BENEFICIAL REUSE OF SULPHIDIC MINE TAILINGS AS FINE SAND REPLACEMENT IN COMPOSITE MORTAR AND CONCRETE MIX PROPORTIONING FOR UNDERGROUND MINE APPLICATIONS

Tikou Belem[1], Bruno Bussière[1], Yasser Chtaini[2], Kumar Sandra Rohit[3]
[1]Research Institute in Mining and Environment, Université du Québec en Abitibi-Témiscamingue, Canada;
[2]Department of Civil, Geological and Mining Engineering, Polytechnique, Montreal, Quebec, Canada;
[3]Department of Mining Engineering, Indian Institute of Technology, Kharagpur, India;
E-mail corresponding author: tikou.belem@uqat.ca

ABSTRACT

This paper assesses the possibility of re-using mine tailings as raw material for composite cementitious materials for temporary underground mine workings. More specifically, this paper presents the results of investigation of the compressive strength of composite mixtures (concrete, mortar and mortar-like paste backfill) containing sulphidic mine tailings as raw fine aggregate. For this purpose, ten different mixtures were formulated and prepared using two types of cement: the sulphate-resistant Portland cement (type HS) and a blend of 50% general use Portland cement (GU) and 50% HS cement. These formulations include conventional concrete (control mixture), composite concrete (sans is replaced by sulphidic tailings), conventional mortar (control mixture), composite mortar (sand is replaced by sulphidic tailings), and mortar-like cemented paste backfill. All mixtures were prepared following the conventional formulation scheme of concrete and mortar. All mixtures had the same ratio w/c = 0.5 and a slump of about 20 cm. The results show that the mortar-like cemented paste backfill compressive strength (UCS) can reach 5 MPa after 28 days of curing time. Also, the UCS of the composite concrete is half the UCS of control concrete, while the UCS of the composite mortar is close to the UCS of control mortar.

Keywords: Mine tailings, Concrete, Mortar, Composite concrete, Composite mortar, Paste backfill

INTRODUCTION

For countries rich in mineral resources, the mining industry generally contributes to the economic development of these countries. However, despite this positive impact on economic force, mines generate solid and liquid wastes which may affect the surrounding environment. Recently, a proactive sustainable mining policy was implemented throughout Canada. This policy has two main objectives [1]: *i*) to limit the impacts of mining activity on the environment, and *ii*) to rehabilitate orphaned/abandoned mine sites and ensure they do not generate pollution.

Fig. 1 presents a schematic diagram illustrating the different relationships in mine waste management (volume reduction and pollution control). In recent decades, numerous research teams around the world are working on the research topic of "integrated management of mine waste", in particular, on the sulphide mine tailings management [2]. The focus of this paper is integral part of the objective *i*) of the proactive sustainable mining policy and includes two approaches limiting mining impacts on the environment through [3]:

- Underground backfilling using part of the tailings (a proportion not exceeding 50% of total tailings produced) coupled with storage of the remaining tailings in impoundments;
- Environmental desulphurization of pyrite within sulphide-rich tailings coupled with underground backfilling (harmful and reactive parts) and surface storage in tailings impoundments (non-reactive part).

Environmental desulphurization technology is still new and thus has not yet gained popularity. The most standard approach is therefore the coupling between underground backfilling and surface storage. Even if underground backfilling has many advantages especially in terms of preserving the environment and ensuring ground support, a portion of tailings (~50%) is still in excess and must be managed properly (Fig. 2).

One alternative has been recently proposed which consists of reusing mine tailings in the production of shotcrete as ground support [5]. This approach would reduce by 10 to 15% the amount of tailings to be sent to tailings impoundments. To further reduce the volume of tailings, alternative techniques involving further solid waste reutilization are encouraged.

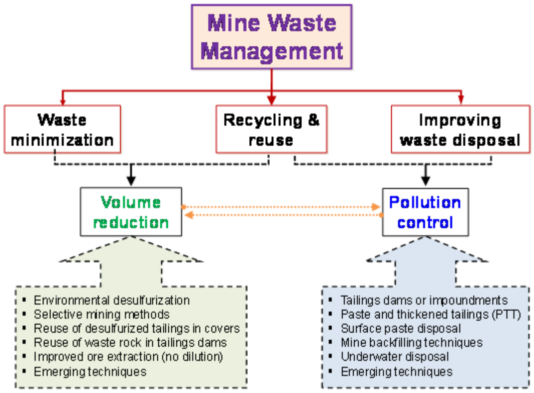

Fig. 1 Schematic diagram prioritizing aspects related to the reduction of volume of mine waste (adapted from [4])

Fig. 2 Illustration of surface and underground mine waste disposal

The main objective of this paper is to assess the possibility of replacing all or part of the aggregates (sand and gravel) in concrete and mortars with sulphide-rich mine tailings. Concrete is a mixture of cement, sand (fine aggregate), small stone or gravel (coarse aggregate) and water while mortar is a mixture of cement, sand (fine aggregate) and water. More specifically, this paper is assessing the compressive strength of different composite mixtures (normal concrete, composite concrete, normal mortar, composite mortar and mortar-like paste backfill).

MATERIAL AND METHODS

In this paper the following assumptions are considered: *i*) although the grain size distribution (GSD) of tailings is similar to that of silt, it is assumed that the sand can be replaced by the tailings, *ii*) the compressive strength of composite mixtures (concrete, mortar and mortar-like paste backfill) are expected to be lower than that of conventional mixtures because of the sulphidic mine tailings reactivity and its pore water geochemistry.

Materials

The ingredients in the composite mix proportioning are: sand, gravel, sulphidic mine tailings, Portland cement and water. The tailings were sampled from the LaRonde mine, in Quebec.

Sand and gravel

The grain size gradation for the sand (specific gravity G_s = 2.64) and gravel (specific gravity G_s = 2.65) used was 0/5 mm for the coarse sand and 5/25 mm for the gravel.

Sulphidic mine tailings sample

The tailings used in this paper were sampled from the LaRonde mine backfill plant. This mine is Agnico Eagle's flagship mine, and it is located 56 km West of Val D'Or in the Abitibi region of northwestern Quebec. LaRonde is one of the largest gold mining operations in North America. The tailings were first de-cyanided and dewatered using a thickener followed by disc filter systems to get tailings cake with high solid mass content. The initial water content of the tailings sample was 24.4% which correspond to solid mass concentration of 80.4%. The GSD of the tailings sample was determined using a Malvern Mastersizer S2000® laser particle analyzer. Fig. 3 presents the GSD curves of the tailings.

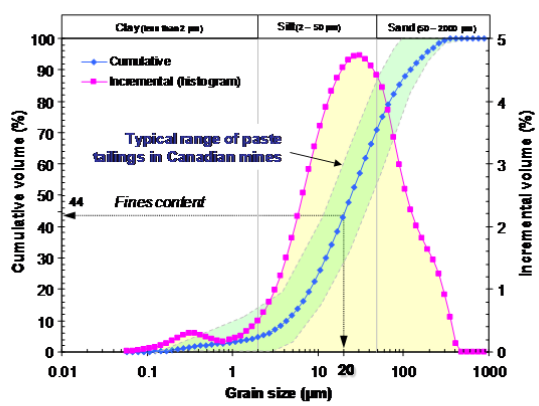

Fig. 3 Grain size distribution of LaRonde sulphidic mine tailings

From the GSD curves (Fig. 3), approximately 44% of the tailings sample is finer than 20 µm (ultrafine), with only 4.7% of clay-sized particles (< 2 µm). Most of the grain size falls into medium to fine sand and silt-sized grains (specific gravity G_s = 3.72). The coefficients of uniformity C_U (= D_{60}/D_{10}) and curvature C_C (= $D_{30}^2/[D_{60}*D_{10}]$) are 7.9 and 1, respectively (classified as ML).

Type of cement and mixing water used

Based on assumption *ii*) the selected cement is a blend of 50% general use Portland cement type GU and 50% sulphate-resistant Portland cement type HS (50GU/50HS). The mixing water was municipal tap water was used for the mixtures preparation.

METHODS

In addition to the composite mixtures, conventional concrete and mortar mixtures will be prepared as control mixtures for comparison purposes. Also, it was decided to prepare cemented paste backfill based on conventional mortar mix proportioning (mortar-like paste backfill). Table 1 summarizes the 5 mixtures tested in this paper. For all mixtures, the water-to-cement ratio *w/c* was fixed to 0.5. Table 2 shows the aggregate (sand, gravel and tailings) combination used in the different mix proportioning.

Table 1 Control and composite mixtures

Control mixtures	Composite mixtures
Concrete (C)	Composite concrete (CC)
Mortar (M)	Composite mortar (CM)
	Mortar-like paste backfill (MPB)

Table 2 Aggregate blending in the mixtures

Mixture	Sand	Gravel	Tailings
Normal concrete (C)	X	X	
Normal mortar (M)	X		
Composite concrete (CC)		X	X
Composite mortar (CM)	X		X
Mortar-like backfill (MPB)			X

Mix proportioning

To have better control of *w/c* ratio for composite mixtures, the tailings were first oven-dried at 50°C for 2 days even though it is obvious that on a mine site it would be easier to get filtered tailings cake rather than dried tailings. The mixture ingredients are proportioned by mass for 1 m^3 of concrete or mortar (more accurate than by volume due to tailings GSD and density). The workability of the mixtures was determined through standard slump measurements (the texture must be similar to that of conventional concrete and mortar). The average slump was in the range 15-20 cm. Table 3 presents the final mass composition of ingredient in the mixtures prepared.

Table 3 Mass of ingredient in the mixtures (in kg)

Mix	Sand	Gravel	Tailings	Water	Cement	w/c
C	35	48	0	6	12	0.5
M	66*	0	0	11	23	0.5
CC	0	26	26	16	32	0.5
CM	24**	0	19	19	38	0.5
MPB	0	0	36	21	43	0.5

**This mass includes 33 kg of fine sand and 33 kg of coarse sand; **this mass corresponds to coarse sand alone.*

Mixture preparation and molds pouring

The mixtures were prepared using small size conventional concrete-mixer. The ingredients are successively added in the mixer and the mixing take place until obtaining workable mix (after approximately 12 minutes). The order of addition of the ingredients is as follows: gravel (1 min.) + sand (1 min.) + cement (2 min.) + water (8 min.) Once the mixtures were prepared, concrete, mortar or MPB are poured into cylindrical rigid plastic molds of 100 mm diameter and 200 mm height (Fig. 4). Eight molds were prepared for each mixture of concrete (control or composite) and of mortar (control or composite), while twelve molds were prepared for the mortar-like paste backfill; that is to say a total of 44 specimens.

Fig. 4 Photos showing cast plastic molds

Mixture preparation and molds pouring

Twenty four hours after preparation all the specimens were stored in a humidity chamber (Fig. 5). The specimens were kept in the humidity chamber and continuously sprinkled by gentle water jets. The selected curing times were 3, 7, 14 and 28 days.

Unconfined compression tests

The apparatus used for the uniaxial compression tests is a high capacity universal mechanical press TECNOTEST having a maximum loading capacity of 1,000 kN (Fig. 6). This compression machine is usually used to measure the uniaxial or unconfined compressive strength (UCS) of rock and concrete samples. It is a semi-automatic compression machine which increases the load as per the desired rate depending upon the quality and strength of the specimen. The machine also automatically stops increasing the load when the sample reaches its breaking point.

Fig. 5 Specimens curing in the humidity chamber

Fig. 6 Compression test machine used

Fig. 7 Photo showing the capping process prior to UCS testing

After each curing time (3, 7, 14 and 28 days), specimens are taken from the humidity chamber six hours before UCS testing. Each test sample is removed from the mold and their two ends capped with a molten sulphur capping compound to ensure a uniform load distribution during the UCS test (Fig. 7).

RESULTS

Preliminary observations

Fig. 8 shows a comparison of control concrete, mortar-like paste backfill and composite mortar specimens color after 14 days of curing. It is observed that the color of mortar-like paste backfill specimen is brownish orange (Fig. 8a). This is expected to be originated from surface oxidation of the sulphides present in the LaRonde mine tailings. The same observation was made from composite mortar and concrete specimens, but the oxidation was less pronounced. This figure illustrates the evidence that the color of mortar-like paste backfill (Figs. 8a, c) is much more brownish orange than that of composite mortar (Fig. 8d). It can be also seen that orange color was observed neither on the outer surface of control concrete (Fig. 8b) nor on the surface of control mortar specimens (as there were no sulphides present in these mixtures) not shown.

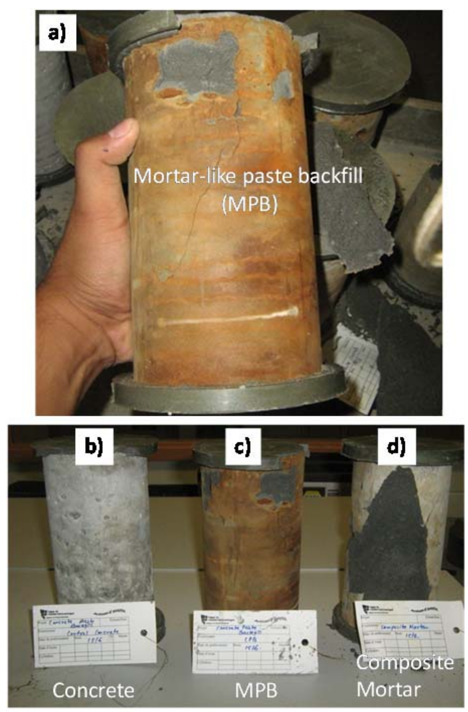

Fig. 8 Photos showing the difference in specimen color between: a) mortar-like paste backfill, b) control concrete, c) mortar-like CPB and d) composite mortar

Fig. 9 shows a typical photo of a broken composite concrete specimen after curing for 14 days. The failure pattern and texture of the matrix are easily observed.

Fig. 9 Photos showing the breaking pattern of a composite concrete specimen after 14 days of curing

Compressive strength results

Table 4 summarizes the UCS data obtained from the 44 specimens. Each UCS value for the concrete and mortar (control or composite) is an average value from duplicate test samples, while for the mortar-like paste backfill the average value is obtained from triplicate test samples.

Table 4 Compressive strength (UCS) results

Mixture	Curing time (day)	UCS (MPa)
Control concrete (C)		
C	3	16
C	7	27
C	14	34
C	28	36
Control mortar (M)		
M	3	18
M	7	23
M	14	30
M	28	31
Composite concrete (CC)		
CC	3	13
CC	7	17
CC	14	24
CC	28	26
Composite mortar (CM)		
CM	3	6
CM	7	19
CM	14	28
CM	28	26
Mortar-like paste backfill (w/c = 0.5) - MPB		
MPB1	3	6
MPB1	7	19
MPB1	14	19
MPB1	28	21

Fig. 10 shows the curves of the UCS as a function of curing time for all mixtures. From this figure it can be seen that all UCS curves are relatively close to each other. The overall trend is consistent with what is usually observed in concrete literature [6]. The maximum compressive strength reached about 36 MPa for the control concrete (C) and about 31 MPa for the control mortar (M). These compressive strengths fall well within the range defined in the concrete literature which is between 25 and 50 MPa [6, 7].

From Fig. 10 it can be observed that the control concrete has higher compressive strength than composite concrete (CC). Indeed, the maximum UCS value reached (at 28 days of curing) is 36 MPa for the control concrete and 26 MPa for the composite concrete (a difference of 28%). The compressive strength of control mortar is higher than that of composite mortar (CM) which starts to slightly drop after 28 days of curing. The maximum UCS value (at 28 days of curing) is 31 MPa for the control mortar and 28 MPa (reached at 14 days of curing) for the composite concrete (a difference of 10%). It can also be concluded that:

$UCS_{concrete} > UCS_{mortar} > UCS_{composite\text{-}mortar} > UCS_{compo\text{-}site\text{-}concrete} > UCS_{mortar\text{-}like\ pastefill}$.

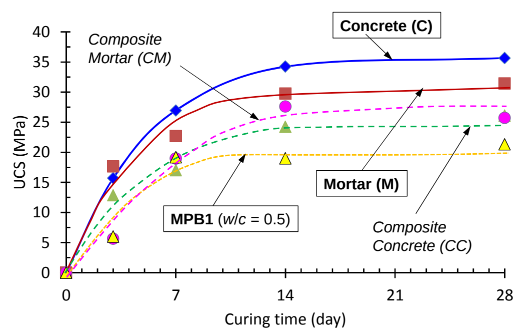

Fig. 10 Variation in compressive strength with curing time for all mixtures

In addition, Fig. 10 shows that the compressive strength of the composite concrete is higher than that of the composite mortar after 3 days of curing. At 7 days, however, the UCS of the composite mortar (28 MPa) is slightly higher than the composite concrete (24 MPa). But at 28 days, the compressive strength of the composite concrete and mortar becomes similar (26 MPa). At 3 and 7 days of curing the composite mortar and mortar-like backfill (MPB1) exhibit similar compressive strength. Beyond these curing times, the UCS of CM increases to about 28 MPa while remains almost constant for the MPB1. At 28 days of curing the UCS is 26 MPa for the CM and 21 MPa for the MPB1.

DISCUSSION

Effect of mix proportioning on MPB strength

Based on Table 3 data, It is clear that the MPB1 has been over-proportioned in the amount of cement although the *w/c* was maintained at 0.5 (M_{cement} > $M_{tailings}$). As it seemed that this mass of cement (42.79 kg) is neither realistic nor cost effective and for comparison purposes, a second mortar-like paste backfill (MPB2) mixture was prepared with higher water-to-cement ratio *w/c* = 1.67 and reduced mass of cement (8.9 kg) and using the LaRonde mine tailings at their initial water content of 24.4%. Note that MPB2 mixture had the same workability than the other previous mixtures (slump in the range 15-20 cm).

Fig. 11 presents the variation in the UCS of the two MPB mixtures (*w/c* = 0.5 and 1.67) with curing time. It can be seen that reducing the mass of cement by about 86% (from 42.72 kg to 8.9 kg) and tripling the *w/c* ratio (from 0.5 to 1.67) lead to a reduction of UCS of about 81% (from 21 MPa to 4 MPa). These results suggest that the constraints of *w/c* = 0.5 along with a constant slump of 20 cm was not sufficient for the composite mixture. The texture of all composites concrete and mortar were similar to those of conventional concrete and mortar.

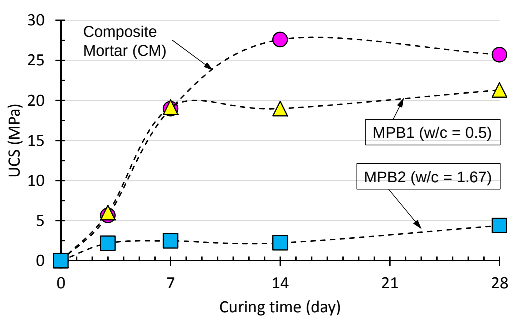

Fig. 11 Variation in compressive strength of the two mortar-like paste backfills with curing time

Effectiveness of the mix proportioning

The comparison of cement proportion in the composite mixtures and the conventional concrete and mortar mixtures can be done through the calculation of cement content by dry mass of the aggregate $B_w(\%)$, given by the following relation:

$$B_w(\%) = \frac{100 \times M_{cement}}{M_{sand} + M_{tailings} + M_{gravel}} \qquad (1)$$

In terms of cement content by dry mass of aggregate $B_w(\%)$, it can be seen that:

- The difference between the control mortar (M) and concrete (C) mixtures was only ±5%. This indicates the composite mixture proportioning is similar to the conventional mixture;
- The composite concrete (CC) cement content was over-proportioned by 43% (almost twice). This could explain why the UCS was higher and close to that of M;
- Composite mortar (CM) cement content was over-proportioned by 61%. This may explain why the UCS of CM was higher and close to that of M and CM;
- The mortar-like paste backfill (MPB1, *w/c* = 0.5) cement content was highly over-proportioned by 91%. This is why the UCS is higher and close to that of CC and CM;
- The mortar-like paste backfill (MPB2, *w/c* = 1.67) cement content was under-proportioned by 12%.

So, even if the *w/c* ratio was kept constant for the first 5 batches, the fact remains that the proportion of cement in the composite mixtures was overestimated. Although the resultant UCS is higher, it appears that the proportioning was not effective. If this proportioning was selected for an *in situ* preparation, one would expect that these mixtures should produce concrete and mortar with acceptable strength and durability. However, further study is required to assess options for reducing the amount of cement in composite mixtures.

Effect of cement content on the strength of mixtures

To see the effect of under/over dosage of cement in the concrete and mortar mixtures, all the UCS evolution curves were plotted together as a function of curing time as shown in Fig. 12. To eliminate the direct effect of cement under/over proportioning, the UCS data in Fig. 12 are normalized (UCS_n = MPa/% of cement) by the cement content by dry mass of aggregate $B_w(\%)$: $UCS_n = UCS/B_w(\%)$.

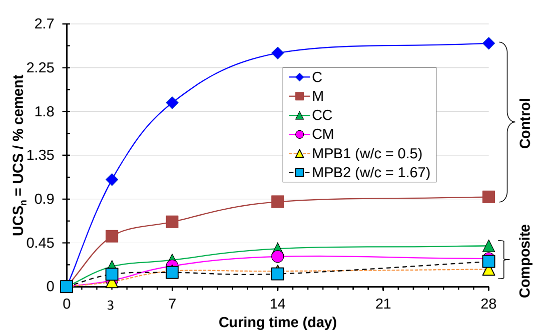

Fig. 12 Variation in compressive strength of the two mortar-like paste backfills with curing time

From this figure, one can now see a clear difference between the controls concrete (C) and mortar (M) and the composite mixtures (CC, CM and MPB). The evolution curves of UCS_n for composite mixtures are grouped together. There is also a large gap between UCS_n of control concrete and control mortar (C and M) which is 63% at 28 days of curing. After the same curing time, the difference between the UCS_n is 55% for the control mortar and composite concrete (M and CC), 31% for composite concrete and composite mortar (CC and CM), and 38% for the composite mortar and mortar-like paste backfill (CM and MPB). From Fig. 12 it can be also derived that:

$$UCS_n(C) > UCS_n(M) > UCS_n(CC) > UCS_n(CM) > UCS_n(MPB),$$

and:

$$B_{w(\%)}(C) < B_{w(\%)}(M) < B_{w(\%)}(CC) < B_{w(\%)}(CM) < B_{w(\%)}(MPB).$$

As can be seen, this trend clearly follows the cement dosage in the mixtures. This also confirm that the quantity and size distribution of aggregates play a significant role in terms of mechanical strength development.

CONCLUDING REMARKS

This preliminary study has shown that it was possible to make composite concrete (CC), mortar (CM) and mortar-like paste backfill (MPB) containing sulphide tailings. The uniaxial or unconfined compressive strengths (UCS) obtained are promising but it should be noted that the cement was over-proportioned even if the *w/c* ratio was kept constant and equal to 0.5. It was also ensured that all the composite mixtures exhibit similar slump (approximately in the range 15-20 cm) and texture. The main concluding remarks are:

- $UCS_{CM} > UCS_{CC} > UCS_{MPB}$;
- $\%Cement_{(CC)} < \%Cement_{(CM)} < \%Cement_{(MPB)}$;
- The maximum UCS values were 36 MPa for control concrete, 31 MPa for control mortar, 26 MPa for composite concrete (coarse sand replaced by sulphidic tailings), 28 MPa for composite mortar (fine sand replaced by sulphide-rich tailings), 21 MPa for mortar-like paste backfill with w/c = 0.5 (all sand replaced by sulphide-rich tailings), and 4 MPa for mortar-like paste backfill with w/c = 1.67;
- When compared with control samples, replacing the sand by tailings reduces the resultant compressive strength.

In future work, it would be interesting to consider more constraints such as varying w/c and slump, cement content by dry mass of aggregate, volumetric proportioning of the sulphidic tailings, assessment of two types of Portland cement. Also, the effect the tailings grain size distribution must be considered.

ACKNOWLEDGEMENTS

This research was financially supported through NSERC Discovery Grant Program and the Research Institute in Mining and the Environment. The authors gratefully acknowledge their support. The authors would also like to thank our mining partner, Agnico Eagle (LaRonde Division) for their collaboration in the completion of this work. We would also like to acknowledge Mr Yvan Poirier (URSTM lab technician) for his help and arrangement of the materials required for this study. We are also gratefully thankful to Mr Pierre-Alain Jacques (Civil Engineering Laboratory technician, Cégep A.-T.) and Ms Suzanne Prévost-Rheault (Civil Engineering Laboratory coordinator) for their invaluable helps and support during the laboratory works. The authors would like to acknowledge Lafarge North America Inc. for kindly providing us with all the Portland cement and Supplementary Cementitious Materials.

REFERENCES

[1] Mining Association of Canada (MAC), "Report on the situation of the Canadian mining", *The MAC*, Ottawa, ON, Canada, 2008.

[2] Aubertin M, Bussière B and Bernier L, "Environnement et gestion des résidus miniers", 1st ed. CD, *Presses Internationales Polytechnique*, Montréal, QC, Canada, 2002.

[3] Benzaazoua, M., Bussière, B., Demers, I., Aubertin M, Fried E, and Blier A, "Integrated mine tailings management by combining environmental desulphurization and cemented paste backfill: Application to mine Doyon, Quebec, Canada", *Minerals Engineering*, 21(4), 2008, pp. 330-340.

[4] Yilmaz E, "How efficiently the volume of wastes produced from mining operations can be reduced without causing any significant environmental impact?", *Comprehensive exam*, Ph.D. Program in Environmental Sciences, UQAT, Rouyn-Noranda, QC, Canada, 2007.

[5] Zou D and Sahito W, "Suitability of mine tailings for shotcrete as a ground support", *Canadian Journal of Civil Engineering*, NRC, 31(4), 2004, pp. 632-636.

[6] Kosmatka S, Kerkhoff B and Panarese W, "Design and Control of Concrete Mixtures", *Portland Cement Association*, 14th ed. CD, Skokie, IL, USA, 2009.

[7] Mehta PK and Monteiro PJM, "*Concrete: microstructure, properties, and materials*", McGraw-Hill, New York, NY, USA, 2006.