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A UNIQUE RESEARCH PROGRAM

Assessment of Paste Rock as a Cover Material in Mine Reclamation at the Canadian Malartic Mine

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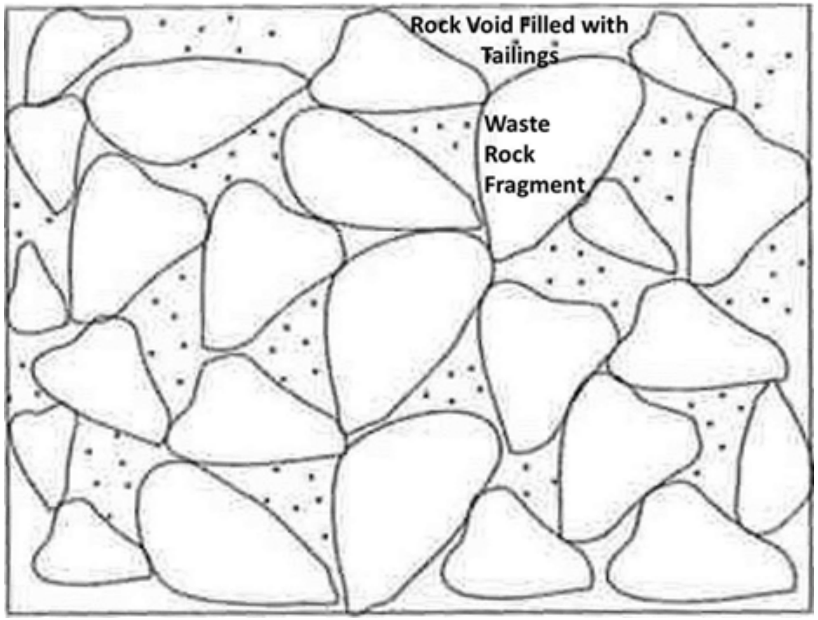
MINE CANADIAN MALARTIC

AGNICO EAGLE YAMANAGOLD

What is a Paste Rock Mixture ?

- What we call « paste rock » or « co-mixing » is in fact an homogeneous mixture of fine tailings and waste rock;
- Used in the past by coal mines and some oil sands operations;
- Work previously done by Wilson and Wickland (2008) as a way to co-dispose waste rock and tailings.



Could this material successfully be used as a reclamation cover?

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About the Canadian Malartic Mine

- The Canadian Malartic Mine is one of Canada's biggest open pit gold mine. Owned by a partnership – 50% Agnico Eagle Mines and 50% Yamana Gold.

- Commercial production started in 2011 and is presently at a rate of 55 000 tpd.

- Canadian Malartic mine is currently conducting an assessment of various reclamation scenarios for both potentially acid generating (PAG) waste rocks and PAG tailings.

MINE CANADIAN MALARTIC
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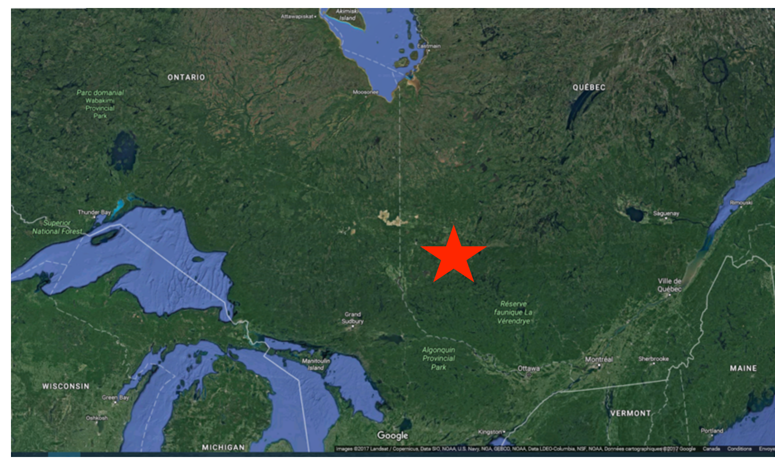

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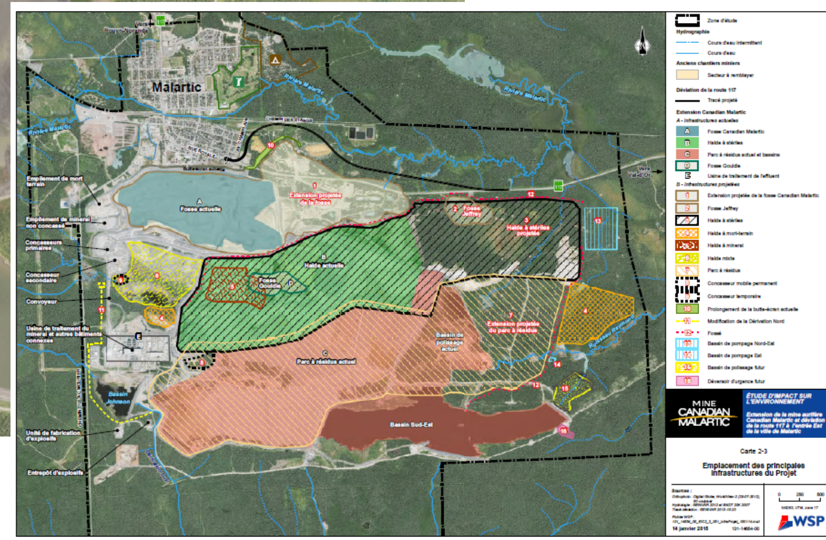
THE CANADIAN MALARTIC MINE



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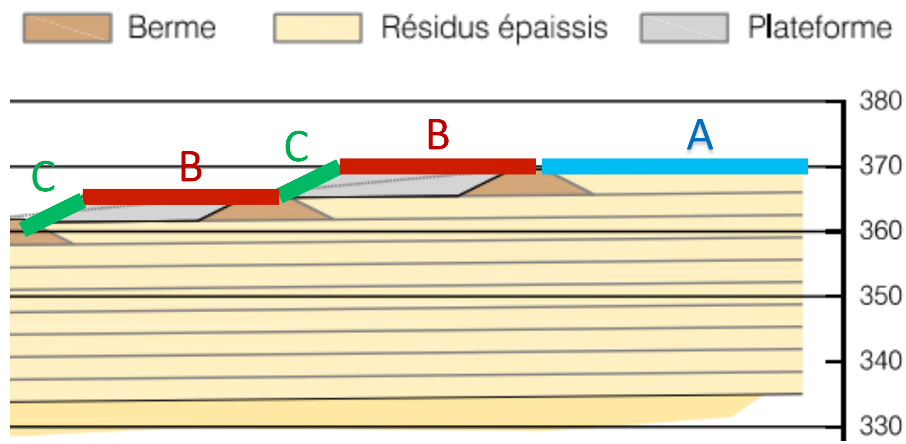
Reclamation domains (5)

TSF : 639 ha

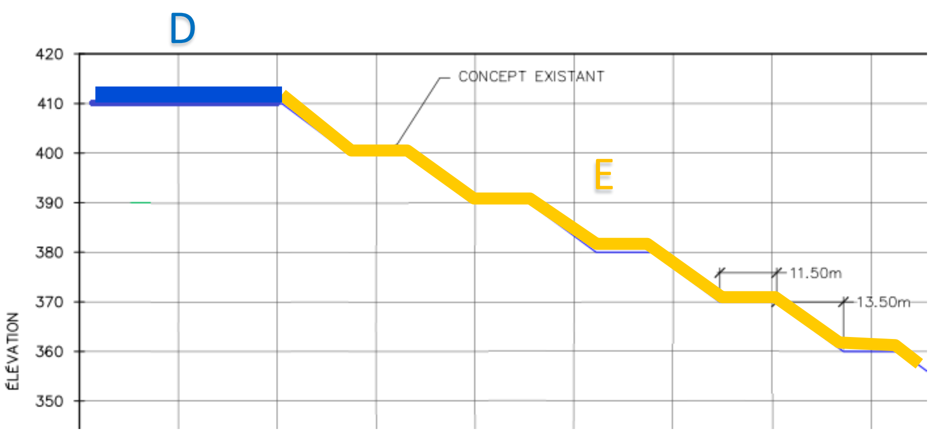
A. Flat areas – Top of the tailings : 354 ha
B. Flat areas – berms : 234 ha
C. Inclined areas – Bench faces : 51 ha



Source : Golder, 2014

WRF : 417 ha

D. Flat areas – Top of the pile : 253 ha
E. Inclinded areas – Benches and terraces : 164 ha



Source : WSP, 2016

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RECLAMATION CHALLENGES

- ✓ Size
- ✓ Chemical (ARD) and geotechnical stability
- ✓ Cover material availability
- ✓ Constructability
- ✓ Progressive rehabilitation
- ✓ Community consultations

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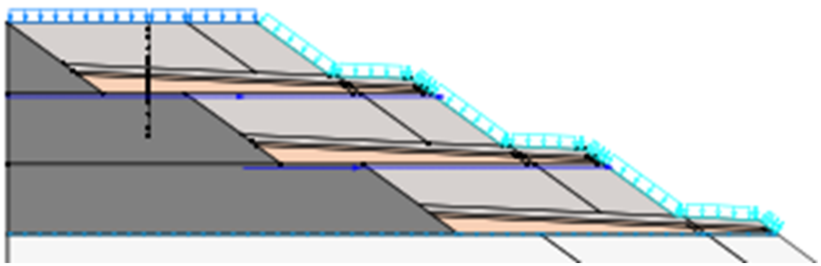
OUTLINE

- **RECLAMATION OPTIONS**
- LABORATORY CHARACTERIZATION
- RECLAMATION CELLS FOR TAILINGS AND WASTE ROCK
- SUMMARY AND ON-GOING WORK

Reclamation Options

1. Cover with capillary barrier effect (CCBE)
    I. Desulfurized or amended tailings + Waste rock
    II. Paste rock + waste rock
2. Bilayer cover
    I. Desulfurized or amended tailings + Waste rock
    II. Paste rock and waste rock
3. Monolayer – Paste Rock
4. Geosynthetic cover
5. Flow control layer
   (WRF only)



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Comparative analysis of possible reclamation scenarios for CMM

– All closure methods → Go / No Go threshold criteria

– Analysis
- Costs
- Construction Feasability
- Environmental Performance
- Stakeholder consideration

Weight of category	
1	neutral
3	low
6	medium
9	high
15	critical

Category of criteria	Weight of category	Evaluation criteria	TSF: Original concept	TSF: In-pit tailings disposal	TSF: Tailings relocation	TSF: Multi-layer	TSF: Monolayer	TSF: Bylayer	TSF: Synthetic cover	TSF: Paste-rock cover
Cost		Capital cost (CAPEX)	48	60						
		Operational cost (OPEX)	36	45						
	9	Minimizes risk of future reinvestment	12	30	6	24	18	24	24	18
		Compatibility with mine production (slow down of production and/ or change in mine plan)	45	45	45	27	36	27	45	27
Weighted sub-total			42,3	54	15,3	15,3	16,2	15,3	20,7	13,5
Construction feasability		Allows progressive construction	45	36	9	27	27	27	36	27
		Technical and construction feasability (and potential impacts)	24	30	18	12	18	18	24	12
		Potential compatibility issues and interaction with other cover systems	24	30	18	30	24	30	30	30
	6	Material availability	36	60	60	36	48	48	48	48
		Applicability of the concept (which sector)	30	30	18	18	18	18	24	30
		Constructibility of surface water management								

Evaluation criteria	WRF: Original concept	WRF: In-pit waste disposal	WRF: Waste relocation	WRF: Multi-layer	WRF: Monolayer	WRF: Bylayer	WRF: Synthetic cover	WRF: Paste-rock cover
Capital cost (CAPEX)								
Operational cost (OPEX)								
Minimizes risk of future reinvestment	12	30	6	12	12	12	18	18
Compatibility with mine production (slow down of production and/ or change in mine plan)	27	45	45	27	36	27	45	27
Weighted sub-total	11,7	22,5	15,3	11,7	14,4	11,7	18,9	13,5
Allows progressive construction	45	36	9	27	27	27	45	27
Technical and construction feasability (and potential impacts)	12	30	18	12	12	12	18	18
Potential compatibility issues and interaction with other cover systems	24	30	18	30	24	24	30	30
Material availability	36	60	60	36	48	48	48	48
Applicability of the concept (which sector)	30	30	18	18	12	12	18	18
Constructibility of surface water management								

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RECLAMATION COSTS EVALUATION

1 – Materials, Area and Volumes

Option 1 - Recouvrement de Paste Rock et de résidus désulfurés

Description et portée :		
Nb d'années de restauration :	8	ans
Halde à stériles et bermes du parc - plat	2,0 m de paste rock ™	
Halde à stériles et bermes du parc - incl	2,0 m de paste rock ™	
Plateau supérieur du parc à résidus :	1,7 m de RM désulfurés et 0,3 m de CPO 0-38 mm	
Travaux d'hiver requis ? (O/N)	O : Couche de 0,3 m de CPO sur RM	

1 Informations de base sur le concept

1.1 Halde à stérile et bermes du parc - SURFACES HORIZONTALES

1.1.1 Superficies (ha)

Localisation	Surface horizontale (ha)
Halde	775,8
Berme du parc	0,0
TOTAL	775,8

1.1.2 Recouvrement *(Ref : cellule URSTM CP-1)*

Couches	Matériau	Épaisseur (m)	Superficie (m^2) ou Volume (m^3)		Besoins annuels	
Couche de support (#5 - en bas)	(aucun)	0,0	0	---	0	---
Couche de faible perméabilité (#4)	Paste Rock™	2,000	15 516 000	m^3	1 939 500	m^3/an
Couche de protection (#3)	(aucun)	0,8	6 206 400	m^3	775 800	m^3/an
Couche minérale (#2)	Mort-terrain	0,4	3 103 200	m^3	387 900	m^3/an
Couche végétale (#1 - en haut)	Terre végétale	0,1	775 800	m^3	96 975	m^3/an
TOTAL		3,3	0	m^2	0	---
			25 601 400	m^3	3 200 175	m^3/an

2 – Preparation costs

2.0 Coûts - préparation du terrain

Description :

Mise en place de roches stériles dans le parc jusqu'à ce que le fond soit dur... Travaux d'hiver ... Reprofilage des pentes des bermes...

	Qté	Unité	Taux unitaire		Coût		Détails / Source
Nivellement		m^2		$\$/m^2$			Passer la niveleuse uniquement
Excavation et/ou remblai sans transport		m^3		$\$/m^3$			Temps de pelle uniquement, la pelle excave
Excavation / remblai avec transport		m^3		$\$/m^3$			La pelle excave du matériel qu'elle dépose
Excavation / disposition loin ou hors		m^3		$\$/m^3$			Applicable ? La pelle excave du matériel qu'

3 – Materials costs – Production and supply

3.0 Coût - Production/ obtention des matériaux

Description :

Prendre du CPO des réserves pour concasser en 0-38 mm au site xxx. Mélange avec des résidus miniers désulfurés qui ont été séchés... Tamisage du mort-terrain...

		Qté	Unité	Taux unitaire		Coût		Détails / Source
3.1	**Fourniture et manutention de matériaux (hoi**	**Qté**	**Unité**	**Taux unitaire**		**Coût**		**Détails / Source**
	PEHD 2 mm lisse		m^2	9,00	$\$/m^2$		$	Rapport WSP (2016)
	PEHD 2 mm texturé		m^2	9,00	$\$/m^2$		$	Rapport WSP (2016)
	Drains tubes		m^2	9,00	$\$/m^2$		$	Rapport WSP (2016)
	GCL		m^2		$\$/m^2$		$	
3.2	**Production de matériau (par MCM)**	**Qté**	**Unité**	**Taux unitaire**		**Coût**		**Détails / Source**
	Dynamitage		m^3		$\$/m^3$		$	
	WR CPO 0-38 mm - concassage		m^3	2,50	$\$/m^3$		$	Fournier pour Paste Rock
	WR CPO 0-25 mm - tamisage		m^3		$\$/m^3$		$	
	Mort terrain - tamisage		m^3		$\$/m^3$		$	Spectre de tamisage à spécifier (xxx - xxx mm

4 – Construction costs →

4.0 Coût - Mise en place des matériaux

Description :

Mise en place du sable par fines couches... Compaction du sable...

	Qté	Unité	Taux unitaire		Coût	Détails / Source
Déposition des résidus miniers		m^3	0,25	$\$/m^3$		Déposé avec les infrastructures actuelles
Remblayage - par couches minces (<50 cm)		m^3		$\$/m^3$		pour WR, Paste Rock, Sable, MT mais pas TV
Remblayage - par couche moyenne (50-100 cm)		m^3		$\$/m^3$		pour WR et Paste Rock
Remblayage de masse		m^3		$\$/m^3$		Applicable ?
Compaction (rouleau compacteur)		m^2		$\$/m^2$		Faire des items compacté et non compactés
Pose PEHD 2mm lisse / texturé		m^2		$\$/m^2$		
CQ installation PEHD	1	LOT		$\$/LOT$		
Pose et installation drains tubes		m^2		$\$/m^2$		
Mise en place terre végétale (10 cm)		m^2		$\$/m^2$		
Ensemencement hydraulique		m^2		$\$/m^2$		
Plantation arbres		m^2		$\$/m^2$		

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Paste rock as cover materials

Hypothesis: paste rock mixture can be used as low permeability layer of a reclamation cover that can be used to reduce water infiltration and limit the diffusion of oxygen towards reactive materials.

- Well designed paste rock posesses both similar mechanical properties as the waste rock and the hydrogeological properties of the tailings (Wilson, 2008);
- Previous field work (Wilson, 2008) demonstrated that infiltration rates and drainage are reduced when the mixture is used to construct a cover system on mine tailings;
- It promotes the use of mining waste in mine site reclamation instead of impacting additional areas to get natural materials.

Outline

- Reclamation options
- **Laboratory characterization**
- Field test cells
- Summary and on-going work

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Laboratory Characterization

- Physical
  - Grain size distribution
  - Relative density (D_r)
  - Proctor tests
- Chemical
  - ICP-AES
  - Carbon and Sulphur analysis
- Mineralogy
  - X Ray Diffraction (XRD)
- Hydrogeological
  - Saturated hydraulic conductivity (K_{sat})
  - Water retention curve (WRC)

CHOICE OF RATIO AND IN-LAB PASTE ROCK MIXING

Several ratios tested (waste rock/ tailings): 2.4/1, 3/1, and 3.6/1

Several tailings solid % (C_w) tested: C_w tailings = 68%, 70%, 75%, 78%

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LABORATORY CHARACTERIZATION

Properties of different paste rock mixture

Paste rock mixture preparation

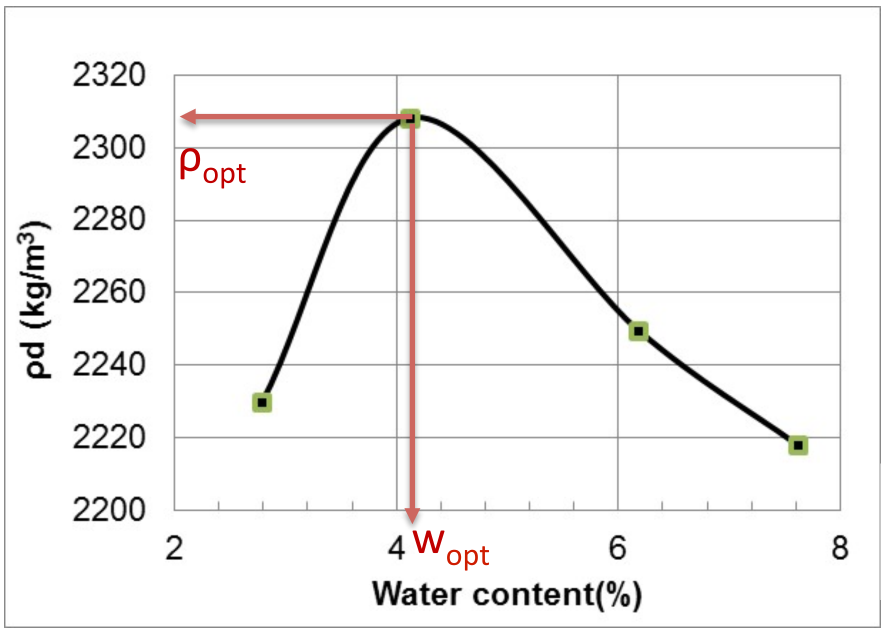
- C_w tailings=68%
  - *Pasterock* mixture with ratio 2.4/1
  - *Pasterock* mixture with ratio 3/1
  - *Pasterock* mixture with ratio 3.6/1
- C_w tailings=75%
  - *Pasterock* mixture with ratio 2.4/1
  - *Pasterock* mixture with ratio 3/1
  - *Pasterock* mixture with ratio 3.6/1
- C_w tailings=70%
  - *Pasterock* mixture with ratio 2.4/1
  - *Pasterock* mixture with ratio 3/1
  - *Pasterock* mixture withRatio 3.6/1
- C_w tailings=78%
  - *Pasterock* mixture with ratio 2.4/1
  - *Pasterock* mixture with ratio 3/1
  - *Pasterock* mixture with ratio 3.6/1

Laboratory characterization

Properties of different paste rock mixtures

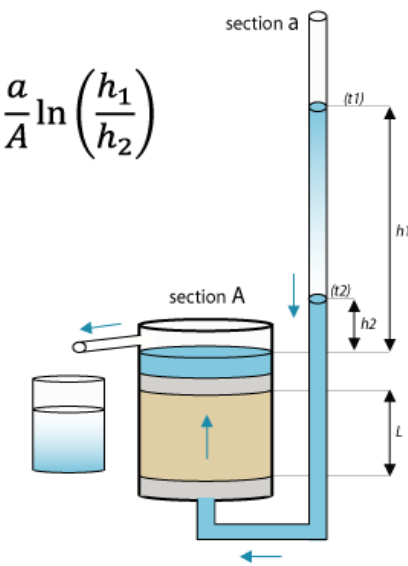
Hydrogeotechnical characterization

- Variable head permeability tests
- Compaction tests



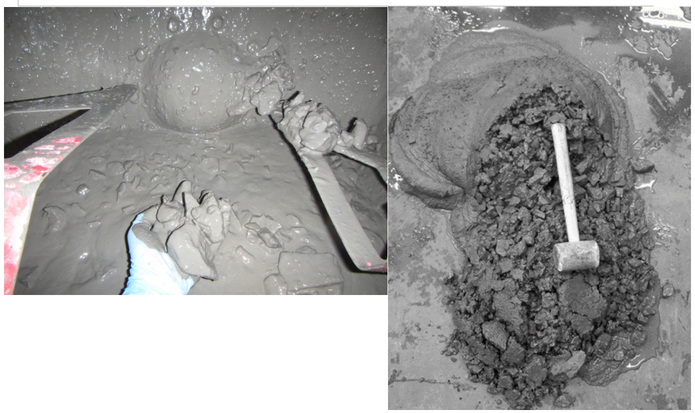
Example of Proctor test results

$$k_{sat} = \frac{L}{(t_2 - t_1)} \frac{a}{A} \ln\left(\frac{h_1}{h_2}\right)$$



LABORATORY CHARACTERIZATION

Appearance of the Paste rock



Ratio 2.4/1 (waste rock/tailings):
C_w tailings= 68%

Column dismantling

Ratio 3.6/1 (waste rock/tailings):
C_w tailings= 70%

Ratio 3/1 (waste rock/tailings):
C_w tailings= 75%

LABORATORY CHARACTERIZATION

Results

Ratio (Waste rock/Tailings)	Tailings C_W (%)	k_{sat} (cm/s)	ρ_{dry} (Kg/m^3)	w_{opt} (%)	n_{opt}	Slump (on 40cm)	Particles segregation
2.4 / 1	68	3.4×10^{-5}	2310	4.2	0.18	40 cm	High
2.4 / 1	75	1.4×10^{-5}	2290	7.2	0.18	/	zero
2.4 / 1	78	5.8×10^{-6}	2390	6.4	0.15	/	zero
3 / 1	75	1.0×10^{-5}	2315	7.4	0.17	/	zero
3.6 / 1	70	1.9×10^{-5}	2320	6.1	0.17	15 cm	zero
3.6 / 1	75	9.3×10^{-6}	2320	5.6	0.17	/	zero

Best hydrogeological properties

Ratio 3/1 with tailings C_w of 75% is the paste rock ratio used for the construction of the reclamation cells

Outline

- Reclamation options
- Laboratory characterization
- **Field test cells**
- Summary and on-going work

Field test cells

Objective: To assess *in situ* the efficiency of the paste rock as cover material in regards to ARD control (as both water and oxygen barrier)

Cells configuration (see Slide 22)

	Cell configuration	Materials volume (m^3)
Monolayer cover of paste rock cell on tailings (CR-4)	2 m of non-amended paste rock	171
	1 m of CM tailings	7
Monolayer cover of paste rock cell on waste rock on horizontal surfaces (CS-4)	2 m of non-amended paste rock	285
	4 barrels filled with 1 m of each lithology 0-38mm	
Monolayer paste rock cell on waste rock on slope (CP-1)	2 m of non-amended paste rock	498

Field test cells

Paste rock preparation

Belt sieving the rough mix and spilling at a height of 2 m

Paste rock at the belt sieve output

Forming of a ball to test the paste rock cohesion

Carrying the paste rock to the storage area

Final paste rock

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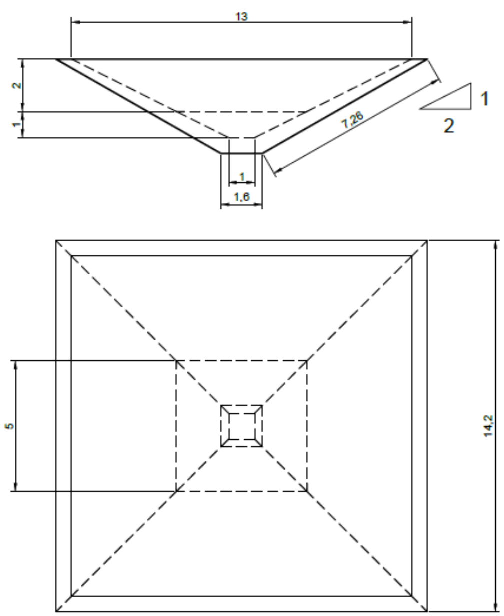
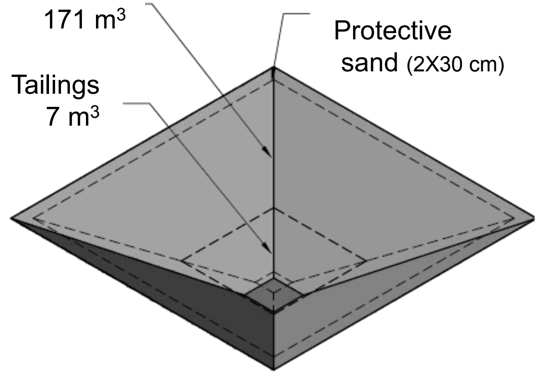
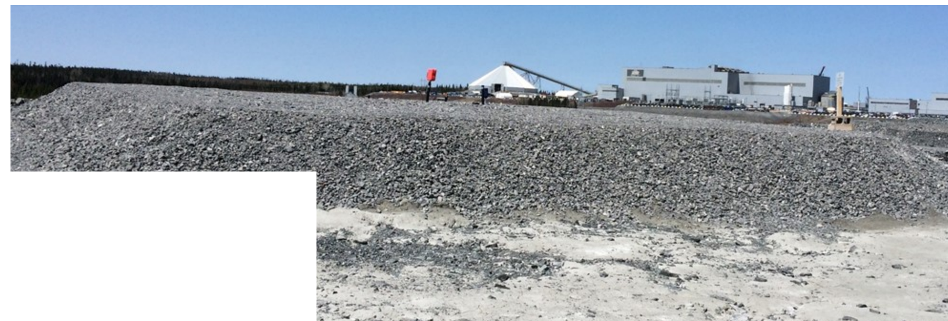
FIELD TEST CELLS

Cells configuration: Monolayer cover of *paste rock* on tailings

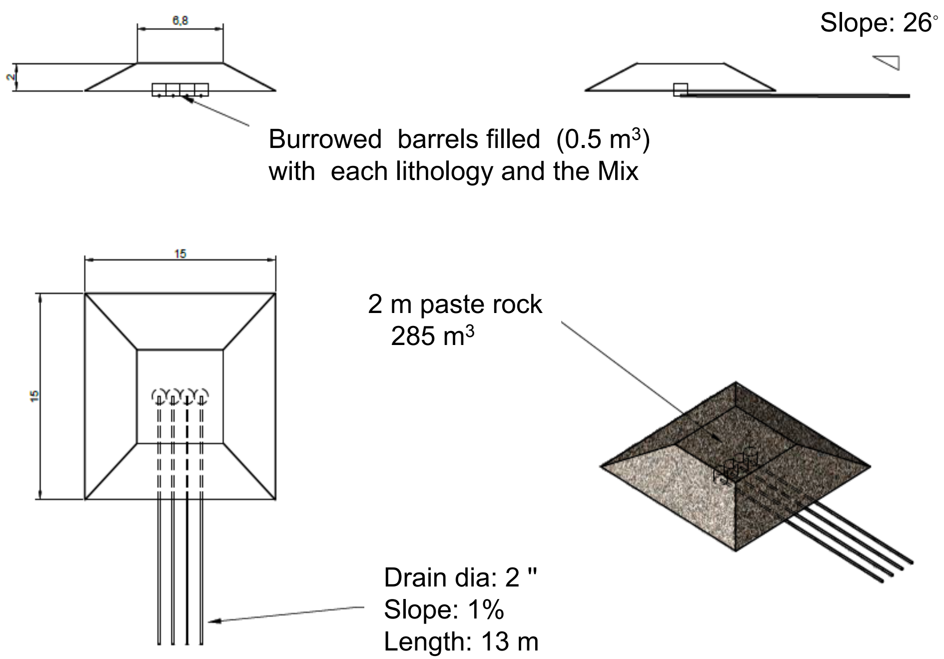






Field test cells

Cells configuration: Monolayer cover of *paste rock* on waste rock on horizontal surfaces



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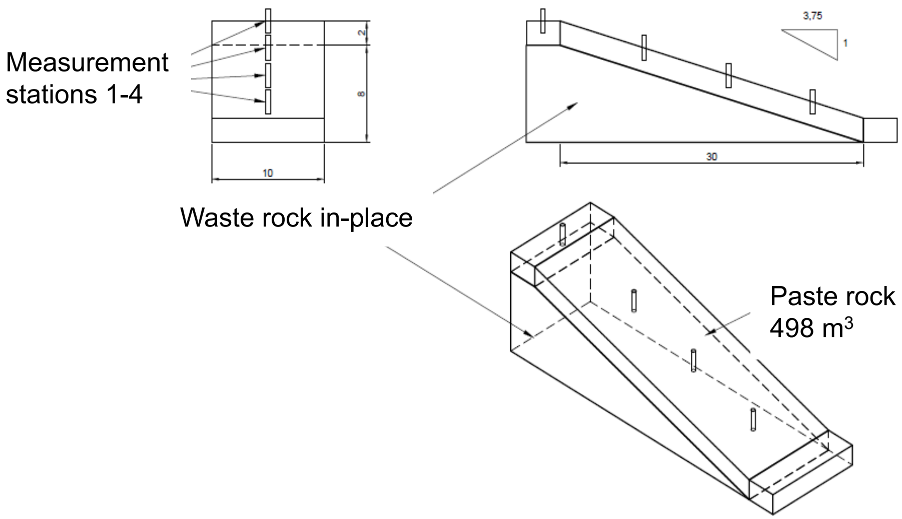
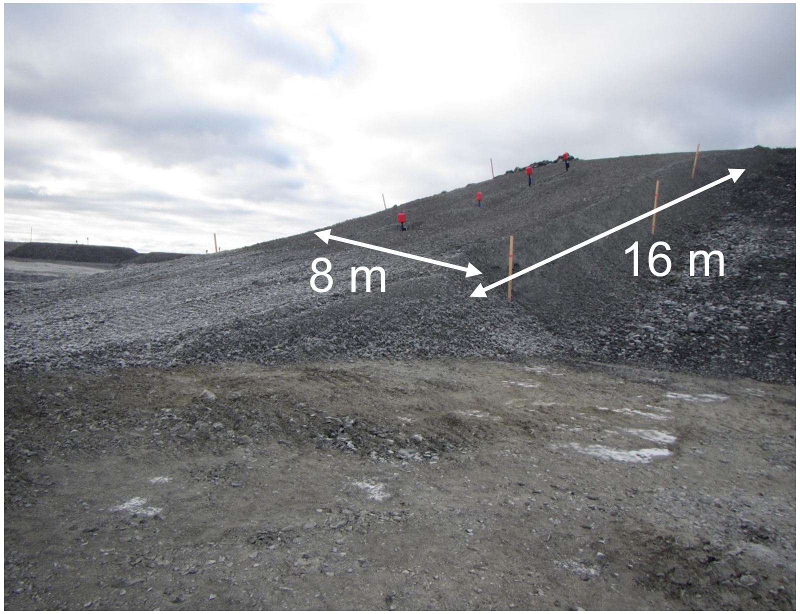
FIELD TEST CELLS

Cells configuration: Monolayer *paste rock* on sloping waste rock





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FIELD TEST CELLS

Cells instrumentation

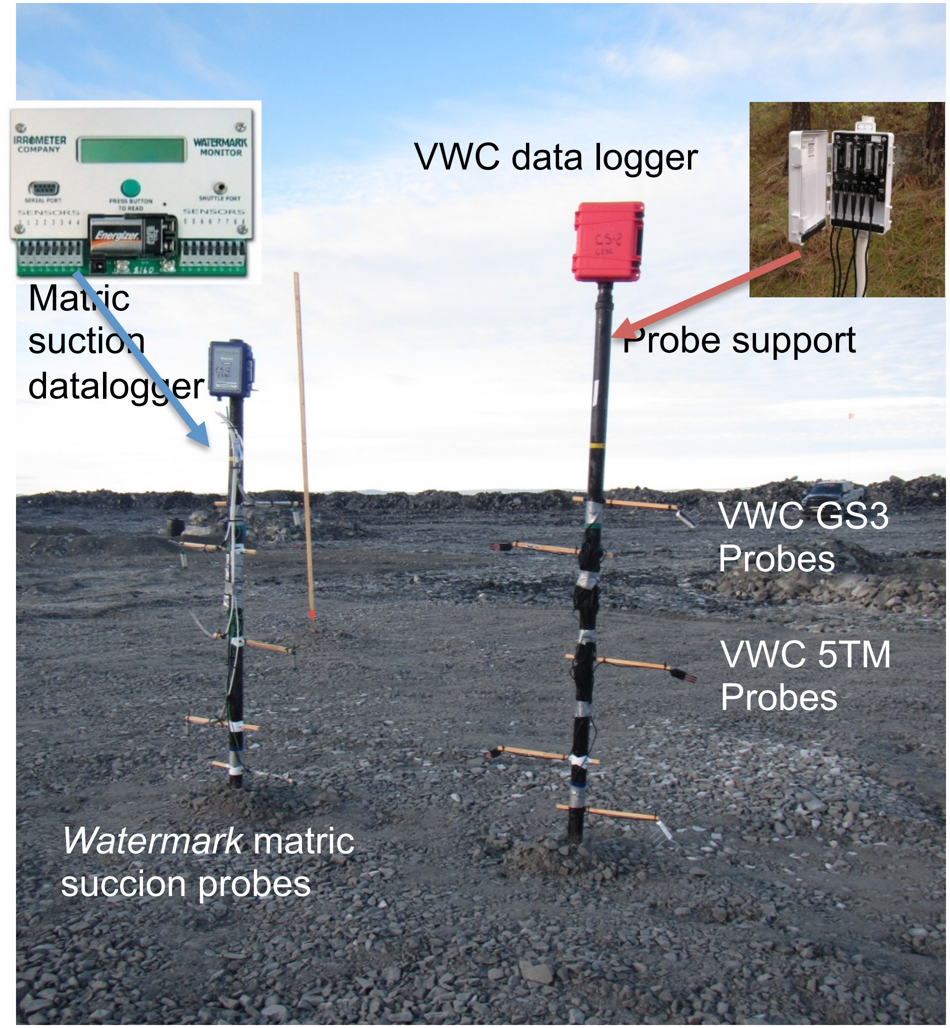
5TM for tailings

GS-3 for waste rock

VWC probes

Matric suction probes

Water level probes



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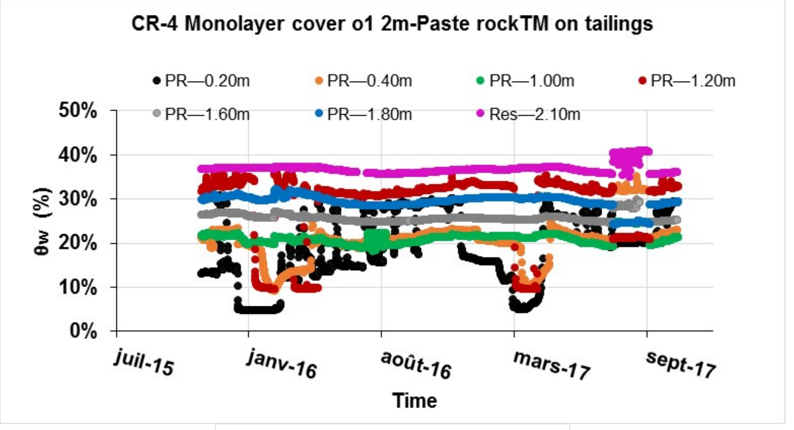
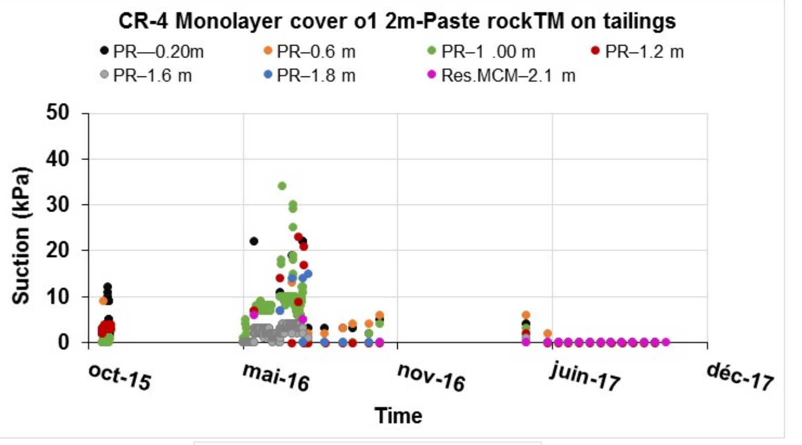
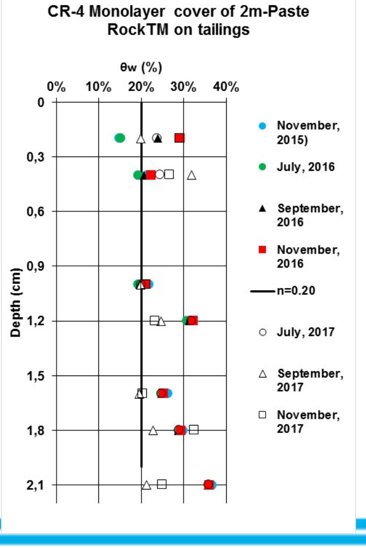
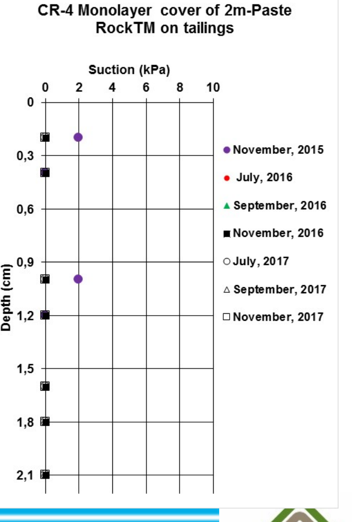
FIELD TEST CELLS

Hydrogeological behavior monitoring (example of results)









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FIELD TEST CELLS

Leachates water quality monitoring (examples of results)

Measured parameters	Control cell	Reclamation cell (example of Monolayer of 2m-*paste rock™*)
pH (–)	7–8	7–8
As (mg/L)	< 0.06 (DLM)	<DLM
Cu (mg/L)	<0.003 (DLM)	<DLM
Fe (mg/L)	<0.1	<0.1
Ni (mg/L)	0.04-0.05	0.04-0.05
Pb (mg/L)	<0.02 (DLM)	<0.02
Zn (mg/L)	0.006-0.05	0.006-0.05
SO_4	≈2500	≈1500
Period	May 25- November 07, 2017	May 25-November 07, 2017
Area (m^2)	25	179
Precipitations (m)	0.5	0.5
Precipitations (m^3)	12	89
Discharged water (m^3)	1.5	5
Infiltration(%)	**13**	**6**

WASTE ROCK SIZE VS CONSTRUCTABILITY

Objective: To evaluate the influence of waste rock particle size on the performance of paste rock as cover materials

- Three field pads (CPR-1, CPR-2 and CPR-3) made with paste rock were constructed over a horizontal portion (1D) of the waste rock disposal area.

- Three different paste rock recipes were preliminary prepared using different waste rock particle size.

Cell	Thickness	Dimensions	Slope	Ratio Waste rock/ tailings	Waste rock Grain size	Volume
CPR-1	1 m	5x5 m	1H:1V	3/1	0-50 mm	17 m^3
CPR-2	1 m	10x10 m	1H:1V	1.3/1	0-100 mm	82 m^3
CPR-3	1 m	10x10 m	1H:1V	1.3/1	50-100 mm	82m^3

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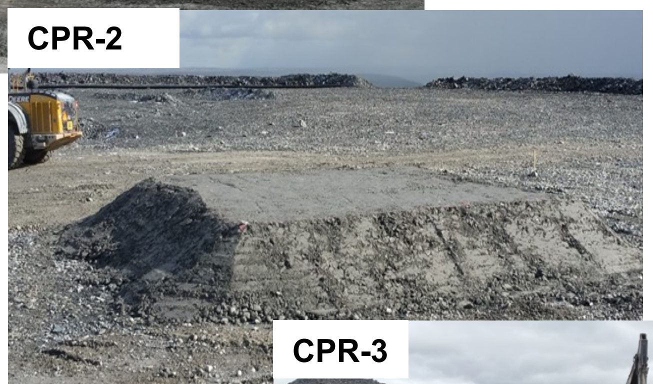
WASTE ROCK SIZE VS CONSTRUCTABILITY

Paste rock pad construction

Monolayer of 1m paste rock (ratio 3/1 - Cw 75%); using waste rock of 0-50mm



Monolayer of 1m paste rock (ratio 1.3/1 - Cw 75%);
using waste rock of 0-100mm

Monolayer of 1m paste rock (ratio 1.3/1 - Cw 75%);
using waste rock of 50-100mm

WASTE ROCK SIZE VS CONSTRUCTABILITY

Result: In-situ density and unit weight Results and in-situ porosity estimations

Cell	Layer	Dry density (Kg/m^3)		Water content (%)		Porosity (-)	
CPR-1 0-50mm	0-0.25m	2162	2160*	7	7*	0.21	0.21*
	0.25-0.50m	2174		6		0.2	
	0.50-0.75m	2196		6		0.2	
	0.75-1m	2106		7		0.23	
CPR-2 0-100mm	0-0.25m	2025	1834*	11.0	10*	0.27	0.33*
	0.25-0.50m	1938		11.0		0.29	
	0.50-0.75m	1689		9.0		0.39	
	0.75-1m	1682		10.0		0.39	
CPR-3 50-100mm	0-0.25m	1951	2017*	10.5	12*	0.29	0.27*
	0.25-0.50m	2050		14.0		0.25	
	0.50-0.75m	2080		12.0		0.24	
	0.75-1m	1985		12.0		0.28	

- In-situ porosity > in pads CPR-2 et CPR-3 than that in pad CPR-1:
  - more tailings in the paste rock (ratio 1.33/1) than in pad 1 (3/1) to get a better mixture.
  - the porosity in pads 2 and 3 is controlled by the tailings porosity

Outline

- Reclamation options
- Laboratory characterization
- Field test cells
- **Summary and on-going work**

Summary

- The option of using paste rock as cover material at the Canadian Malartic Mine is investigated through laboratory and field work.
- Preliminary results are encouraging (low k_{sat}, good water retention properties, in situ preparation feasible) but the ratio (waste rock/tailings) used is a critical parameter (both technically and economically).
- The work is performed in close collaboration between the mine, consulting firms and RIME (two master students are working on paste rock as cover material).

ON-GOING WORK

- Other hydrogeological characterization tests are in progress (permeability test after various freeze/thraw cycles, water retention curves).

- Geomechanical characterization is also planned using shear box tests.

- Columns tests are underway to evaluate the geochemical behavior of paste rock and amended paste rock (to mitigate potential ML/ARD)

- Large scale field test (1-2 ha) to be built summer 2018 at the mine site will be part of the program.

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