase of the EC over the considered period. The slight decrease in pH as well as the slight increase in electrical conductivity of the tailings materials could indicate a tailings oxidation activity.

6. Acid Generation Capacity

The acid-base accounting method was conducted on the original materials (OT, BA and FA) although these presented a pH within the alkaline range and therefore with no potential for acid generation.

The resulting pH from the acid generation tests (ABA method) is presented in Table III. A decrease in the pH was observed for all materials tested, in particular for BA (from 7.77 to 5.04), although not enough to suggest having a potential for acid generation. Nevertheless, this should be looked out when selecting the proportion of coal ashes to be added to the tailings. Further tests will be needed to characterize the potential for acid generation of the mixtures as a function of the amount of FA and BA addition.

TABLE III
RESULTING PH FROM THE ACID GENERATION TEST (ABA METHOD)

Materials	pH
Original Tailings	8.75
Fly Ash	8.45
Bottom Ash	5.04

7. Mechanical Tests

The results of the mechanical strength tests for the original tailings as well as for the prepared mixtures are presented in Fig. 9. Although both tests were performed, flexural and compressive, the results of concern refer to the unconfined compressive test.

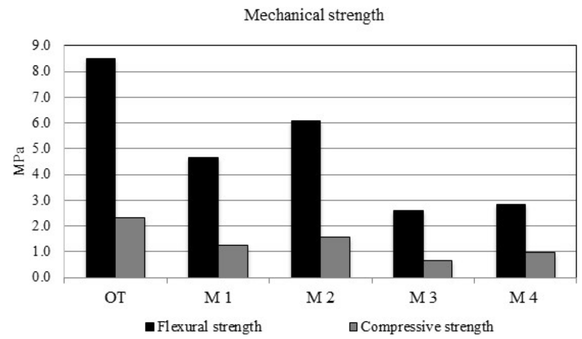

Fig. 9 Flexural and compressive strength of the original tailings and the prepared mixtures

The compressive strength varies between 0.7 and 2.3 MPa, for M3 and the original tailings, respectively. Also, the compressive strength of the original tailings decreased with an increase in the replacement of coal ash. The mixtures without fly ash incorporated (M3 and M4) presented the lowest strength values. Also, within the mixtures, an incorporation of a blend of fly and bottom ash, up to a percentage of 10 % (M2), seems to be the best option in what concerns the mechanical strength.

The compressive strength is influenced by several factors but the most relevant include the particle size distribution, the addition of binders and, in particular, the curing time [32]-[34].

8. Slump Tests

The results of the slump test are presented in Fig. 10 for the original tailings and for the prepared mixtures, for a solids percentage of 77%.

The results show that there are considerable differences between the original tailings and the prepared mixtures, with slumps ranging from 10 to 49 mm (OT and M3, respectively).

Concerning the mixtures, the lower consistency was obtained for mixture M3 (80% OT + 20% BA) and the highest consistency was obtained for mixture M4 (90% OT + 10% BA). These results can be explained by the coarser particle size distribution of BA making up these mixtures; slump vary considerably with particle size and size distribution where the presence of coarser particles will result in lower consistency (higher slump).

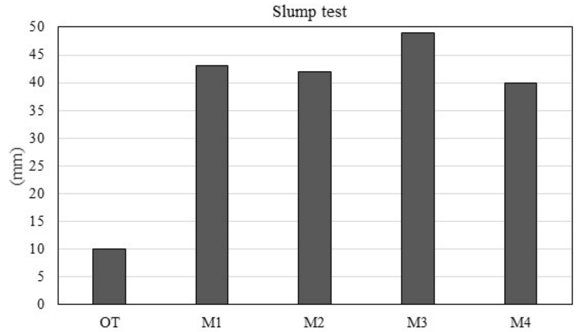

Fig. 10 Slump test results for the original tailings and for mixtures

Between mixtures M1 and M2 there was no significant variation although being composed by different percentages of OT, FA and BA.

Comparing the results of mixtures M3 and M4, we can say that the incorporation of BA affects the consistency of the mixture. However, the incorporation of a blend of BA and FA into the OT (M1 and M2) allows to obtain a consistency closer to M4 mixture's consistency.

The slump test provides a way of characterizing a material's consistency that can be related to transportability. A low-slump material will flow less easily than a high-slump material even if both are batched from the same material.

There has been also an attempt to accurately evaluate the yield stress of mineral suspensions by modifying the slump test as a way of simplifying yield stress measurements [35]-[37]. However, this relation will be highly dependent on the density.

9. Final Considerations

In general, the addition of coal ash to the studied tailings resulted in a more stable final product in what concerns to pH, electrical conductivity and salinity.

The potential for acid generation of the mixtures, as a function of FA and BA addition to the tailings, will need to be studied in order to interpret the pH variation and determine the fractional composition of fly and bottom ashes that still allow to obtain a non-acid-generating mixture.

Paste's mechanical strength was lower when blended only with bottom ash than when blended with a combination of fly and bottom ash. On the contrary, a better slump was obtained for a mixture with the incorporation of bottom ash alone (M4).

Although relevant results were obtained with the mixtures prepared with bottom ashes, not only at operational level but also with economic and environmental benefits (every ton of bottom ash used beneficially is one not disposed in a landfill) a higher percentage of solids, between 77% and 82%, should be tested and the mixtures studied through all the process. The incorporation of bottom ash with the minimum need to reduce particle size should also be tested.

IV. Conclusion

Mining waste management and in particular, traditional tailings disposal methods, will need to move towards to more sustainable disposal methods as the one promising surface paste tailings disposal. The tailings dewatering allows thereby recovering water, reducing the space required for waste management and, more importantly, reducing the risk associated with conventional tailings storage facilities. Also, the possibility of incorporating large-volume wastes of other industries represents a powerful financial, operational, environmental and regulatory incentive for using paste technology. Nevertheless, the successful use of paste technology as an alternative disposal method will depend on the complete process which includes thickening, pumping and disposal designs. Each phase of the process has critical parameters that must be integrated to provide a successful installation. Therefore, the implementation and optimization of the paste disposal involves the determination of three main streams: i) the optimum solids percentage required for the management of the tailings storage area, ii) the optimum conditions for pipeline transport, and iii) the feasibility of dewatering the slurry to the required solids percentage.

The technical methods outlined in this study provide the basis for a comprehensive characterization of the paste tailings production which is essential to all segments of the process. These should be integrated when evaluating the paste production to meet the necessary (rheological) requirements at the "end of the pipe".

Acknowledgment

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