Use of mine tailings as raw material in concrete and mortar mix proportioning

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ABSTRACT
In this preliminary study, three composite mixtures (1 concrete CC, 1 mortar CM and 1 mortar-like paste backfill MPB) and two standard/control mixtures (1 concrete C and 1 mortar M) were prepared. Composite mixtures contain sulphide tailings as a substitute for sand (fine or coarse). All mixtures had the same ratio w/c = 0.5 and a slump of about 20 cm. Nevertheless, it was observed that the cement has been over-proportioned. The results show that: $UCS_C > UCS_M > UCS_{CM} > UCS_{CC} > UCS_{MPB}$.

RÉSUMÉ
Dans cette étude préliminaire, 3 mélanges composites (1 béton BC, 1 mortier MC, et 1 remblai en pâte-mortier RPM) et 2 mélanges standards (1 béton B et 1 mortier M) ont été formulés. Les mélanges composites contiennent des résidus miniers sulfureux comme substitut au sable (fin ou grossier). Tous les mélanges ont été préparés avec un même ratio w/c = 0.5 et un affaissement d'environ 20 cm. Malgré cela, il a été observé que le ciment a été sur-dosé. Les résultats montrent que : $UCS_B > UCS_M > UCS_{MC} > UCS_{BC} > UCS_{RPM}$.

1 INTRODUCTION

The mining industry is an important component of the Canadian economy. For example, more than 58 billion dollars in profits were generated by this industry two years ago (Mining Association of Canada, MAC 2008). However, despite these positive contributions, 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 (MAC 2008): *i*) limit the impacts of mining activity on the environment, and *ii*) rehabilitate orphaned/abandoned mine sites and ensure they do not generate pollution.

Figure 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 theme of "integrated management of mine waste", in particular, on the sulphide mine tailings management (e.g., Aubertin et al. 2002). This theme is integral part of the objective *i*) and includes two approaches limiting mining impacts on the environment through (Benzaazoua et al. 2008):

- Underground backfilling using part of the tailings (a proportion not exceeding 60% of total tailings produced) coupled with storage of the remaining residue in tailings impoundments;
- Environmental desulphurization of pyrite coupled with underground backfilling (harmful and reactive parts) and surface storage in tailings impoundments (non-reactive part).

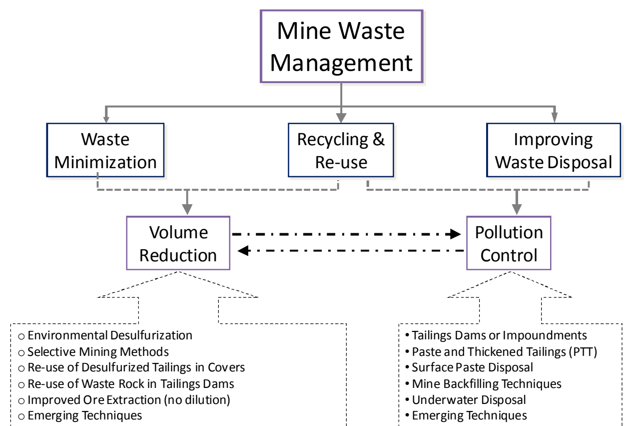

Figure 1. Schematic diagram prioritizing aspects related to the reduction of volume of mine waste (from Yilmaz 2007)

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 (up to 40%) is still in excess and must be managed properly.

One alternative has been recently proposed which consists of reusing mine tailings in the production of shotcrete as ground support (Zou and Sahito 2004). 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.

The main objective of the research is to assess the possibility of substituting 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 study is assessing the mechanical behaviour of different composite mixtures (concrete, mortar and mortar-like paste backfill).

2 MATERIAL AND METHODS

In this research, 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 tailings can substitute for the conventional sand, *ii*) the strength of composite mixtures (concrete, mortar and mortar-like paste backfill) will be lower than that of conventional mixtures because of the reactivity of sulphide mine tailings and its pore water geochemistry.

2.1 Material

The ingredients in the composite mix proportioning are: sand, gravel, sulphide-rich mine tailings, Portland cement and water. Based on assumption ii) the selected cement is a blend of general use Portland cement GU (ex Type 10) and sulphate resistant Portland cement HS (ex Type 50) at a ratio of 1:1 (GU-HS@50:50 %). The tailings were sampled from the LaRonde mine, in Quebec. 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 included in this study.

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)

The particle size range for the sand (G_s = 2.64) and gravel (G_s = 2.65) used was 0/5 mm for the coarse sand and 5/25 mm for the gravel. The GSD of the tailings sample was determined using a Malvern Mastersizer S2000® laser particle analyzer. From the GSD curves, approximately 44% of the tailings sample is finer than 20 µm, 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 (G_s = 3.72). The coefficients of uniformity C_U (= D_{60}/D_{10}) and curvature C_C (= $D_{30}^2/[D_{60}\times D_{10}]$) are 7.9 and 1, respectively (classified as ML). The initial water content of the tailings sample was 24.4%.

2.2 Methods

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 2. Aggregate combinations 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

2.2.1 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 (kg)

Mix	Sand	Gravel	Tails	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.*

2.2.2 Mixture preparation and moulds

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 moulds of 100 mm diameter and 200 mm height (Figure 2). Eight moulds were prepared for each mixture of concrete (control or composite) and of mortar (control or composite), while twelve moulds were prepared for the mortar-like paste backfill; that is to say a total of 44 specimens.

Figure 2. Photos showing cast plastic moulds

2.2.3 Specimen curing conditions

Twenty four hours after preparation all the specimens were stored in a humidity chamber (Figure 3). 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.

Figure 3. Specimens curing in the humidity chamber

2.2.4 Uniaxial 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 (Figure 4). 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.

Figure 4. Compression test machine used

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 mould and their two ends capped with a molten sulphur capping compound to ensure a uniform load distribution during the UCS test. (Figure 5).

Figure 5. Photo showing the capping process prior to UCS testing

3 RESULTS

3.1 Preliminary observations

Figure 6 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 (Figure 6a). 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 (Figure 6a&c) is much more brownish orange than that of composite mortar (Figure 6d). It can be also seen that orange color was observed neither on the outer surface of control concrete (Figure 6b) nor on the surface of control mortar specimens (as there were no sulphides present in these mixtures) not shown.

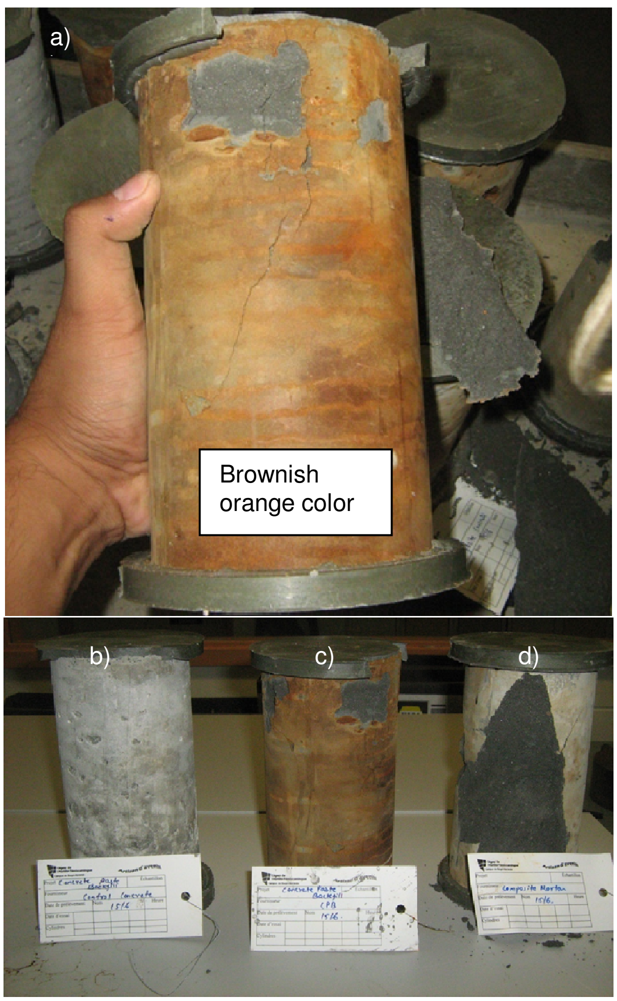

Figure 6. Photos showing the difference in specimen color between: a) mortar-like paste backfill, b) control concrete, c) mortar-like CPB and d) composite mortar

Figure 7. Photos showing the breaking pattern of a composite concrete specimen after 14 days of curing

Figure 7 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.

3.2 UCS test 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. UCS test results

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

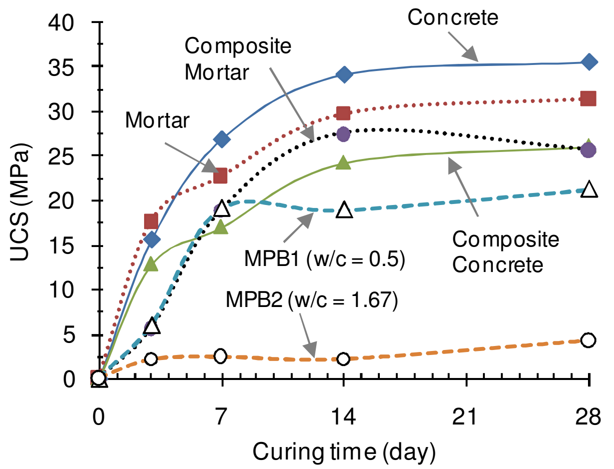

Figure 8. Variation in compressive strength with curing time for all mixtures

Figure 8 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 (e.g., Kosmatka et al. 2009). 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 (Mehta and Monteiro 2006, Kosmatka et al. 2009).

From Figure 8 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%). From Figure 8 it can also be concluded that:

$$UCS_C > UCS_M > UCS_{CM} > UCS_{CC} > UCS_{MPB}.$$

Figure 8 also 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 theese 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.

4 DISCUSSION

4.1 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).

Figure 9 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.

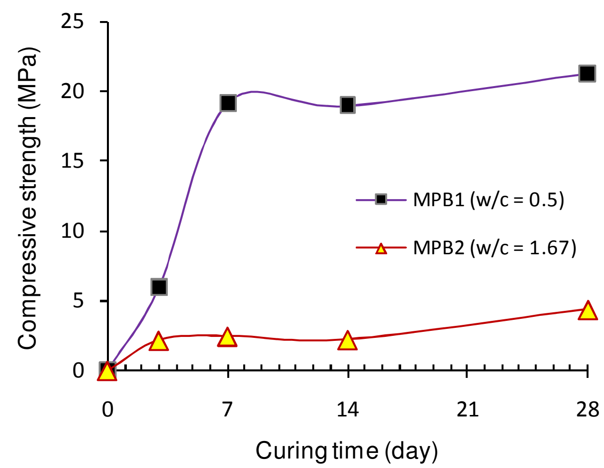

Figure 9. Variation in compressive strength of the two mortar-like paste backfills with curing time

4.2 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:

$$B_{w\%} = \frac{100 \times M_{cement}}{M_{sand} + M_{tailings} + M_{gravel}} \quad [1]$$

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 significant. 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.

4.3 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 Figure 10.

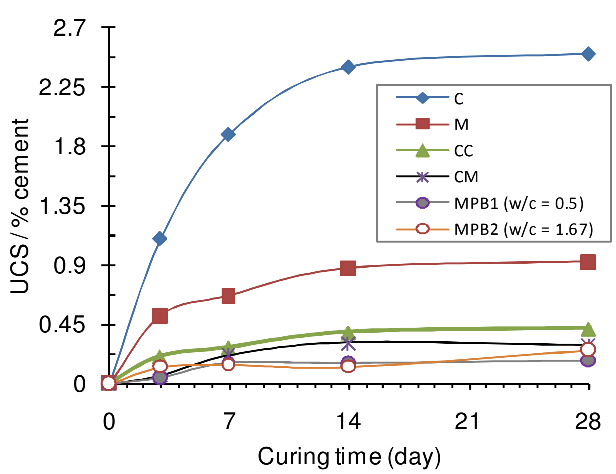

Figure 10. Variation in normalized UCS of all mixture with curing time

To eliminate the direct effect of cement under/over proportioning, the UCS data in Figure 10 are normalized (UCS_n = MPa/% of cement) by the cement content by dry mass of aggregate $B_{w\%}$ ($UCS_n = UCS/B_{w\%}$). 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–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–CC), 31% for composite concrete and composite mortar (CC–CM), and 38% for the composite mortar and mortar-like paste backfill (CM–MPB). From Figure 10 it can be also derived that:

$$UCS_{n(C)} > UCS_{n(M)} > UCS_{n(CC)} > UCS_{n(CM)} > UCS_{n(MPB)},$$

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

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.

5 CONCLUSION

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 sulphide-rich 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 sulphide-rich tailings, assessment of two types of Portland cement. Also, the effect the tailings grain size distribution must be considered.

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