Phase Change Materials: Innovation in Adaptation Technology to Address Permafrost Thaw

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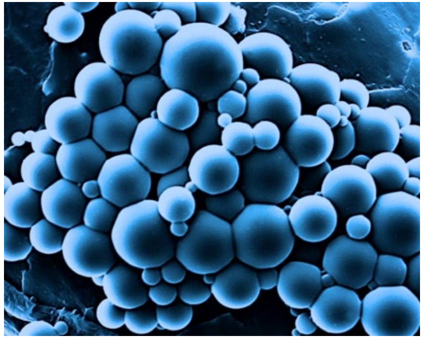

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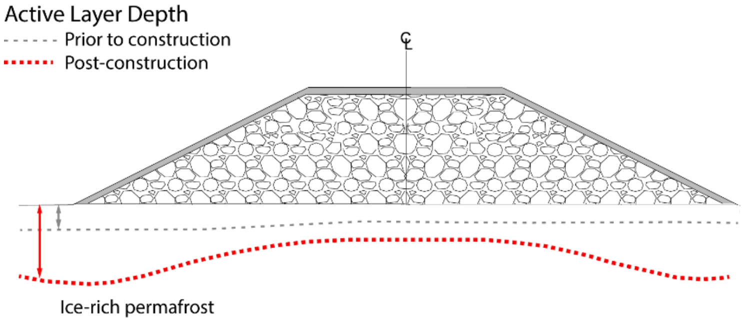
Current Design Approach

- Design approach
  - Maintain permafrost foundation (most common)
  - Thermal conduction cover
  - Reduce heat gain to underlying foundation
  - Limit thaw depth to embankment fill
- Common outcomes
  - Thaw exceeds fill thickness
  - Perpetual thaw of ice-rich permafrost
  - Embankment distress
  - Potential for ROW ponding of water & advection
  - Increased O&M costs
  - Risk to users with potential for injury or fatality



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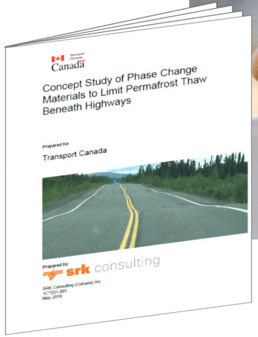
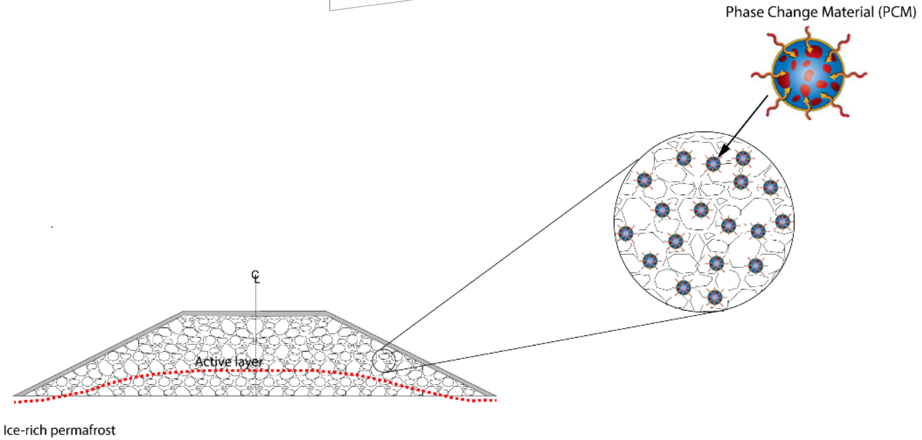
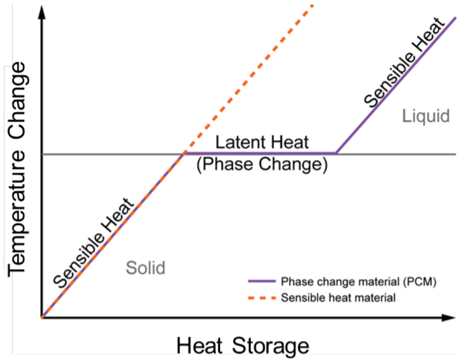
Concept Study

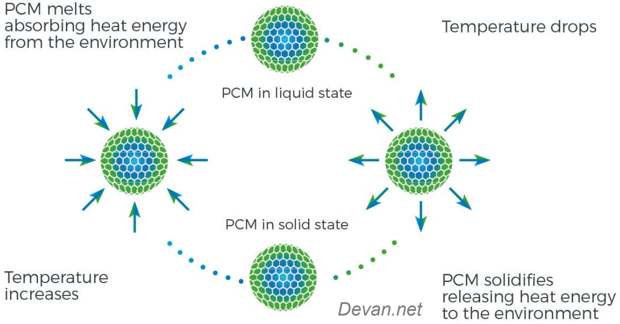
- Integration of PCM to alter thermal properties of fill
  - High heat of fusion
  - Capable of storing large amounts of energy
  - Select PCM certified environmentally safe & biodegradable
- Control placement and transfer of energy
  - Placement of energy within PCM fill
  - Delayed propagation of thawing front





Phase Change Materials





Latent heat to break hydrogen bonds (melting phase 334,000 J kg^{-1})

Macroencapsulated

Phase Change Materials

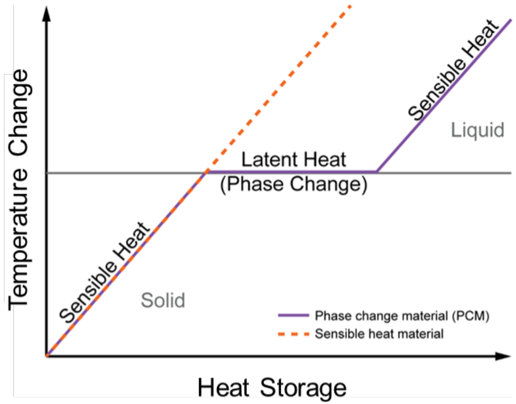
Salt hydrates
- Salts and water
- Phase change temperatures extend 15 to 80°C
- Large volume change, some toxic, vulnerable to supercooling

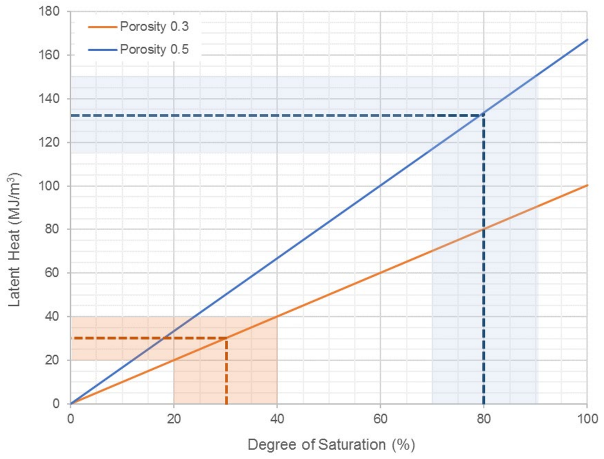
Paraffins
- Petroleum based, waxy substances
- Phase change temperatures extend -8 to 40°C
- Many hazardous to health and environment

Biobased
- Organic compounds animal fats and plant oil
- Phase change temperatures extend -40 to 151°C
- Non-toxic, minimal volume change, relatively low cost

Embankment Fill

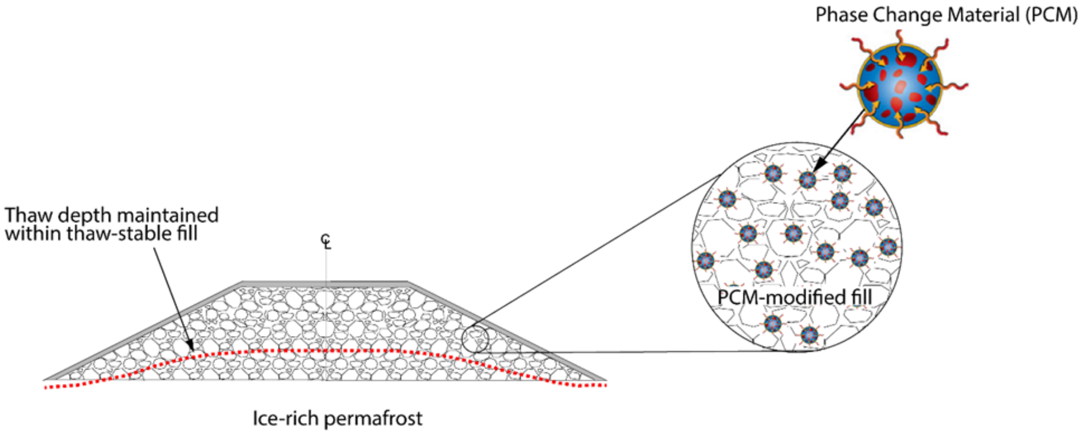
- Material type
  - Well-graded sand and gravel
  - Crushed rock
- Moisture and thermal properties
  - Relatively low moisture content
  - Reduced latent heat of fusion
  - Reduced heat capacity
- Leads to more rapid changes in sensible heat



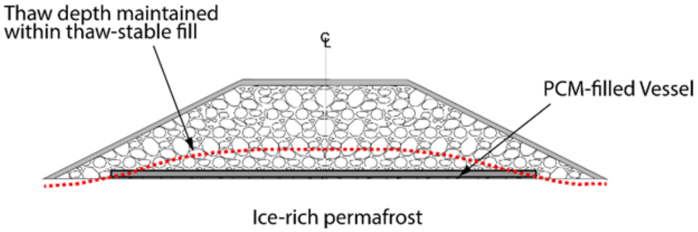


PCM added to fill to alter the thermal properties (increase latent heat requirements and heat capacity) to control placement and transfer of the energy.

Integration of PCM into Fill – Concept Level



PCM-modified Fill
Micro /macro encapsulated PCMs blended with the granular



PCM-filled Vessel
Interlocking PCM-filled vessels to form a horizontal layer

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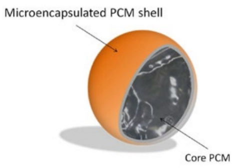
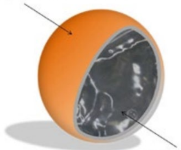
Phase Change Materials

- Phase change temperatures
  - Within expected range of ground temp.
- Thermal conductivity
  - Liquid values similar to water
  - Solid values several similar to water
- Heat of fusion
  - High, generally lower than water
- Range of specific heat values

Product	Phase Change Temperature (°C)	Thermal Conductivity (W/m°C)		Latent Heat (kJ/kg)	Specific Heat (kJ/kg°C)	
		Liquid	Solid		Liquid	Solid
Water	0	0.56	2.24	334	4.18	2.10
1	-15	0.55	2.34	301	2.06	1.84
2	-2	0.60	2.21	277	4.02	2.10
3	5	0.15	0.25	187	2.26	1.78
4	8	0.14	0.22	178	2.15	1.85
5	15	0.15	0.25	182	2.56	2.25
6	18	0.15	0.25	192	1.74	1.47
7	20	0.14	0.23	171	2.15	2.07
8	23	0.15	0.25	227	1.99	1.84



PCM-Modified Fill



PCM-modified Fill		PCM Mass (kg)	Latent Heat of Fusion (MJ m^{-3})	Thermal conductivity (W m^{-1}°C^{-1})		Volumetric Heat Capacity, (kJ m^{-3}°C^{-1})	
PCM%	Mineral %			Unfrozen	Frozen	Unfrozen	Frozen
0	100	0	52	1.83	2.09	2,140	1,784
10	90	81	75	1.70	2.09	2,315	1,790
20	80	161	97	1.57	2.09	2,491	1,796
30	70	242	119	1.45	2.09	2,667	1,803
40	60	322	142	1.32	2.09	2,843	1,809
60	40	484	186	1.07	2.10	3,195	1,821

Fill Thermal Properties (without PCM)

Increase in PCM% based on total volume

Increase in latent heat of fusion

Decrease in unfrozen thermal conductivity

Increase in unfrozen volumetric heat capacity

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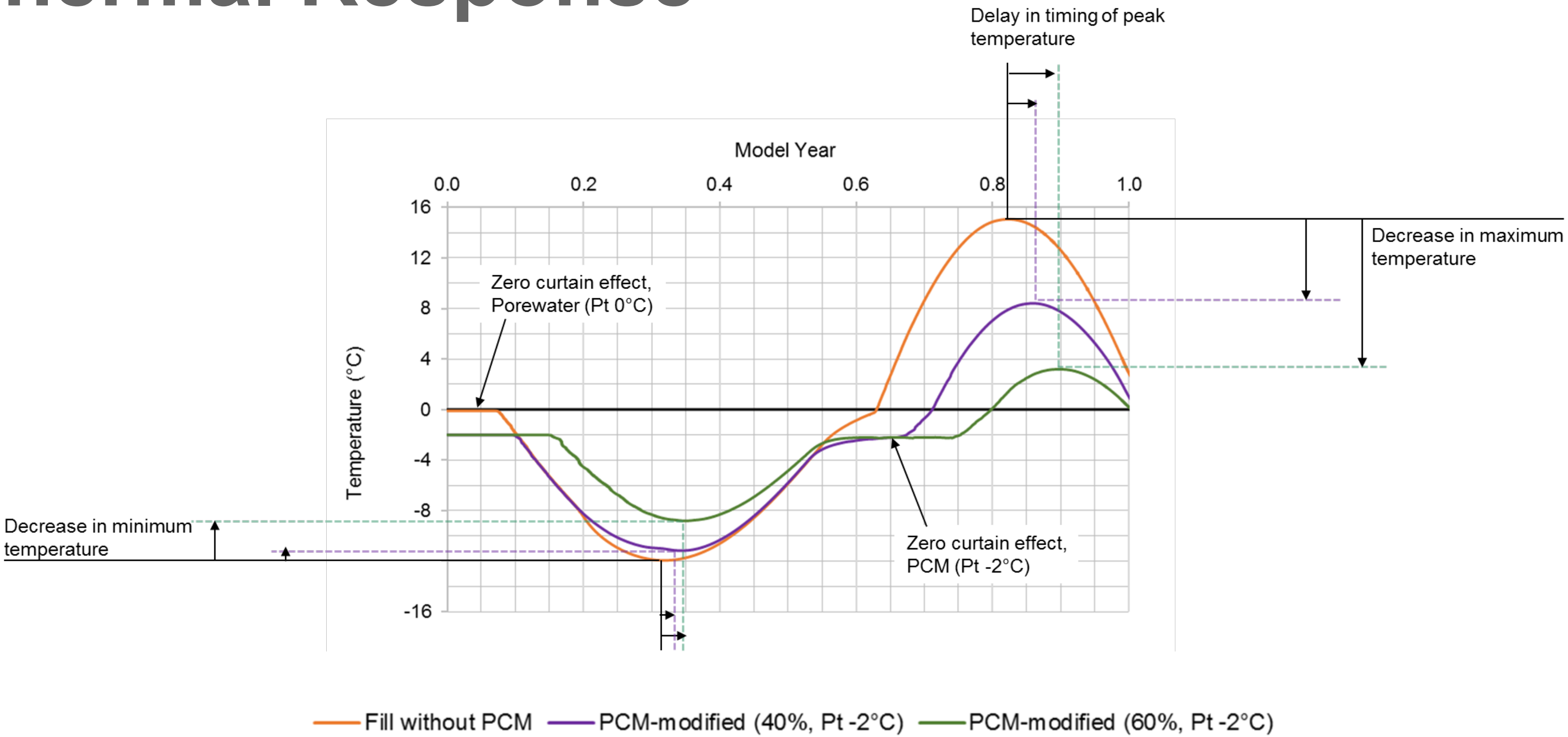
Thermal Response



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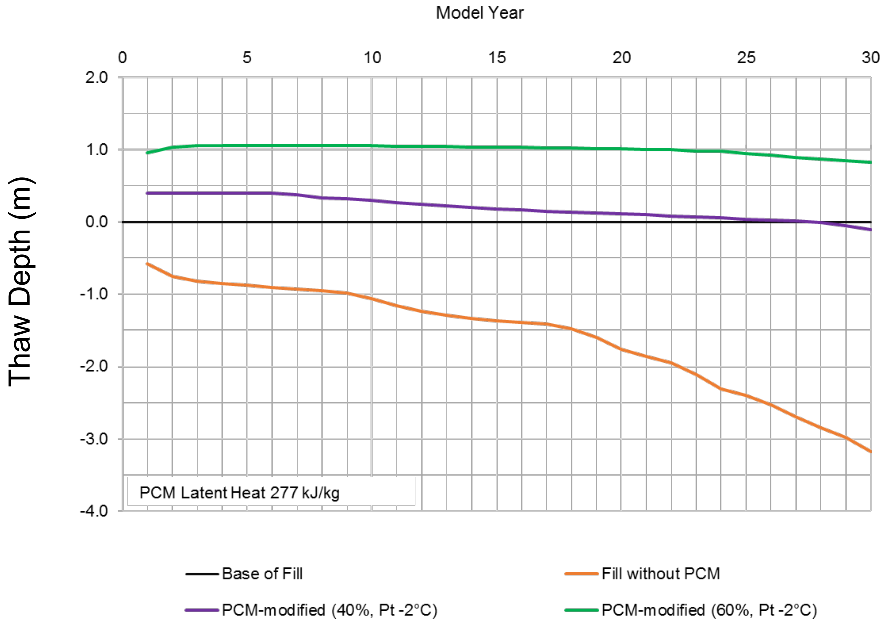
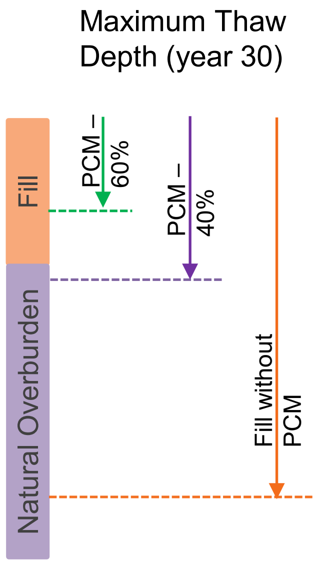
Thermal Modeling

- Theoretical model cases – not completed for specific site
- FlexPDE 1D and 2D models
- PCM integrated as apparent heat capacity term
- 1D model results shown today
- Warm permafrost (-1°C) (most difficult)

Thermal Modeling Results – Maximum Thaw Depth





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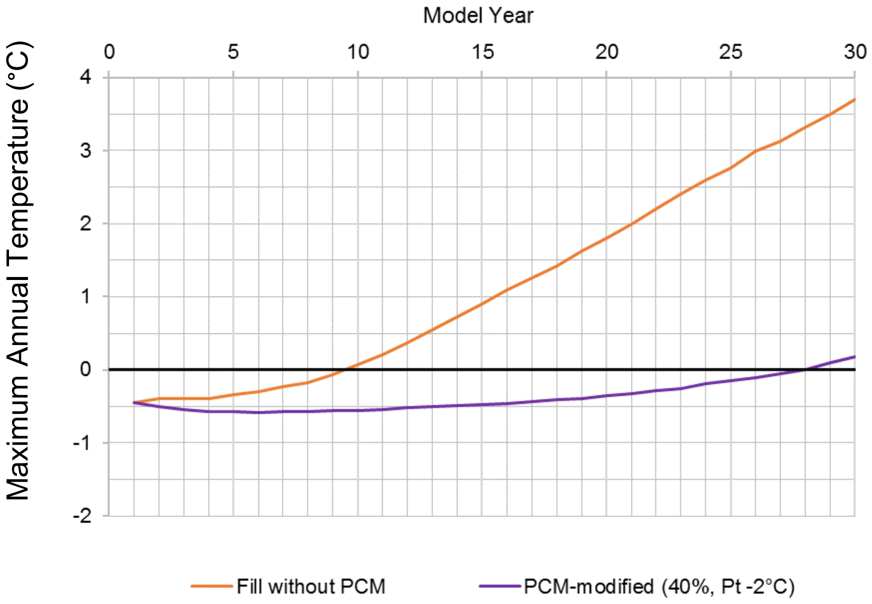
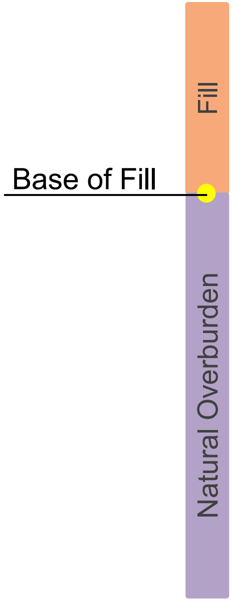
Thermal Modeling Results – Maximum Annual Temperature





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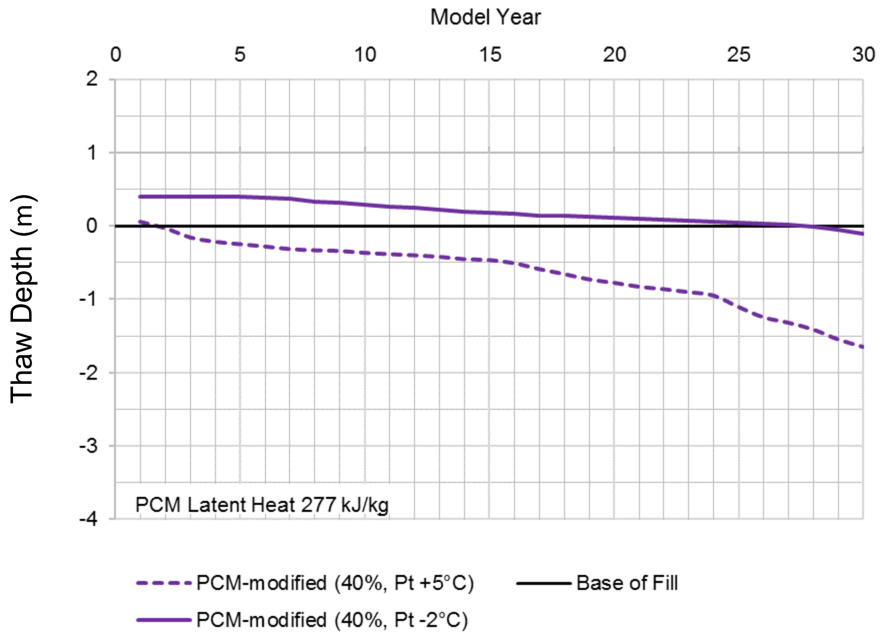
Thermal Modeling Results – Phase Change Temperature



Phase change temperature -2°C

Phase change temperature +5°C

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Conclusions

- PCMs are well-suited for temporary storage of thermal energy due to the high latent heat and specific heat of the material.
- Products are being used by a wide-range of industries and some are certified for environmental applications and biodegradable if released to the surrounding environment.
- Thermal modeling has demonstrated that PCMs could effectively store seasonal energy in construction fill and delay propagation of the thawing front which would otherwise lead to more rapid warming of permafrost and potential for thaw-settlement. This approach is distinct from insulation.
- PCM-modified fill was estimated to have the best thermal performance due to the distribution and quantity of PCM added to the granular fill. The PCM vessel showed some thermal benefit, however; at this time, it is determined to not be practical due to the vessel thickness needed to achieve the energy requirements.
- Thaw depth for PCM-modified fill was maintained within or immediately below the embankment fill for a warm permafrost case (-1°C) and would be expected to limit permafrost degradation over a 30-year period.
- PCM concept is unlikely to be applied alone as a measure to mitigate disturbance at sites that already have extensive permafrost degradation beneath the highway embankment. The concept would be more applicable sites with relatively minor permafrost degradation or newly constructed highways.