

Use of mine tailing and rock waste as construction materials: an experimental study

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ABSTRACT

In order to reduce the environmental and economic impacts of the surface storage of the solid mine waste generated each year, it is imperative for the mining companies to find efficient ways for their reuse in other industrial applications. This paper investigates concrete and mortar mixtures made by replacing the fine sand and coarse aggregates with fine mine tailings from five mines in Quebec (LaRonde, Canadian Malartic, Casa Berardi, Westwood and Goldex) and crushed waste rock from the Canadian Malartic mine, respectively. Two types of mortars were produced by varying the water-to-cement (W/C) ratio (0.8 for M1 and 1.3 for M2). W/C and C/S ratios of 0.75 and 0.65 respectively were applied to all the concrete mixes by varying the source of the tailings used. The results showed that the mechanical and elastic properties (compressive and tensile strengths, Young modulus) vary with curing time, W/C, particle gradation and the solid mine waste mineralogy, without any clear relationship between these parameters. The 28-d UCS (uniaxial compressive strength) varied between 8 and 22 MPa for the composite mortars and between 13 and 26 MPa for the concrete composites. The 28-d indirect tensile strength (σ_t) of the composite concretes varied between 1 and 3 MPa. These results agree with the microstructural analysis of the composite concretes. Our results indicate that the hydration reactions and the strength development are influenced by the physicochemical properties of the mine tailings.

RÉSUMÉ

Afin de réduire les impacts environnementaux et économiques du stockage en surface des déchets miniers solides générés chaque année, il est impératif pour les compagnies minières de trouver des moyens efficaces pour leur réutilisation dans d'autres applications industrielles. Cet article présente les résultats obtenus de formulations de béton et de mortier fabriqués en remplaçant le sable fin et les granulats grossiers par des résidus miniers fins provenant de cinq mines du Québec (LaRonde, Canadian Malartic, Casa Berardi, Westwood et Goldex) et des stériles concassés de la mine Canadian Malartic. Deux mélanges de mortier ont été produits en variant le rapport eau/ciment (E/C) (0,8 pour M1 et 1,3 pour M2). Des rapports respectifs E/C et S/C de 0,75 et 0,65 a été appliqué à tous les mélanges de béton en variant la source des résidus utilisés. Les résultats ont montré que les propriétés mécaniques et élastiques des mélanges (résistance à la compression et à la traction, module d'élasticité) varient avec le temps de cure, le rapport E/C, la granulométrie des particules et la minéralogie des déchets miniers solides, sans qu'il n'y ait de relation déterminée entre ces paramètres. La résistance à la compression uniaxiale (UCS) à 28 jours varie entre 8 et 22 MPa pour les mortiers composites et entre 13 et 26 MPa pour les composites en béton. La résistance à la traction indirecte à 28 jours des bétons composites varie entre 1 et 3 MPa. Ces résultats sont en accord avec l'analyse microstructurale des bétons composites. Les résultats indiquent clairement que les réactions d'hydratation et le développement de la résistance sont influencés par les propriétés physico-chimiques des résidus miniers.

1 INTRODUCTION

In Canada, mining operations generate nearly 800 million tonnes/year of solid mine waste (Lapointe, 2020). These wastes are mainly composed of mine tailings and waste rock and often contain metallic sulphides and heavy metals. However, the mining industry must manage their solid waste according to several factors while complying with the guidelines issued by the Quebec Ministry of the Environment (MDDELCC, 2015). In 2013, Quebec amended the Regulation respecting the attestations of remediation in industrial environments to be able to tax each ton of solid mine waste stored on the surface (MDDELCC, 2015). Therefore, the reuse of solid mine waste would be very advantageous since tons of waste reclaimed will not be taxed. This vision of reclamation has

become a priority for the mining industry, not only for environmental reasons, but also for the costs associated with the penalty.

When ore is mined underground using the backfill method, almost half of the tailings are returned underground as cemented paste backfill (CPB) and a large portion of the waste rock is reused as cemented rock fill (CRF). This has the advantage of providing both secondary ground support while reducing the environmental impacts associated with the storage of solid mine waste on the surface and the cost of treatment and/or government taxation (e.g., Aubertin et al., 2002; Belem et al., 2003; Belem & Benzaazoua, 2008).

This research project is part of an approach to the valorization of solid mine as alternative raw materials for civil and mining engineering works. The project

investigated the replacement of tailings from five mines in Quebec (Goldex, Canadian Malartic, Casa Berardi, LaRonde and Westwood) and waste rock from the Canadian Malartic mine, in mortar and concrete mixes.

2 MATERIAL AND METHOD

2.1 Material

The material used in this study are mine tailings, sand, aggregates, crushed waste rock, tap water and general use (GU) Portland cement. For the preparation of the concrete and mortar "composite" mixes, conventional materials (sand and coarse aggregates) were fully replaced with fine mine tailings and crushed waste rock.

Each type of tailings was characterized by a different particle size distribution parameters (Table 1). The median particle size was used to classify the five tailings. It shows that the coarsest tailings are LaRonde mine tailings, with 50% v/v having a diameter of 40 µm. The finest tailings are from Canadian Malartic and Casa Berardi mines, with 50% v/v having a diameter of 15 and 12 µm, respectively. In the middle, the Westwood and Goldex mine tailings have 50% v/v of a diameter of 21 µm. The reference sand shows a coarser particle size class than the tailings with 50% of the particles having a size of 800 µm.

Table 2 shows that the main mineralogical phases detected in the five tailings are quartz (between 25% and 66%) and albite (between 8% and 47%). The presence of sulphides was found in certain tailings such as LaRonde, Westwood and Casa Berardi. The most sulphidic tailings are from the LaRonde (17%).

The Micro-Deval test performed on crushed waste rock shows a high abrasion resistance of the tested aggregates. The abrasion resistance was calculated according to LC 21-070. The percentage of wear was 3.9% compared with a maximum value of 10%. This low percentage indicates that the crushed waste rock from the Canadian Malartic mine lost very little of its weight during the frictional movements (abrasion) in the test cell. Therefore, these materials represent an interesting granular source for concrete manufacturing by replacing conventional aggregates.

Table 1. Common particle size parameters of mine tailings

	D ₁₀ (µm)	D ₃₀ (µm)	D ₅₀ (µm)	D ₆₀ (µm)	C _u (-)	C _c (-)
Control sand	510	650	800	1000	1.50	0.8
LaRonde	6.0	20	40	55	9.16	1.2
Canadian Malartic	2.3	7	15	20	8.6	1
Westwood	4.5	13	21	28	6.2	1.3
Casa Berardi	2.5	6.5	12	15	6	1.1
Goldex	2.3	9.5	21	30	13	1.3

Table 2. Mineralogy of tailings

Mineral	G	C	W	M	L
Proportion %tailings					
Quartz	25.1	41.2	47.8	25.6	66.2
Albite	42.7	8.7	12.5	42.5	
Pyrite	-	9	7.67	-	17.1
Chlorite	7.5	0.7	22.1	6.57	-
Muscovite	4.4	20.3	0.66	-	0.13
Cordierite	11.7	17.1	12.5		8.16
Calcite	6.9	-	-	5.46	6.75
Gypsum	0.9	-	-	-	0.27
Anhydrite	1	-	6.03	-	-
Sphalerite	-	-	0.78	7.5	-
Ankerite	-	17.1	-	8.87	-
Magnetite	-	-	2.33	-	-

G : Goldex; C : Casa Berardi; W : Westwood; M : Canadian Malartic ; L : LaRonde.

2.2 Methods

2.2.1 Preparation of mixes

Mortar mixes were produced for each tailings source. Two water-to-cement (W/C) ratios were used: 0.8 (M1) and 1.3 (M2). These values are based on the research work from Belem et al. (2010), Argane et al. (2015) and Hane et al. (2016). 108 cubes of 50×50 mm size for six mortar mixes were produced by varying the source of tailings replacement.

Table 3 shows the concrete mix design. The control concrete was made with standard sand and coarse aggregates. Sand and coarse aggregates were fully replaced with mine tailings and crushed waste rock in the composite concrete. 16 cylinders of dimensions 100 Ø and 200 mm were made by varying the source of the tailing replacement.

Table 3. Concrete mix design

	Composite concrete	Control
Water/Cement W/C	0.75	0.75
Cement/Sand C/S	0.65	0.65
Cement (kg)	14.4	14.4
Water (kg)	10.9	10.9
Wet tailings (kg)	21.8	-
Sand (kg)	-	21.8
Crushed waste rock (kg)	23.7	-
Standards aggregates (kg)	-	23.7

2.2.1 Mechanical properties

Only uniaxial compressive strength (UCS) was determined for the mortars. The UCS was measured according to ASTM C109 on 50 x 50 x 50 mm cubes, at 7, 14 and 28 days on 3 cubes of the same mix or triplicate (Figure 1a).

For the concretes, the UCS (ASTM C39), modulus of elasticity (ASTM C469) and indirect tensile strength (ASTM C496) were determined on 100 Ø 200 mm high cylinders (Figure 1b, c and d). Tests were performed at 28 and 56 days on three samples of each mix (triplicate).

2.2.1 Microstructure analysis

Scanning electron microscope (SEM) was used to conduct microstructural analysis on fresh concrete fractures. SEM images allow observing the cement phases (Portlandite and C-S-H gel) with the microparticles of the tailings in the concrete.

Two 28-day hardened concrete composites samples were analyzed for comparison with the control sample. Concrete samples were kept in ambient air condition (Table 4). That period was relative to the maturity dates of the concrete. Then, according to ASTM C 1723-16 and ASTM C457/C457M-16, pieces of concrete were prepared for SEM investigation.

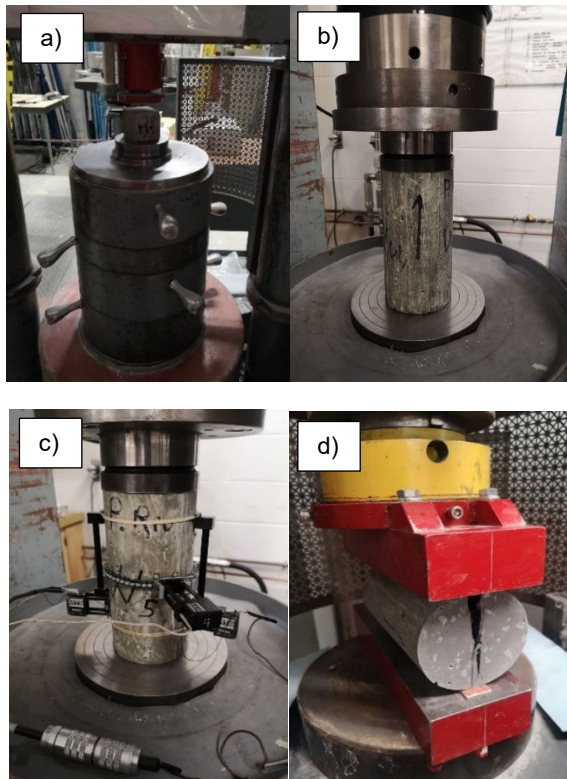


Figure 1. Experimental set ups for uniaxial compression and indirect tensile testing

Table 4: Ages of concrete samples observed under SEM

Mix	Ages	
	Cured in wet room	Kept in ambient air
Control	28 days	54 days
Westwood	28 days	69 days
Goldex	28 days	47 days

3 RESULTS

3.1 Uniaxial compressive strength of mortars

Because tailings have a very fine grain size compared to sand, we expect the fineness of the tailings from the different mines to affect the hydration process of the mortar composite mixtures, and consequently the compressive strengths. Mortar composite mixes showed a general decrease of UCS (Uniaxial compressive strength) compared with control (Table 5). The result indicates that the reduction of the mechanical performance of the composite mortars compared to control mortar was around 30% to 53% for M1, and 60% to 25% for M2. As expected, M2 developed lower UCS due to the higher W/C ratio. Comparing M1 and M2, 29% to 65% were the percentage of the decrease in the compressive strengths of the composite mortar.

In a similar context of study, Argane et al. (2015) worked on the replacement of 100% sand with mine tailings for mortar manufacturing. The authors used W/C of 1.35 with tailings having D_{60} of 140 μ m and 480 μ m. A UCS varying between 8.5 and 13.8 MPa at 28 days was reported. Belem et al. (2010) reported results from LaRonde mine tailings (44% of particles diameter less than 20 μ m) used sand replacement (100%). With a W/C of 0.5, the authors reported UCS of 26 MPa at 28 days. Trying to explain the effect of increasing the W/C on the compressive strength of mortars incorporating mine tailings, Figure 2 shows the effect of W/C alone on UCS. As expected, increasing the W/C from 0.8 to 1.3 reduces the compressive strengths of all mixes. The M1 mix design (W/C = 0.8) performed better than the M2 mix design (W/C = 1.3). An increase of about 60% was noted in the M2 mix compared to the M1 mix with the Canadian Malartic tailings. LaRonde mine tailings mix had the minimum percentage increase of 28% in compressive strengths between the two formulations.

Table 5. Uniaxial compressive strength of mortar mixes M2 (W/C = 1.3) and M1 (W/C = 0.8) at 28 days

Mix	M2 (MPa)	M1 (MPa)	Reduction of M1 compared to M2 (%)
Goldex	11.3	22.2	49
Westwood	4.5	11.0	59
LaRonde	9.9	13.6	27
Canadian Malartic	9.7	24.6	61
Casa Berardi	8.4	11.9	29
Control	11.9	33.2	64

M1 : mortar mixe 1 of, M2 : mortor mix 2.

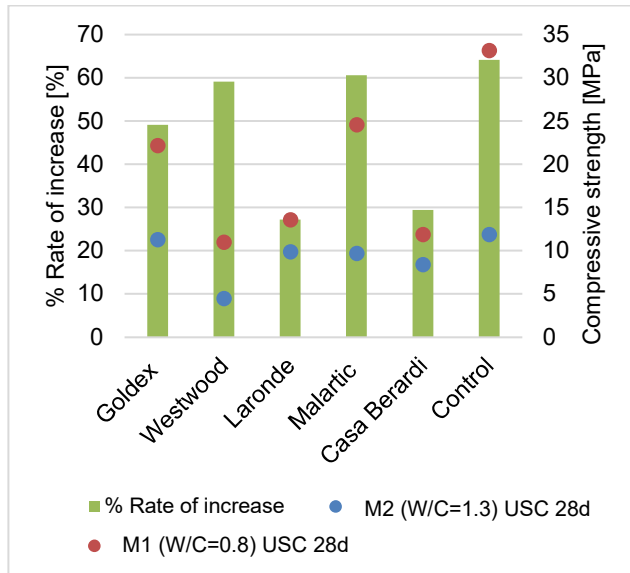


Figure 2. Relationship between compressive strengths and increasing W/C ratio of mortars

Figure 3 shows surface oxidation staining of mortar cubes from LaRonde, Casa Berardi, Westwood and Canadian Malartic mixes at 28 days. This colouration stems from the oxidation of the sulphides near the surface (presence of iron). It should be noted that a high amount of pyrite was detected in LaRonde and Casa Berardi mine tailings. Lower oxidation was observed at the surface of the mortar cubes from the Canadian Malartic and Westwood mixes. The intensity of surface oxidation appears to be proportional to the concentration of sulphurous elements in the tailings.

3.1.2 Strength properties of concrete

As shown in Figure 4, 28-day UCS of Casa Berardi (20 MPa), LaRonde (24 MPa), Canadian Malartic (20 MPa) and Goldex (26 MPa) was higher than the control (14.5 MPa). This difference lies between 33% and 78%.

Westwood mix showed a slight decrease (13 MPa, 12%) compared with control (14.4 MPa). After 56 days of curing, small increases in UCS (0 - 7%) were noted for all mixes incorporating tailings. In contrast, a large increase in UCS of control (208%) was observed and can be considered as an outlier. It is thought that the UCS obtained at 28 days was too low and can be associated with testing artefacts for UCS since tensile strength values seems adequate. For tensile strengths, only Goldex mix reached a value higher than control at 28 days (2.7 MPa, i.e 0.1 MPa higher).

In contrast, the other mixes developed lower tensile strengths. This decrease is 49% (Westwood), 28% (Casa Berardi), 14% (LaRonde), and 8% (Canadian Malartic). A significant evolution of the tensile strength was noted as a function of curing time. This increase is about 10% to 30% at 56 days (Figure 5).



Figure 3. Oxidized mortar cubes

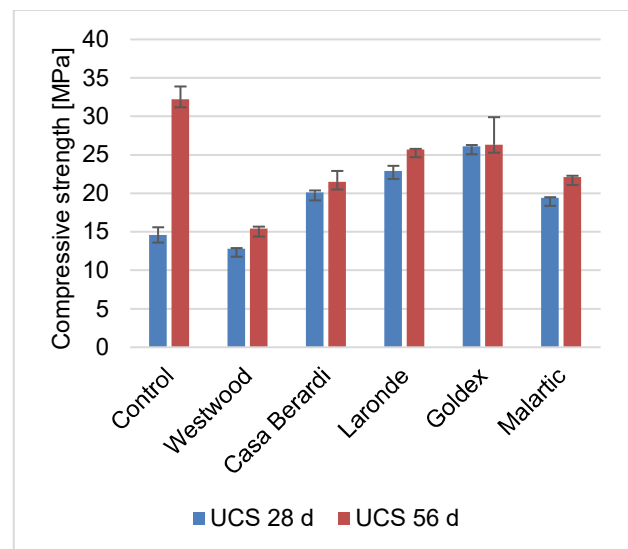


Figure 4. Variation in compressive strength of concrete mixes

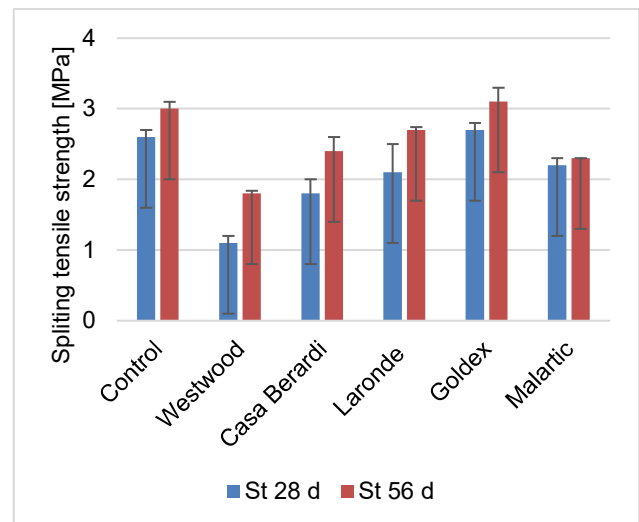


Figure 5. Variation of tensile strength (St) of concrete mixes

3.2 Elastic properties of concrete

Incorporating mine waste materials (crushed waste rock and fine mine tailings) in cementitious materials yields low stiffness. Table 7 shows the variation in the modulus of elasticity (E) for all mixes at 28 and 56 days. The highest performing mix (Goldex) shows a decrease of the modulus of elasticity in the order of 30% (28 days) and 25% (56 days) compared with control. The lowest elasticity was obtained for Westwood mix: 55% at 28 days and 51% at 56 days. For all mixes, the variation in the modulus of elasticity is proportional to the variation in compressive strength.

Table 7. Variation of the modulus of elasticity

Mix	Modulus of elasticity (GPa)	
	28-day	56-day
Control	26.0	26.4
Westwood	11.6	13.0
Casa Berardi	15.0	15.7
LaRonde	16.2	18.3
Goldex	18.0	19.6
Canadian Malartic	14.8	15.5

3.3 Microstructure of concrete samples incorporating mine tailings

The use of tailings of Goldex and Westwood mine played an important role on the hydration reaction. The SEM images help to interpret the results of the mechanical test. It is inferred that the low mechanical properties of Westwood mixes are associated with the low crystallization of the hydrates, in particular the reduced size of ettringite and Portlandite (Figure 6).

In contrast, the high mechanical strengths of Goldex mixes correspond with similar SEM image of the control (Figure 7 and Figure 8). Both exhibit good crystallization of Portlandite (well crystallized platelets) and ettringite (long needles). Therefore, the change in the mineralogical composition of the incorporated tailings as well as its physicochemical nature seems to affect both the hydration and the development of the mechanical properties of the concrete mixes.

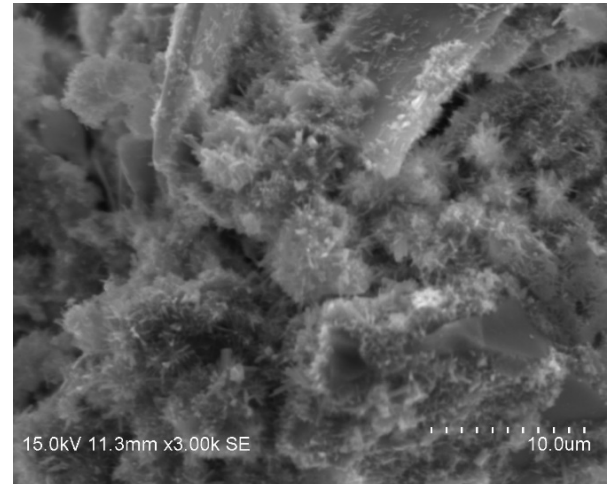


Figure 6. Microstructure of Westwood mix at 28 days

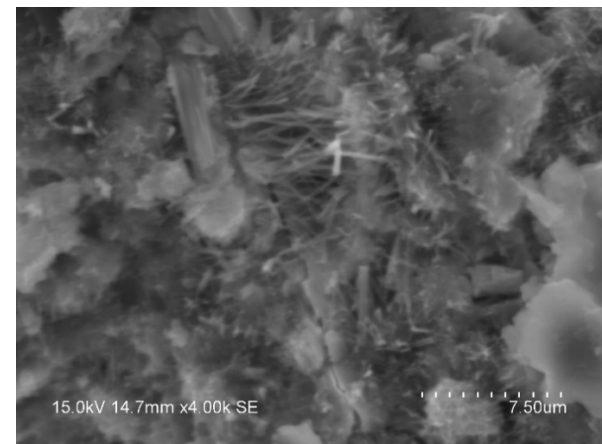


Figure 7. Microstructure of control at 28 days

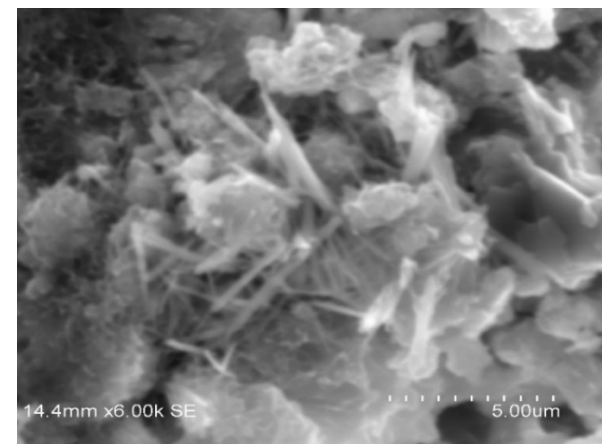


Figure 8. Microstructure of Goldex mix at 28 days

4 DISCUSSION

4.1 Relationship between compressive strength and slump

Comparing the slump of the concrete mixes in their fresh states and the measured compressive strengths of Goldex and LaRonde mixes, a plastic workability of 76 mm and a fluid one of 164 mm was found. The UCS of the two mixes were slightly different at 28 days and similar at 56 days by a value of 26 MPa. Belem et al. (2010) reported that making a composite concrete (replacing 100% of the sand with LaRonde residue) with a W/C of 0.5 and a slump of 200 mm, the compressive strength obtained was 26 MPa at 28 days of curing. In contrast, the Westwood mix had the same slump as LaRonde, but had significantly lower compressive strengths at 28 and 56 days than LaRonde (Figure 9). This variability could be related to the mineralogical nature and fine grading of the different mine tailings (Benzazoua et al., 2000; Benzazoua et al., 2005) used as sand replacement. A comparison between the variation of some tailings parameters such as sulphide content, muscovite content and the median of the particle size curves (D_{50}) confirms that each type of tailings has its own physicochemical parameters. Therefore, in a cementitious matrix, it is difficult to predict the mechanical and physical behaviour of concrete and/or mortar manufactured by replacing conventional materials with mine tailings and/or waste rock. Also, through the mechanical and physical tests employed, it is difficult to specify how each parameters affect the strength development of a mine waste-cement matrix over time.

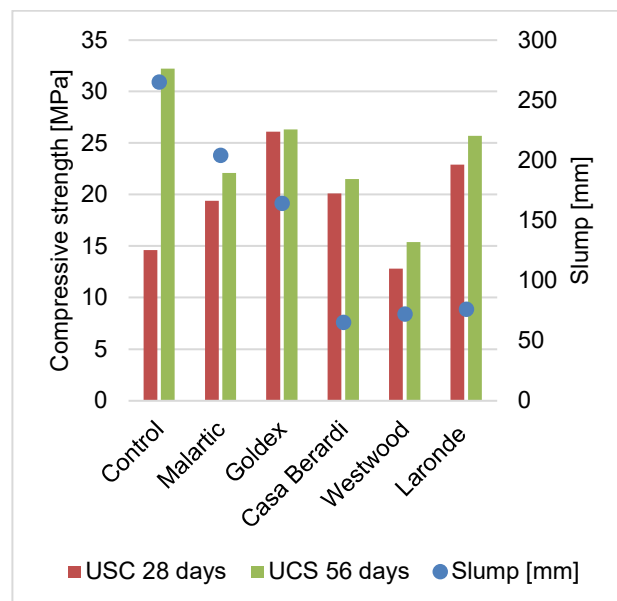


Figure 9. Relationship between compressive strength and slump of concrete

4.2 Effect of replacing sand with tailings and aggregate with crushed waste rock on microstructure

The microstructures of the mixes incorporating Goldex and Westwood mine tailings show that hydrate precipitation changes with varying tailings source and curing. This shows that the physicochemistry would play a role on the microstructure as well as on the mechanical properties. Therefore, in a cementitious matrix, the change in composition of the incorporated tailings affect the hydration reaction between the microparticles (smaller than 20 μm), the cement and the mixing water.

5. CONCLUSION

The possibility of designing some concrete with local mining materials seems particularly interesting as concrete mixes can reach mechanical properties comparable to those of conventional concretes. In this study, the effect of the replacement of 100% of the sand and coarse aggregates with mine tailings and crushed waste rock was investigated. The tailings were used in their raw state without applying any specific treatment.

The compressive strength of concrete incorporating waste was close to that of the control. The average compressive strength at 56 days ranged from 15 MPa (Westwood) to 26 MPa (Goldex) compared with the control which recorded 32 MPa. With respect to the tensile strength, some mixes exceeded the control, which reached 2.7 MPa. The lowest value was obtained for Westwood (1.8 MPa), while the highest was obtained for Goldex (3.1 MPa). Therefore, most composite mixes reached strengths comparable with conventional concrete. However, the elastic properties of the composite mixes were found to be significantly lower than those of the control (25% to 55% lower).

There was a clear effect of the nature of the tailings on both the hydration process of the cement and the mechanical properties. Experiments made on mortars showed that the fineness of the particles, as well as the mineralogical composition yield significant differences in compressive strength. No clear relationship, however, could be made between all these parameters. Therefore, 1) tailings are heterogenous materials and a universal behaviour is not expected; 2) characterization of the tailings and testing mixes prior to be incorporated in any cementitious materials is fundamental.

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