Repeatability evaluation of instrumented column tests in acid mine drainage prediction and cover efficiency evaluation

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ABSTRACT
Instrumented column tests are often used to predict the acid generating potential of mine tailings and to evaluate the effectiveness of methods to prevent acid mine drainage. These tests are seldom duplicated, which can cast some doubt about their repeatability. This paper provides an analysis of a column test study (with duplicates), performed using a methodology progressively developed over the last 15 years. Statistical comparison between duplicates was made using geochemical data, geotechnical data, and gas concentrations. The results indicate that a good repeatability of the column tests can be achieved with a good set-up methodology and rigorous control of the boundary conditions.

RÉSUMÉ
Les colonnes instrumentées sont souvent utilisées pour prédire le potentiel de génération d'acide de rejets miniers et pour évaluer l'efficacité de méthodes de restauration visant à prévenir la production de drainage minier acide. Ces essais ne sont habituellement pas répétés, ce qui peut entraîner un doute sur la repésentativité statistique des résultats obtenus. Des résultats d'essais en colonnes installées selon une méthode développée au cours des quinze dernières années et réalisés en duplicata sont comparés et analysés statistiquement. Les comparaisons des données géochimiques, géotechniques et de concentrations de gaz confirment qu'une bonne méthode de mise en place des colonnes et un bon contrôle des conditions frontières favorisent la répétabilité des essais.

1 INTRODUCTION

Instrumented columns are used in many studies to predict the acid mine drainage generation characteristics of a mine tailings, or to evaluate the performance of cover scenarios for the prevention of acid mine drainage (e.g. Davé and Vivyurka 1994; Aubertin et al. 1999; Bellaloui et al. 1999; Yanful et al. 1999; Bussière et al. 2004; Duchesne and Doye 2005; Ouangrawa 2007). The design of the column tests is typically adapted to the study objectives in terms of height and width, monitoring equipment, and sampling technique in order to obtain representative conditions with the best knowledge of the authors.

However, because of the time and cost involved and the space requirements duplicate columns are not normally part of the testing program. Most authors tend to favour the testing of various scenarios over replicating a given test. Authors who have included replicates usually observed that the column test results were repeatable (Davé and Vivyurka 1994; Aubertin et al. 1995, 1999; Aachib 1997; Yanful et al. 2000). However, very few studies (to the authors' knowledge) evaluated systematically the repeatability of column tests in the case of acidic tailings. This paper presents the results of a limited statistical study on column tests having duplicate columns, with an emphasis on the importance of rigorous installation methodology to ensure repeatability of the results. More specifically, the paper presents first the column set up methodology, followed by the statistical procedure used to compare results from identical columns. The column test results and statistical analyses are then presented, beginning with AMD generation (leaching) tests followed by cover scenario tests.

2 COLUMN SET-UP METHODOLOGY

The column set-up methodology proposed was developed since the early 1990's at Ecole Polytechnique in Montreal (Aubertin et al. 1995, 1999; Aachib 1997). The present study is based on a recently conducted column testing program for the evaluation of the performance of low sulphide tailings as a monolayer cover over AMD generating tailings. Eleven columns were installed, including three duplicate columns. Figure 1 presents the three duplicated columns configuration. Test A represents exposed sulphidic tailings (without cover) with an elevated water table (water table at the surface of the tailings). The purpose of this test was to evaluate the acid generation potential of nearly saturated tailings. Test B represents a 1 m monolayer cover made of desulphurized tailings placed over sulphidic tailings. The water table was kept 1.5 m below the base of the column. Test C columns were made of the same materials as Test B, but the cover had a thickness of 50 cm and the water table was at the interface between the sulphidic and the desulphurized tailings. Tests B and C evaluated the performance of the cover to prevent AMD generation from the sulphidic tailings. All the columns were made of 14-cm internal diameter cylindrical Plexiglas, with several ports drilled on the sides of the column to install instrumentation. Tensiometers were placed near the top and bottom of the cover layer, and gas sampling ports were installed every 10 cm above the interface between cover and reactive tailings. No instrumentation was attached to the column used for Test A.

Several aspects are important to set up a column test; the following sections discuss target porosity and initial state, air-tightness, and suction plates.

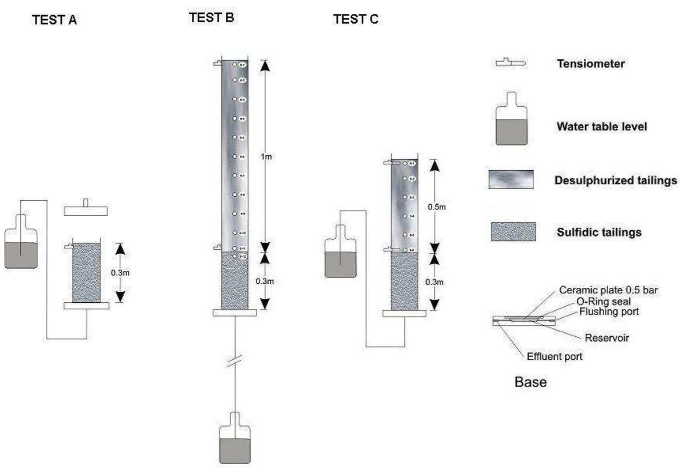

Figure 1: Columns used in the study (gas sampling ports illustrated by small white dots on the columns)

2.1 Target porosity and initial state

The sulphidic tailings were obtained from the feed of the paste backfill plant while the desulphurized tailings were collected at the end of a pilot desulphurization circuit installed at the concentrator. The materials (kept underwater after sampling at the mine to avoid contact with oxygen) were placed in the columns in a saturated state.

It is not desirable to install a column with reactive dry materials, since oxidation can occur before the beginning of the test and eventually affect the water quality at the effluent in a way that would not be representative of the real behaviour. For non reactive material such as natural soils, the initial water content is selected to improve the density of the material and to avoid specific problems such as clods formation. If a high degree of saturation is needed before starting the column test, a vacuum can be applied at the top and water can saturate the column from bottom to top (e.g. Monzon Boj 1998).

Porosity is an important material characteristic that can influence, among others, water flow and gas movement. Target porosity in a column test should be similar to expected field porosity, based on materials properties. Therefore, the first step involves the determination of specific gravity and initial water content. These data, combined with the volume of the column to fill, are used to calculate the exact mass of material to insert in the column to obtain the target porosity. The use of a compaction rod was helpful to fill the right quantity of material into exactly the right volume, a 10 cm lift was used in this case. In other cases, the use of a static load (similar set up than the one used for odometer consolidation test) has been used to reach the desired porosity (e.g. Ouangrawa 2007)

In the columns presented in figure 1, the target porosity was 0.44 for the sulphidic tailings and 0.47 for the desulphurized tailings (typical values for tailings from hard rock mines; Bussière 2007). During the column test, it is important to observe the displacement of the surface of the material in the column between the leaching periods. A significant displacement would indicate a change in porosity due to consolidation of the material (this would have to be taken into account in the interpretation of the results).

2.2 Air tightness

Column tests simulate uni-dimensional water and gas flow, and as such should allow vertical fluid flow from the top surface only. All instrumentation ports must be sealed with Teflon tape and vacuum grease to prevent any air leak. Vacuum grease was also liberally applied on the inside faces of the columns before materials placement to prevent air and water channels being formed at the soil-plastic interface.

2.3 Base of columns

A porous ceramic plate, made of a material with high AEV to ensure that it stays saturated, was placed at the base of the columns to provide an effluent outlet and a means of applying a water table level to the column. The base plate was again sealed with a rubber seal and vacuum grease to prevent water leakage when the bottom of the column is saturated, and to prevent air infiltration.

2.4 Leaching stage

Leaching was done at the beginning of the test, then after four weeks in drainage mode. Leaching began by adding 2 L of deionized water to the top of the columns, either the entire volume at once if there was enough headspace at the top of the column, or by batches as to not overflow the column. Then, the water table elevation was removed and suction was initiated to induce downwards water flow and to allow for leachate collection at the bottom of the columns. The base plate was saturated to remove air bubbles that could have been tapped in the plate. Once all water added from the top had infiltrated (which could take from a few hours to a few days, depending on the height of the column), four extra days were allowed for percolation and leachate collection under suction. After that, suction was removed and water table was replaced at its appropriate level for the test. A new cycle began at that point, for duration of four weeks before the next leaching step.

The leachates collected were measured and analysed (precision for analysis in brackets) for pH (±0.002), Eh (±0.2 mV), metal content (6% relative), acidity (9% relative), alkalinity (±1 mg $CaCO_3$/L) using electrodes, atomic emission spectroscopy, and acid-base titration.

The results presented in this paper cover an experiment that involved 10 cycles, i.e. 11 leachates including the very first one. This paper will not analyse leachate data to evaluate the performance of the covers to prevent acid mine drainage. These results are presented elsewhere (Demers et al. 2008). The purpose of the present paper is to verify the repeatability of the column experiment by comparing results obtained from identical sets of columns.

3 STATISTICAL ANALYSES

Two basic statistical methods were used to analyse the results from the column tests. The objective of the statistical analysis is to confirm the hypothesis that the two sets of data come from the same population, in our case that the results come from two identical tests. Since the quantity of data is limited, Student's t distribution was used. The general notation for the t distribution is:

$$t = \frac{\bar{x} - \mu}{s / \sqrt{n}}$$

Where $\bar{x}$ is the sample mean;
μ is the population mean;
s is the sample standard deviation;
n is the number of data.

3.1 Paired-difference test

The first method is the "Paired-difference test", which allows comparing two sets of data in pairs by looking at the difference between the two sets of data. In this case, the test wants to prove that the difference between the means of data sets 1 and 2 is null:

$$(\mu_1 - \mu_2) = \mu_d = 0$$

The test statistic becomes:

$$t = \frac{\bar{d} - 0}{s_d / \sqrt{n}}$$

Where $\bar{d}$ is the mean of the paired differences;
n is the number of paired differences;
s_d is the standard deviation of the paired differences, defined as:

$$s_d = \sqrt{\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n - 1}}$$

The hypothesis is rejected when the t value obtained is above a pre-determined value. For the study presented here, a two-tailed test at 95% confidence interval was used. The choice of the 95% tail is based on Tchebysheff's theorem that says that ¾ of the measurements will fall in the interval ± 2 standard deviations around the mean, which is defined as the 95% 2-tailed test. The results for ± 3 standard deviation, representing 8/9 of the measurements, were also used. The paired-difference test was used to analyse geochemical data (pH, Eh, alkalinity, acidity, metal content, volume of leachate) and water content.

3.2 Comparing two population variances

The second method used involved comparing two population variances. This method is generally used to compare the precision of measuring devices, among other usages. In the present study, the comparison of population variances was used in the analysis of larger data sets, such as gas concentration measurements.

The basis behind this technique lays in the fact that if the ratio of sample variances s_1^2/s_2^2 is close to one, then the two population variances should be equal. The statistical distribution of the ratio of sample variances from two populations with equal variances is called the F distribution. The test statistics is:

$$F = \frac{s_1^2}{s_2^2}$$

where s_1^2 is the larger sample variance.

The critical value of F is based on the confidence interval, in the present study 95%, and the degrees of freedom of the two samples. Placing the larger variance as the numerator in the F ratio suppresses the lower tail of the distribution; therefore a one-tail 95% test is performed.

4 ACID MINE DRAINAGE PREDICTION COLUMNS: TEST A

4.1 Geochemistry

The measured data from the two columns simulating sulphidic tailings without cover are presented in figures 2 to 8. Only data from leachate analyses were available for these columns since they did not have additional instrumentation.

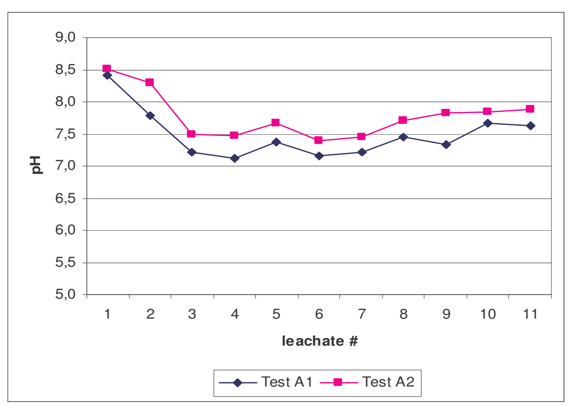

Figure 2: pH data for test A

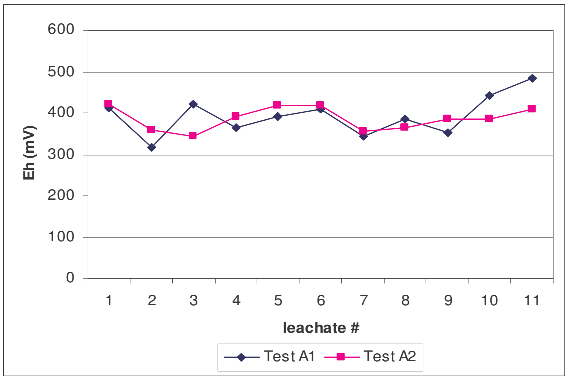

Figure 3: Eh data for test A

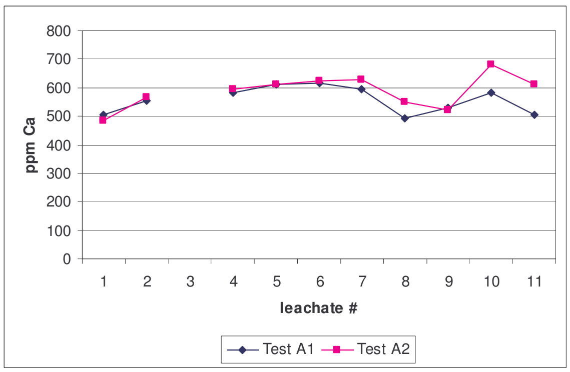

Figure 4: Calcium content in the leachate for test A

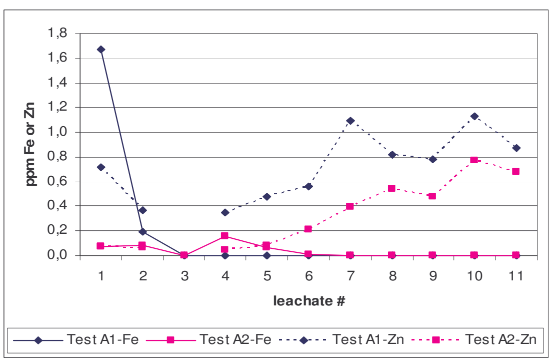

Figure 5: Iron and zinc content in the leachate for test A

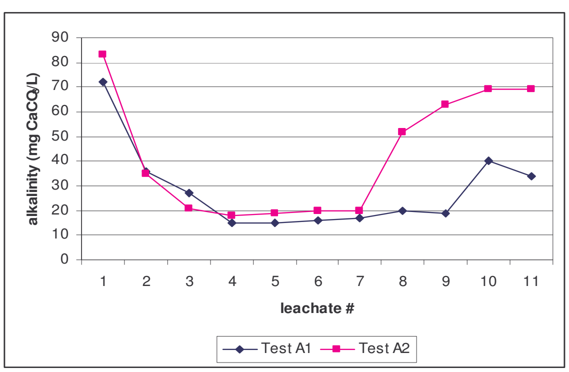

Figure 6: Alkalinity results for test A

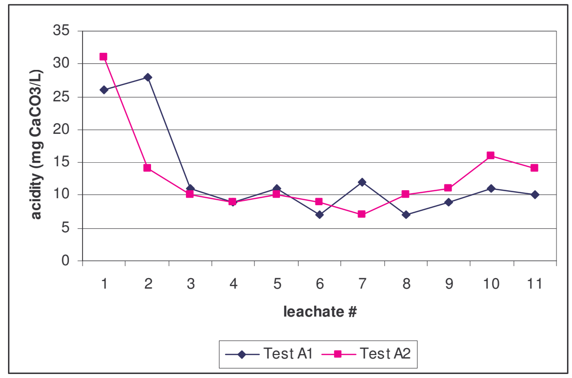

Figure 7: Acidity results for test A

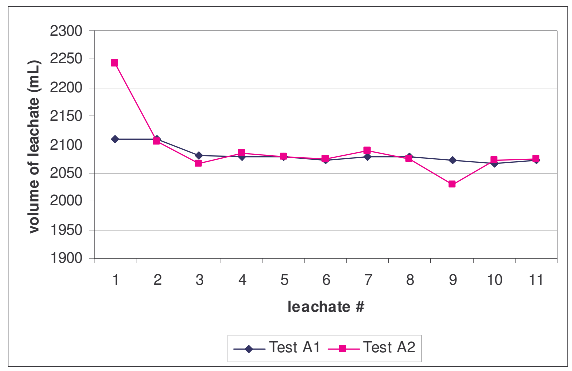

Figure 8: Volume of leachate collected for test A

These graphs show that for most parameters the trends are the same for tests A1 and A2. pH and zinc data have a steady gap between the two tests, although the trends are similar. Some punctual discrepancies are also observed, such as in the Fe content and volume of leachate for the first leaching step.

Observation from the leachate data is by itself not enough to determine if the test is repeatable. Statistical comparisons were made using the paired-difference test. Results are presented in Table 1. For simplicity, the t values are reported in absolute values, since both positive and negative tails are valid.

Test A columns passed the t-test for 4 out of 8 parameters, namely Eh, acidity, Fe content, and volume of leachate. It failed for pH, alkalinity, Zn and Ca content. These results mean that for some parameters, the data can be considered to come from the same population, i.e. from identical tests, while for other parameters there is a difference between the tests. If the interval of + or – 3 standard deviations (3s) is chosen, 8/9 of the measurements would be included, and only the pH data would fall outside the interval.

Table 1: T-test statistics for geochemical parameters from test A[1]

Geochemistry		average d	s	d. o. f.	calculated t	t-test (2s)	pass/fail	pass/fail 3s
pH	test A	0,29	0,13	10	7,5779	2,228	fail	fail
Eh	test A	6,16	44,55	10	0,4589	2,228	pass	pass
Acidity	test A	0	5,53	10	0	2,228	pass	pass
Alkalinity	test A	14,36	17,22	10	2,7668	2,228	fail	pass
Fe concentration in leachate	test A	0,15	0,51	9	0,9144	2,62	pass	pass
Zn concentration in leachate	test A	0,38	0,16	9	7,5399	2,62	fail	pass
Ca concentration in leachate	test A	35,7	37,76	9	2,99	2,62	fail	pass
volume of leachate collected	test A	8,38	43,94	10	0,6327	2,228	pass	pass

[1] d.o.f. means degrees of freedom

4.2 Water content

The gravimetric water content at two different sections in the columns was evaluated at the end of the column test during the dismantling step (after 28 days of drainage). For the first elevation, test A1 had a gravimetric water content of 23.63% while test A2 was at 22.30%. For the second elevation, test A1 had a gravimetric water content of 23.42% while test A2 was at 23.05%. T-test statistics gave a t value of 1.7822, which is well below the critical value of 12.706 for a 95% two-tailed test with one degree of freedom. The columns can be considered identical in terms of water content.

5 COVERED COLUMNS: TEST B AND TEST C

5.1 Geochemistry

The geochemical results from the leachates of the columns in tests B and C are presented in figure 9 to 16. These columns had a low sulphide tailings cover placed over sulphidic tailings, the cover being 1 m thick in test B and 50 cm thick in test C. Both tests results are plotted on the same graph for space considerations. The trends are similar for the two duplicates for most parameters tested. Only acidity data for test B have different behaviour, while in test C there is a stray data point in the fourth leachate. Apart from these two instances, the data seems comparable from one column to its duplicate.

Indeed, the statistical analyses presented in table 2 confirm that the tests are similar. Only one parameter in test C failed the t-test; zinc content. In figure 13, the zinc concentration increased after leachate number 6 for both test C1 and C2, but more significantly for test C1. The gap between these results explains the failure to fulfill the t-test.

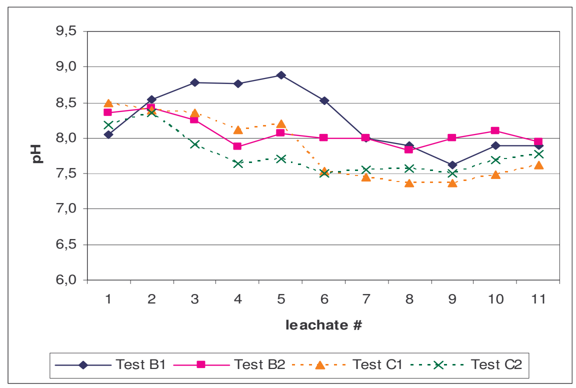

Figure 9: pH data for tests B and C

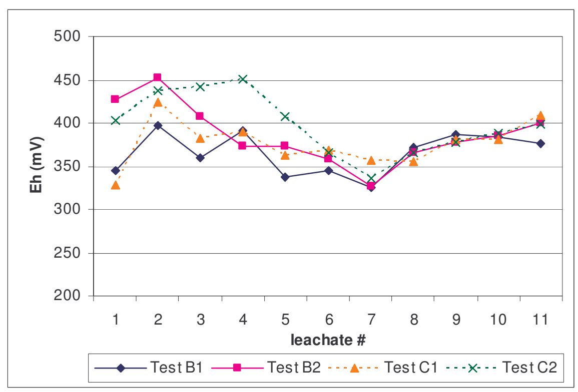

Figure 10: Eh data for tests B and C

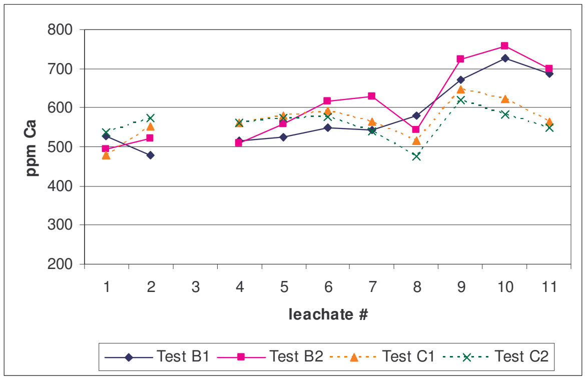

Figure 11: Calcium content in the leachate for tests B and C

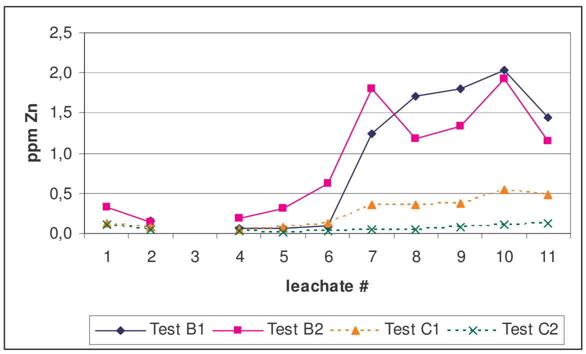

Figure 12: Zinc content in the leachate for tests B and C

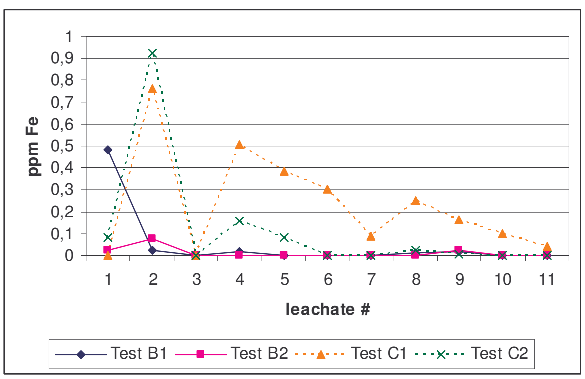

Figure 13: Iron content in the leachate for tests B and C

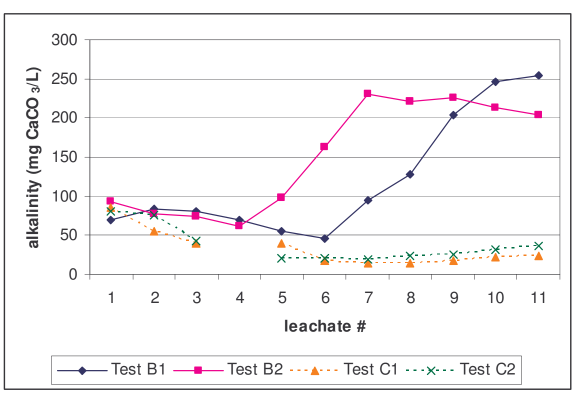

Figure 14: Alkalinity data for tests B and C

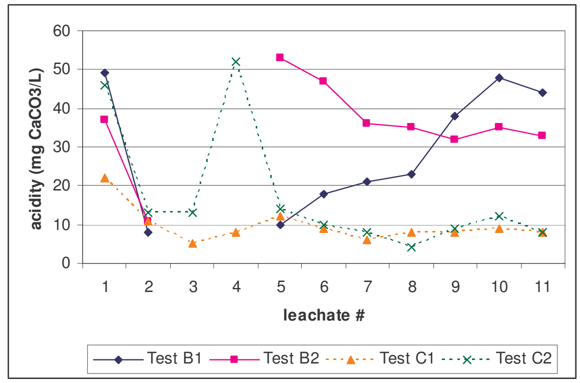

Figure 15: Acidity data for tests B and C

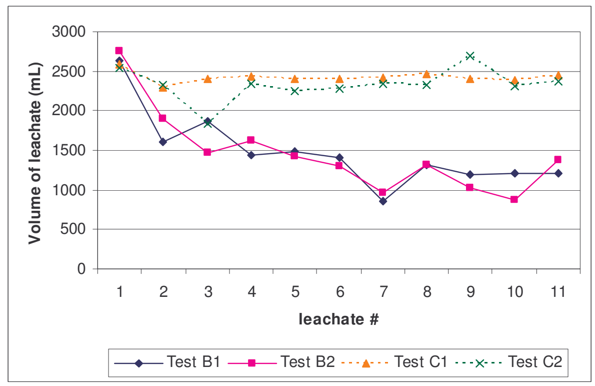

Figure 16: Volume of leachate collected for tests B and C

5.2 Water content

Gravimetric water content was evaluated at the end of the column test, in the same manner as for test A. The results for several elevations are presented in figure 17, followed by the statistical analyses in table 3. The two sets of data are fairly similar, it is only by a fraction of points that test C failed the t-test. However, the results would fall into the +/- 3 standard deviation interval.

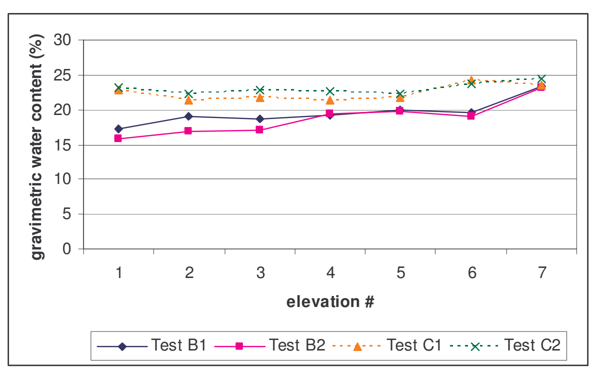

Figure 17: Gravimetric water content evaluated for test B and C

Table 2: T-test statistics for geochemical parameters from tests B and C

Geochemistry		average d	s	d. o. f.	calculated t	t-test (2s)	pass/fail	pass/fail 3s
pH	test B	0,19	0,44	10	1,4062	2,228	pass	pass
	test C	0,09	0,29	10	1,0154	2,228	pass	pass
Eh	test B	21,11	31,58	10	2,2171	2,228	pass	pass
	test C	21,17	32,56	10	2,1567	2,228	pass	pass
Acidity	test B	6,67	19,81	8	1,0098	2,306	pass	pass
	test C	7,55	14,1	10	1,7746	2,228	pass	pass
Alkalinity	test B	30,18	61,22	10	1,6351	2,228	pass	pass
	test C	4,6	10,28	10	1,4156	2,228	pass	pass
Fe concentration in leachate	test B	0,04	0,15	9	0,9266	2,62	pass	pass
	test C	0,13	0,17	9	2,4361	2,62	pass	pass
Zn concentration in leachate	test B	0,004	0,4	8	0,0328	2,306	pass	pass
	test C	0,19	0,16	9	3,7085	2,62	fail	fail
Ca concentration in leachate	test B	24,4	41,42	9	1,863	2,62	pass	pass
	test C	9,1	29,81	9	0,9654	2,62	pass	pass
volume of leachate collected	test B	19,45	220,62	10	0,2923	2,228	pass	pass
	test C	91,42	201,14	10	1,5074	2,228	pass	pass

Table 3: T-test statistics for gravimetric water content from tests B and C

Parameter	test B	test C
average d	0,81	0,6
s	0,9	0,63
d. o. f.	6	6
calculated t	2,3869	2,5061
t-test (2s)	2,447	2,447
pass/fail	pass	fail
pass/fail 3s	pass	pass

5.3 Gas concentration

Oxygen concentration measurements were obtained weekly for the duration of the column test (13 months). Data was collected over the thickness of the cover, so 12 points for the 1 m cover (test B) and 6 points for the 50 cm cover (test C). Since the weekly results were steady, they will not be presented here, only their variance is shown in table 4. Complete data can be found in Demers (2008). The ratio of the variances was compared to the F test value for a 95% confidence interval.

As shown in Table 4, test B performed well statistically, whereas test C failed most of the time. Several factors can explain the difference between test C1 and C2, probably the most important one being the degree of saturation. Indeed, the oxygen concentration is intimately linked to the degree of saturation of the material. In section 5.2 it was shown that test C failed the water content comparison, which means that degree of saturation was possibly a little different in the two duplicate columns. This difference would in turn affect the oxygen concentration present in the material. However, the trends in the data are similar for both sets of results, indicating a similar behaviour. Depending on the precision required, this could be enough to validate the experiment.

6 DISCUSSION AND SUMMARY

Test A was more difficult to duplicate than tests B and C in terms of geochemical results. It appears that columns with a lower quantity of material may be more affected by small differences in water saturation or any other parameter that can influence the leachate geochemistry. The columns installed to evaluate the effectiveness of cover scenarios were more readily duplicated using the proposed set up methodology. Geochemistry of the leachates passed the statistical test, except for zinc in the 50 cm cover case.

The 50 cm cover columns (test C) and acid generation potential columns (test A) had an elevated water table which was maintained by raising a water container connected to the base of the column. Evaporation reduced the level of water in the container, which had to be refilled periodically to maintain the water table level as desired. If the water level became slightly different in the duplicate columns, the column test results can be affected, as it was observed in the water content and oxygen concentration comparisons. Test C1 had a slightly lower water content compared to C2, which translates into a slightly lower degree of saturation and increased oxygen diffusion. In this case, oxygen concentrations in the cover were different enough from test C2 to fail the statistical comparison test. Test A1 had consistently higher water contents than test A2, although the t-test was passed (probably because of the low degree of freedom).

In summary, the operating conditions of the column tests are as important as a rigorous installation methodology. Once set is performed to ensure near identical initial states in the columns, the parameters involved in the test must be carefully monitored to make sure they are also near identical. If all these criteria are met, the column tests can be said to be repeatable. Although a few tests failed, the tendencies observed in the column test results are similar. In the case of many studies which are more interested by tendencies than absolute numbers, column tests are indeed appropriate.

Table 4: F-test statistics for oxygen concentration from tests B and C

	variance (1)	d. o. f.	variance (2)	d. o. f.	calculated F	f-test (2s)	pass/fail	pass/fail 3s
Test B	0,3332	23	0,2713	26	1,2280	1,96	pass	pass
	0,3471	24	0,5350	23	1,5414	1,99	pass	pass
	1,1600	23	1,3274	26	1,1443	1,99	pass	pass
	2,3542	23	3,2519	21	1,3813	2,04	pass	pass
	4,7058	23	3,7218	25	1,2644	1,97	pass	pass
	5,3381	24	7,3307	22	1,3733	2	pass	pass
	7,4577	22	7,7230	24	1,0356	2,03	pass	pass
	10,4159	24	5,9313	23	1,7561	2,01	pass	pass
	10,4887	22	4,8209	24	0,4596	2	pass	pass
	15,7976	13	4,6214	22	3,4183	2,2	fail	pass
	11,3991	20	2,4416	23	0,2142	2,03	pass	pass
	14,4785	22	4,4415	21	3,2598	2,07	fail	pass
Test C	0,1708	24	0,2284	22	1,3372	2	pass	pass
	0,5838	22	0,2367	23	2,4665	2,02	fail	pass
	1,0015	24	0,2337	22	4,2849	2,03	fail	fail
	1,6868	22	0,3201	23	5,2690	2,02	fail	fail
	2,3524	24	0,3954	22	5,9494	2,03	fail	fail
	37,4225	18	11,2454	8	3,3278	3,17	fail	pass

7 ACKNOWLEDGEMENTS

The authors want to acknowledge the support of the NSERC-Polytechnique-UQAT Chair in Environment and Mine Waste Management.

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