Frost in open-graded materials

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PhD

Introduction and background

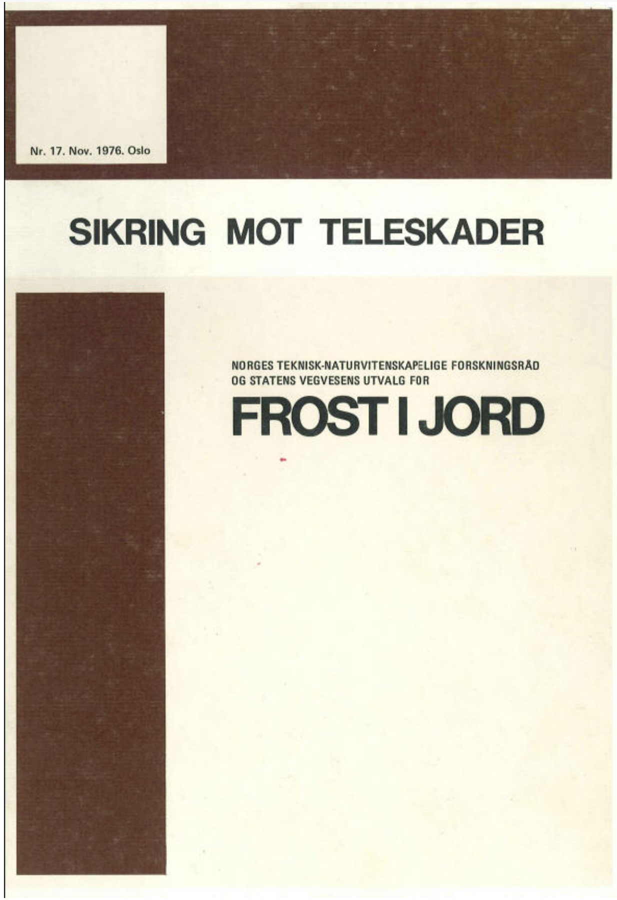
Large scale experimental setup and results

Field test site description and temperature distribution analysis

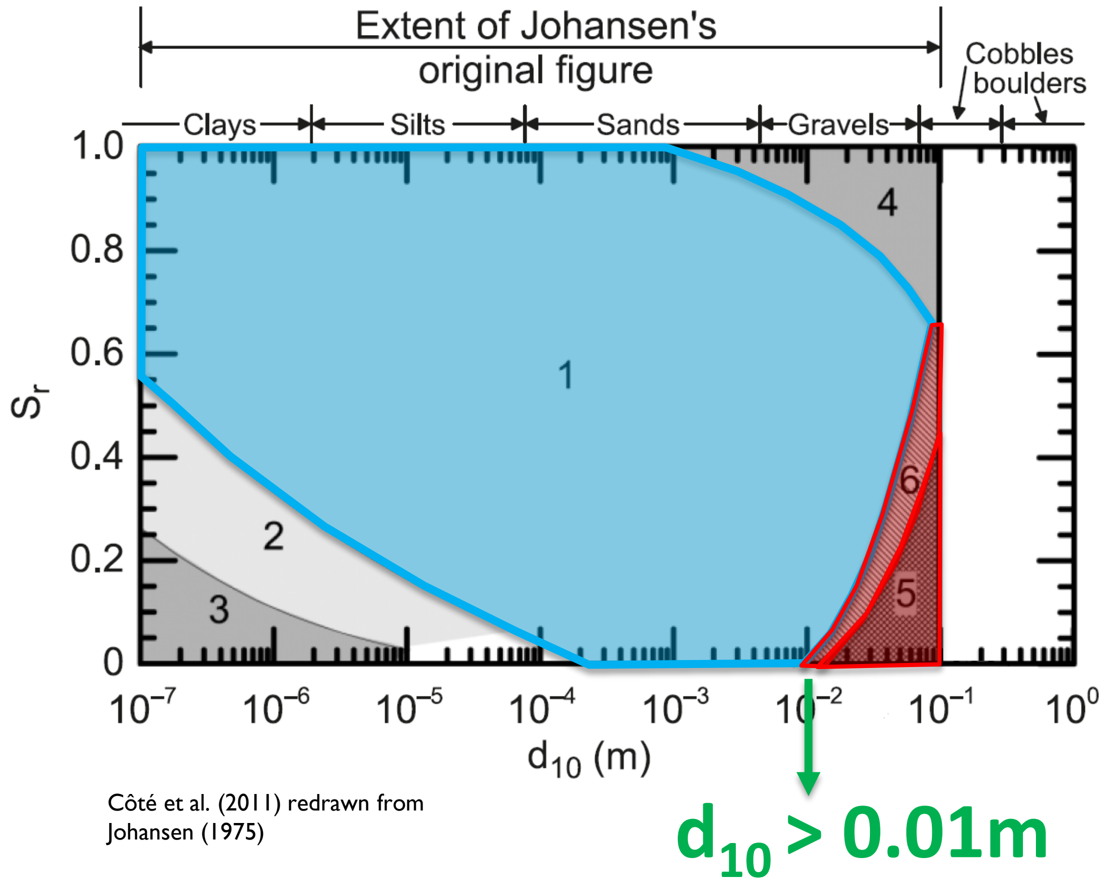
Numerical model of field test site

Conclusions

- The use of crushed rock materials;
- Frost heave on newly built roads/railways;
- Requirements for frost protection layers;
- Other coarse construction materials.



Open-graded materials in road construction



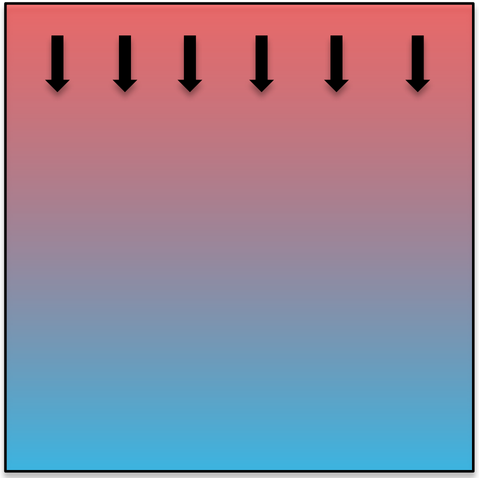
Côté et al. (2011) redrawn from Johansen (1975)

- ❑ Conduction;
- ❑ Free convection;
- ❑ Radiation.

Theory on natural air convection

Downward heat flow

q ↓

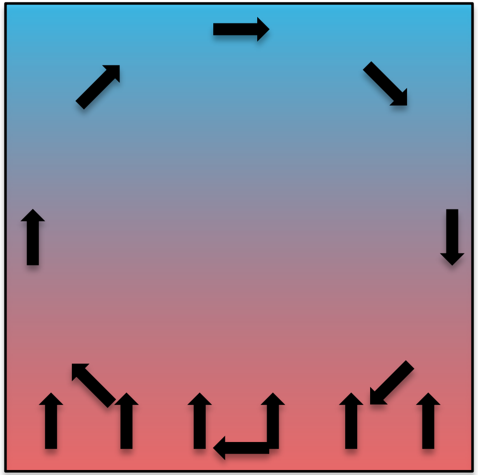


- conduction
- radiation

⇒ effective thermal conductivity

Upward heat flow

q ↑



- conduction
- radiation

- convection

Theory on natural air convection

Nu Nusselt number

$$Nu = \frac{q\uparrow}{q\downarrow}$$

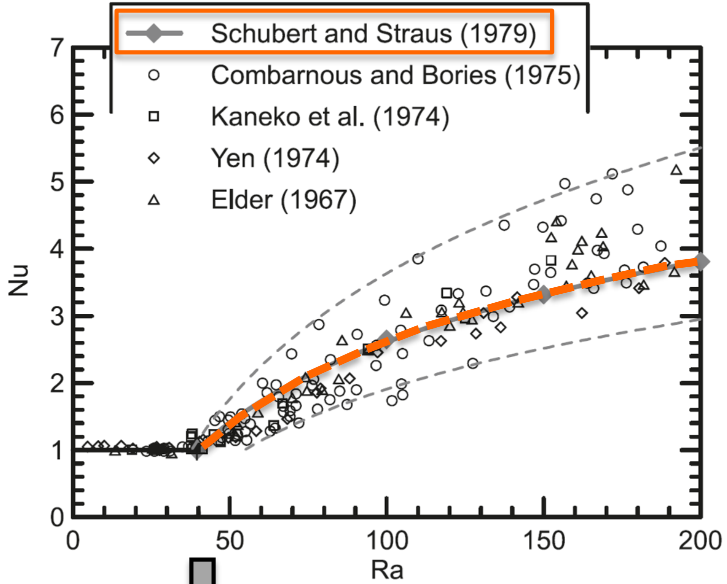
$q\uparrow$ - upward heat flow
$q\downarrow$ - downward heat flow

Ra Rayleigh number

$$Ra = \frac{g\ \beta\ C\ K\ H^2 \nabla T}{\nu\ k_e}$$

g	gravitational acceleration
β	thermal expansion
C	heat capacity
ν	kinematic viscosity
K	intrinsic permeability
H	height
∇T	temperature gradient
k_e	effective thermal conductivity

Theory on natural air convection



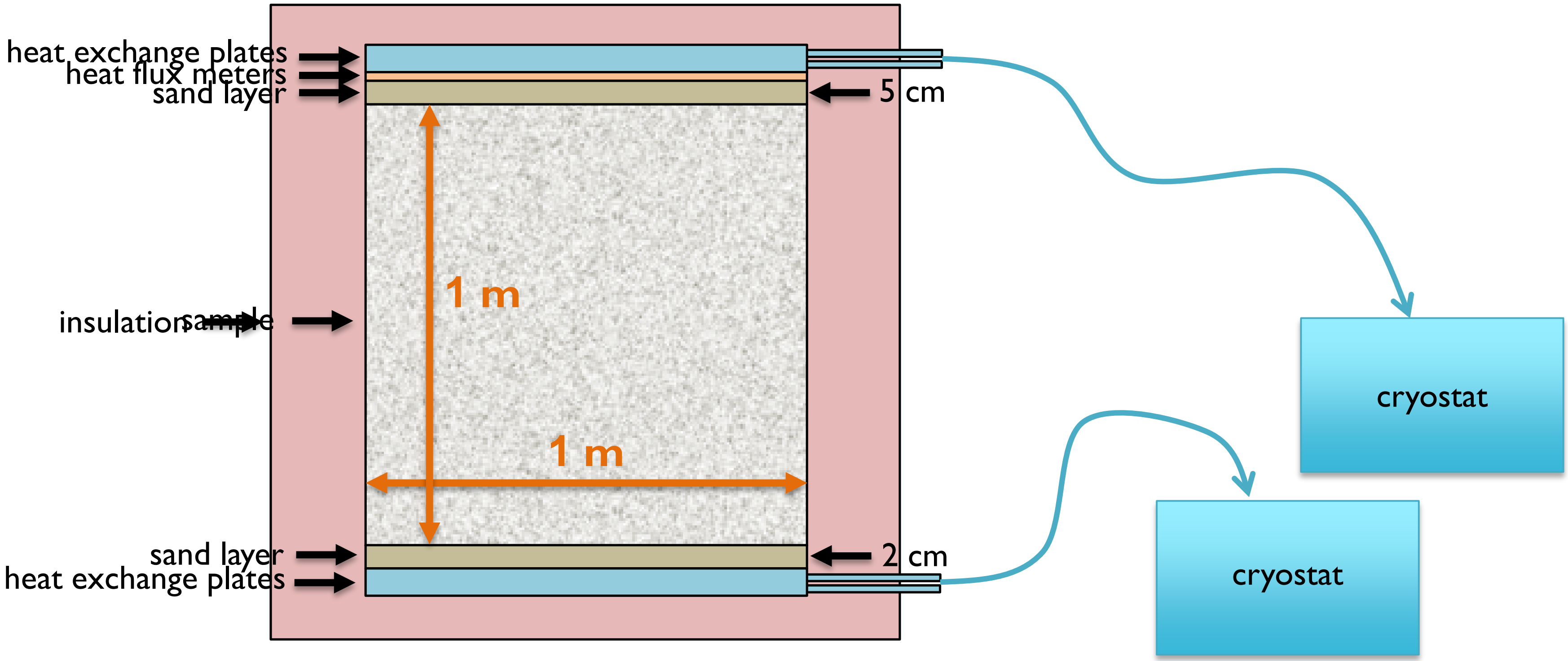
Côté et al. (2011)

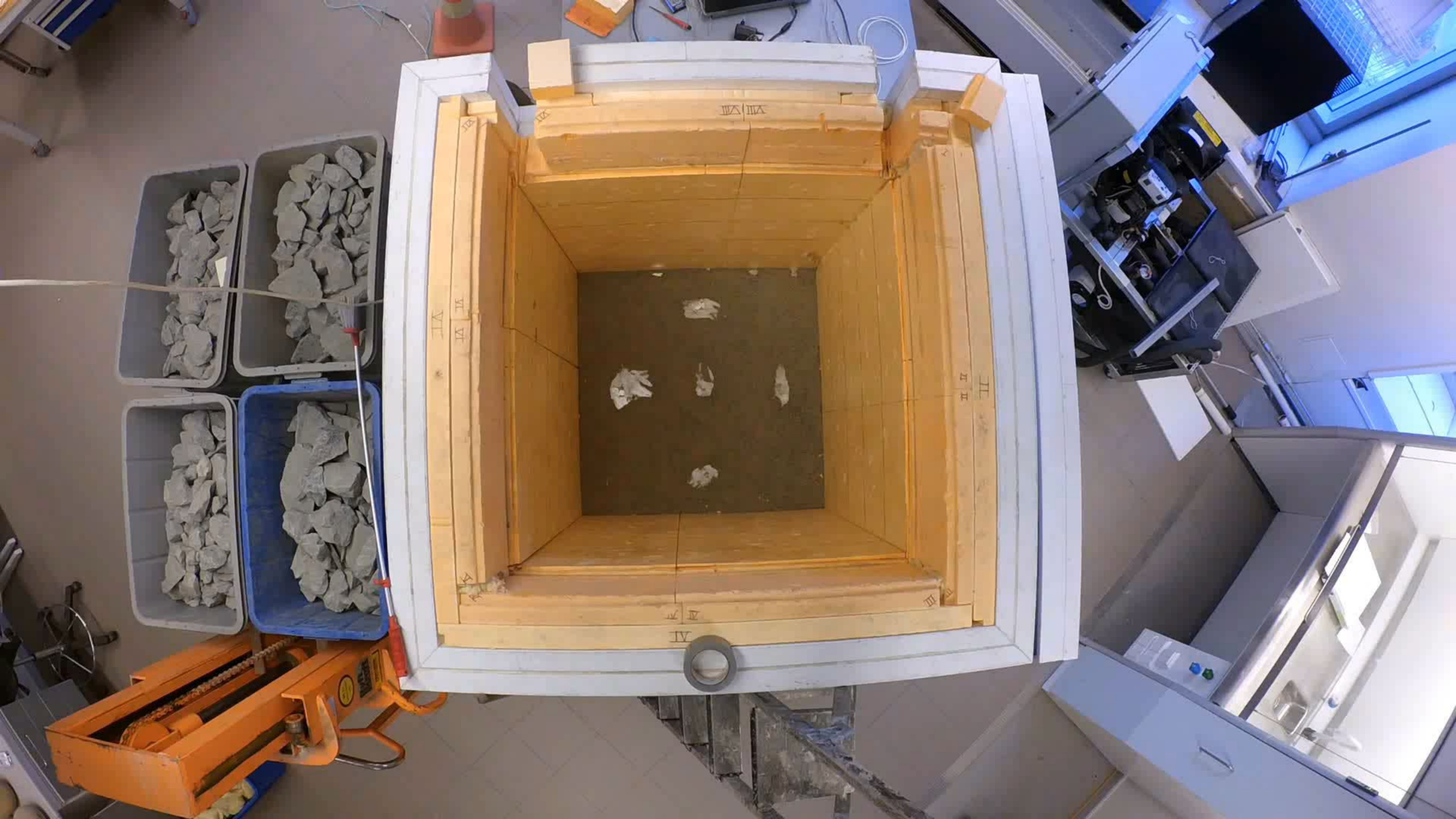
$$Nu = 1.735 \ln(Ra) - 5.38$$

$$\frac{q\uparrow}{q\downarrow} = 1.735 \ln\left(\frac{g\beta C\mathbf{K}H^2\nabla T}{\nu k_e}\right) - 5.38$$

Critical Rayleigh number:

Ra_c = ~40

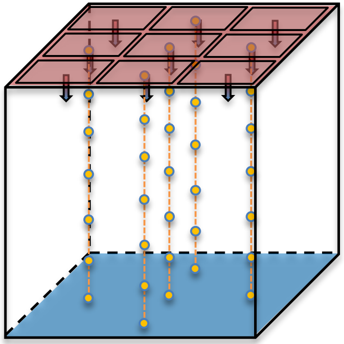

heat exchange plates
heat flux meters
sand layer
5 cm
1 m
insulation sample
1 m
sand layer
heat exchange plates
2 cm
cryostat
cryostat



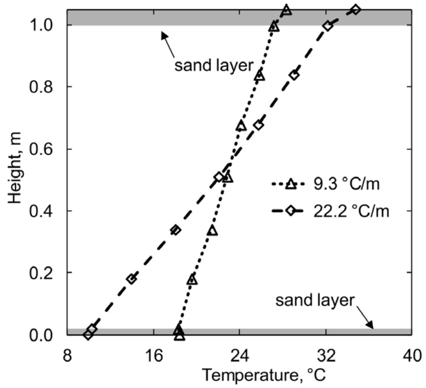
Experimental procedure

Downward heat flow:

q - ∇T



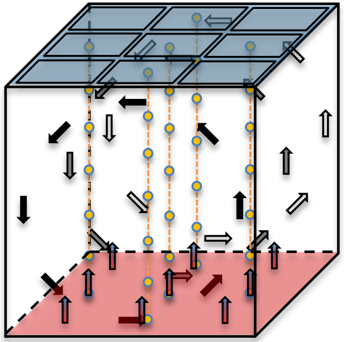
conduction + radiation



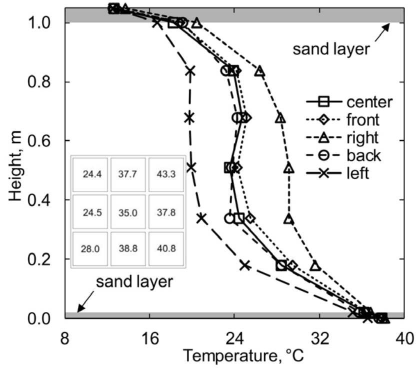
crushed rock 40/120 mm

Upward heat flow:

q - ∇T

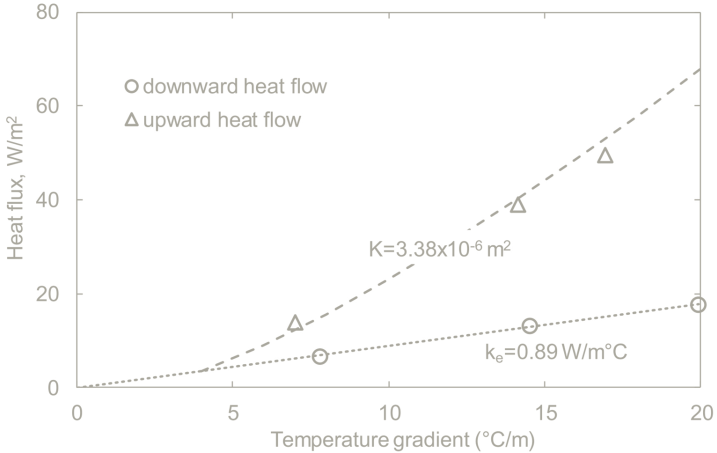


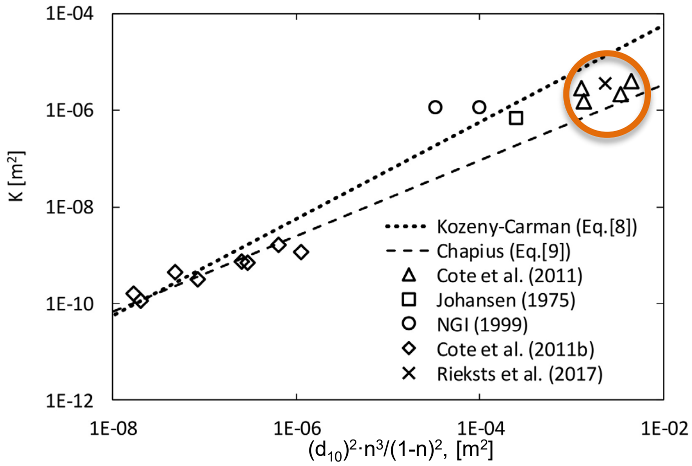
conduction + convection + radiation



crushed rock 40/120 mm

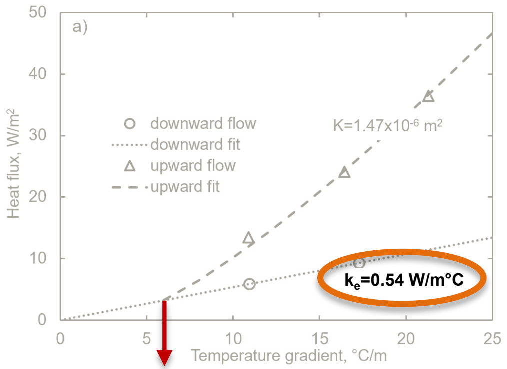
Validation for convective heat transfer with cobbles





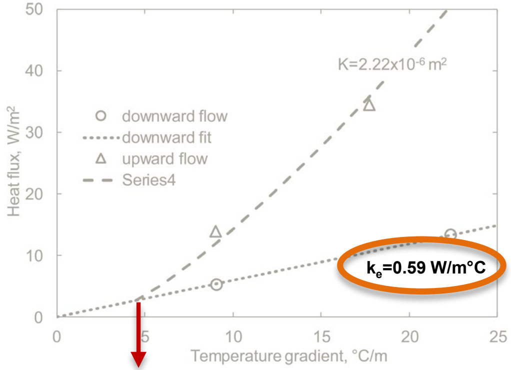
Convection in road construction materials

Crushed rock 20/120 mm (subbase)



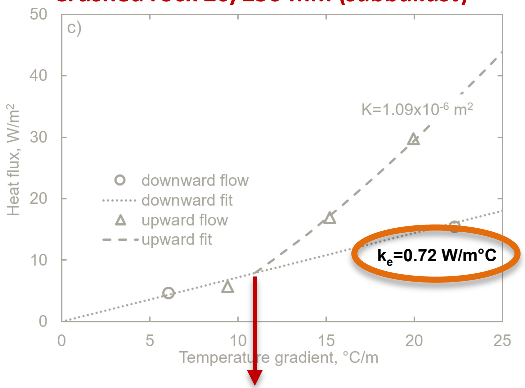
6.0 °C/m

Crushed rock 40/120 mm (frost protection)



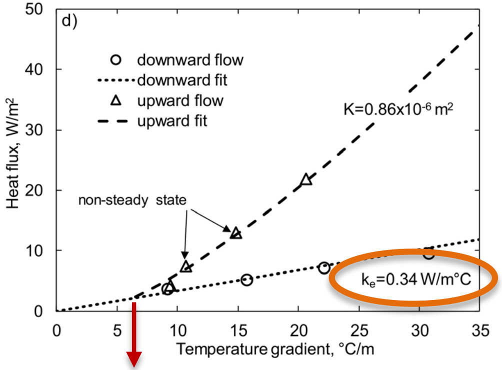
4.5 °C/m

Crushed rock 20/250 mm (*subballast*)



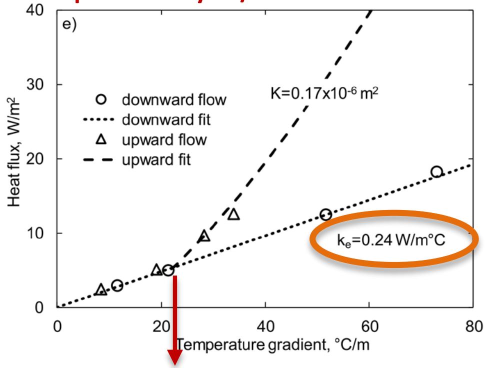
11.0 °C/m

Foam glass 10/60 mm



6.5 °C/m

Expanded clay 10/20 mm

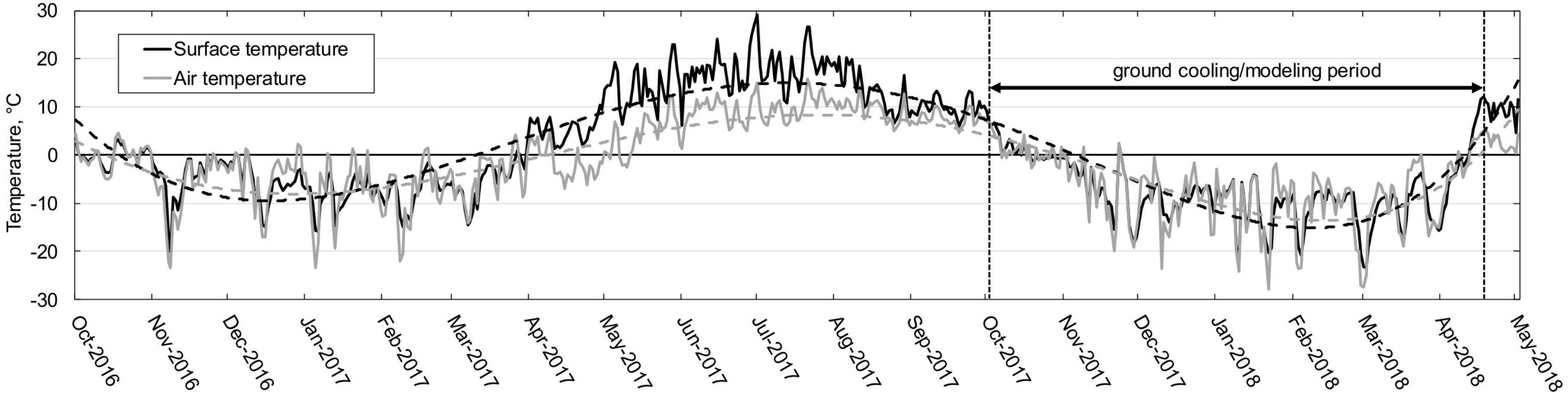


22.5 °C/m

Constructed during fall of 2016

Road sections

Railway sections



Winter 2016 / 2017

FI_a = 25368 °C·h (1057 °C·days)

FI_s = 23160 °C·h (965 °C·days)

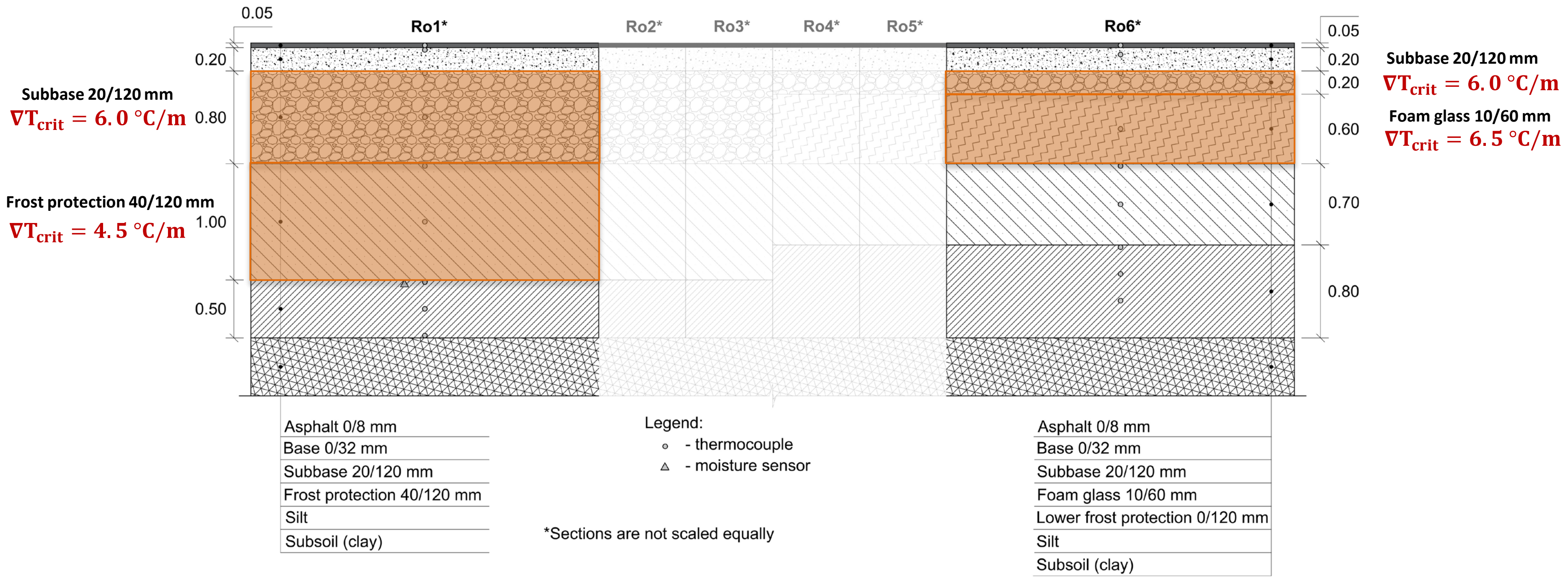
Winter 2017 / 2018

FI_a = 36864 °C·h (1536 °C·days)

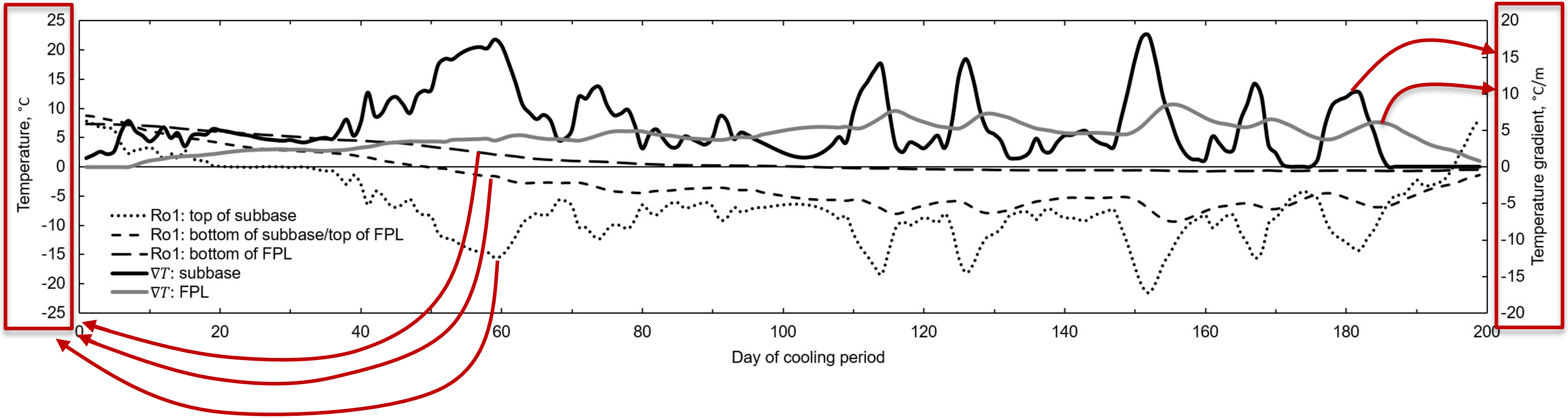
FI_s = 36744 °C·h (1531 °C·days)

Period of analysis: October 2, 2017 to April 19, 2018 → 200 days

Convection in road structural layers



Road section Ro1



Subbase 20/120 mm

$\nabla T_{crit} = 6.0\ °C/m$

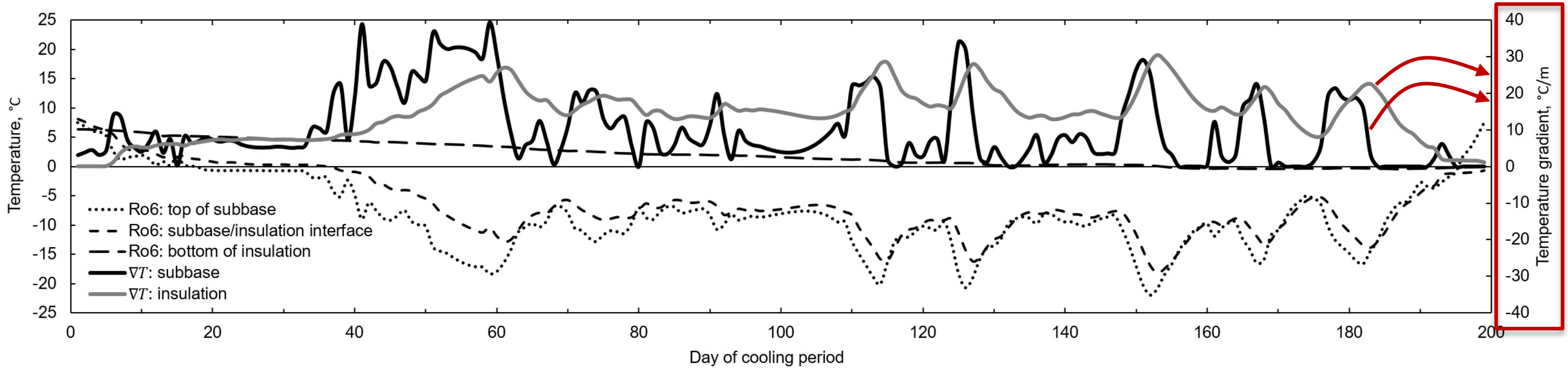
35% of time higher than 6.0 °C/m

Frost protection 40/120 mm

$\nabla T_{crit} = 4.5\ °C/m$

32% of time higher than 4.5 °C/m

Road section Ro6



Subbase 20/120 mm

$\nabla T_{crit} = 6.0\ °C/m$

49% of time higher than 6.0 °C/m

Foam glass 40/120 mm

$\nabla T_{crit} = 6.5\ °C/m$

88% of time higher than 6.5 °C/m

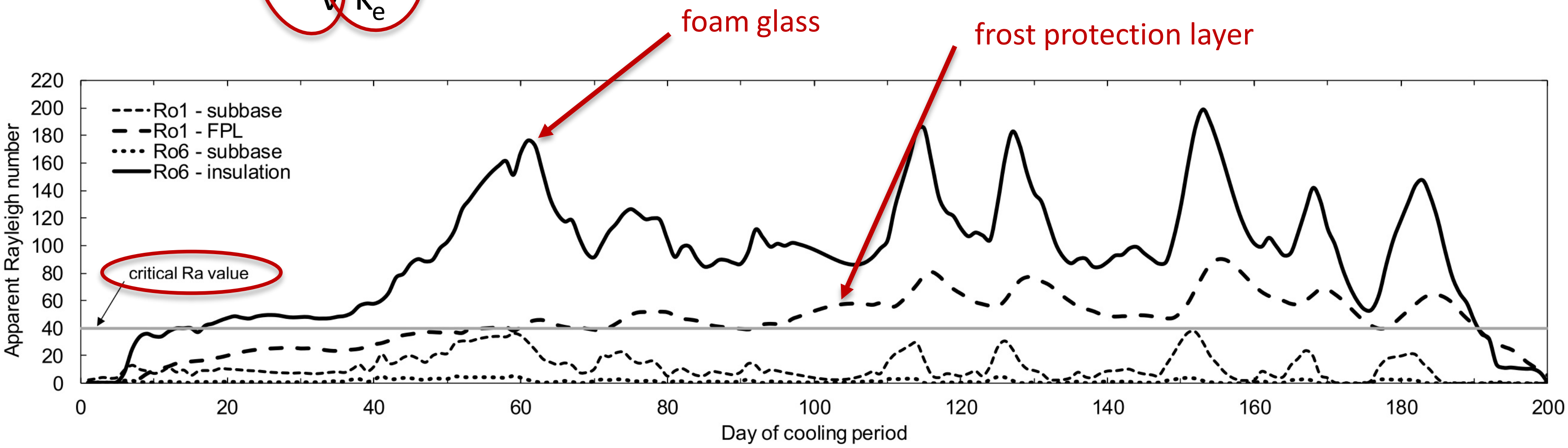
Test-site simple analysis

kept constant

adjusted depending on layer

$$Ra^* = \frac{g \, \beta \, C \, K \, H^2 \, \nabla T}{\nu \, k_e}$$

variable



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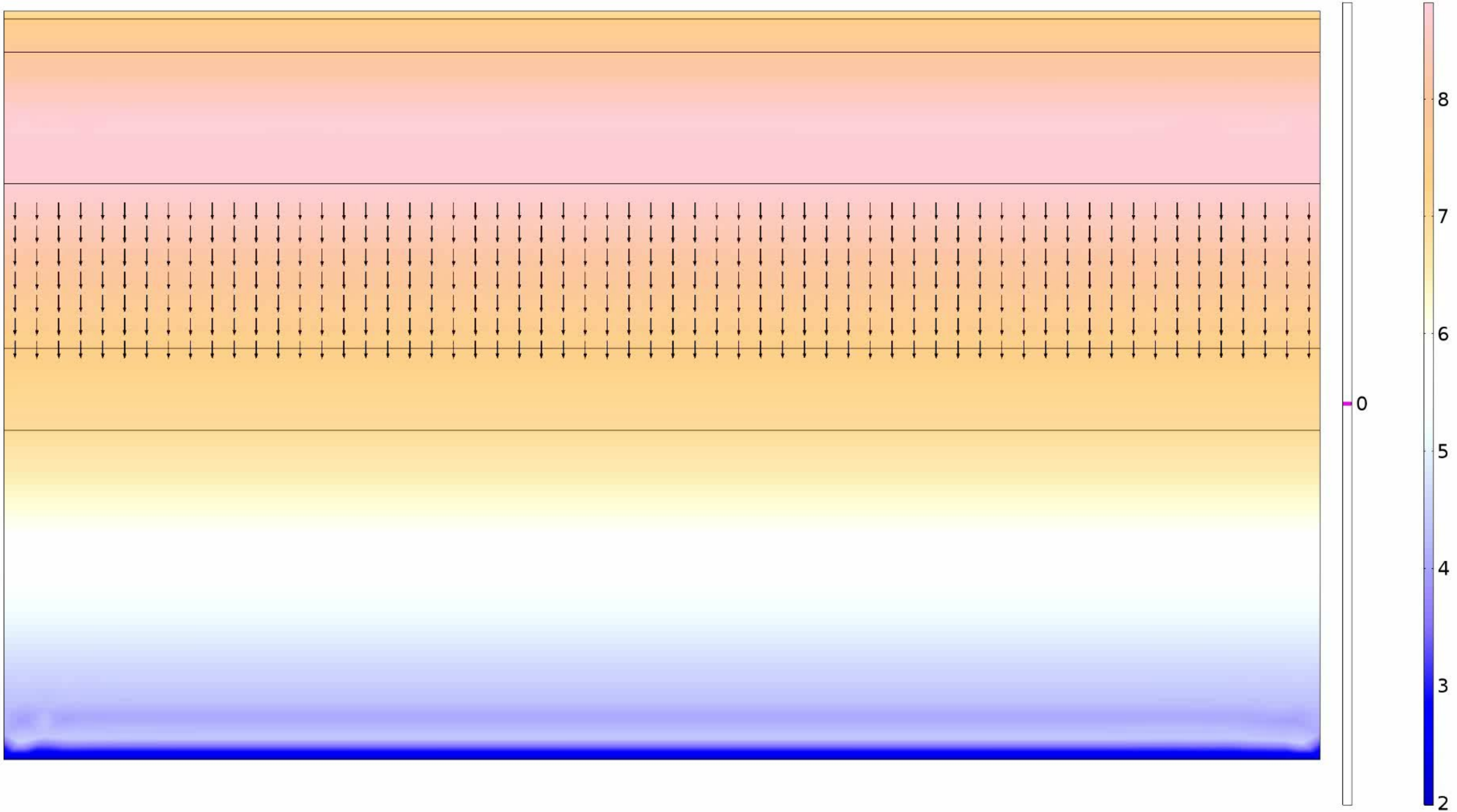
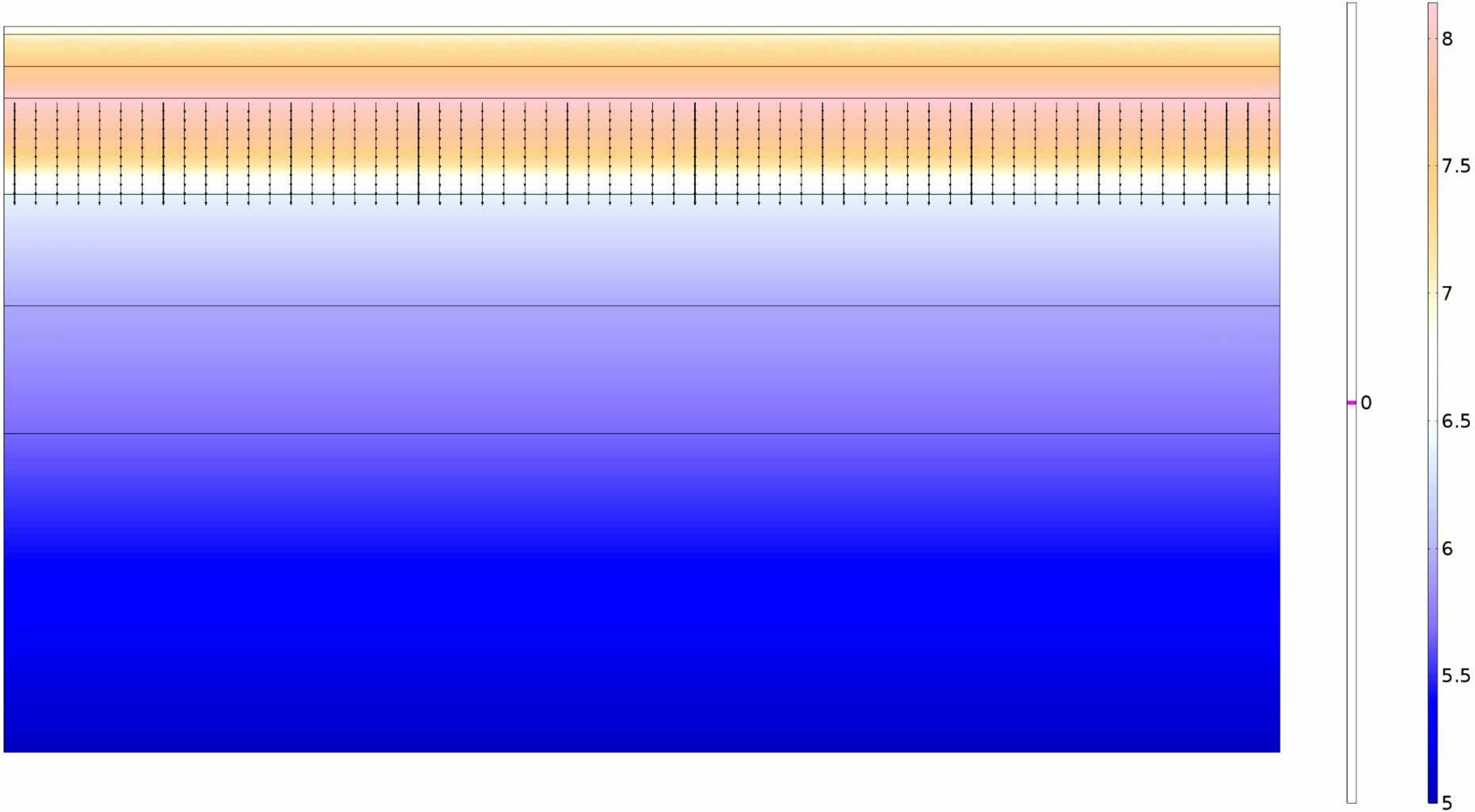
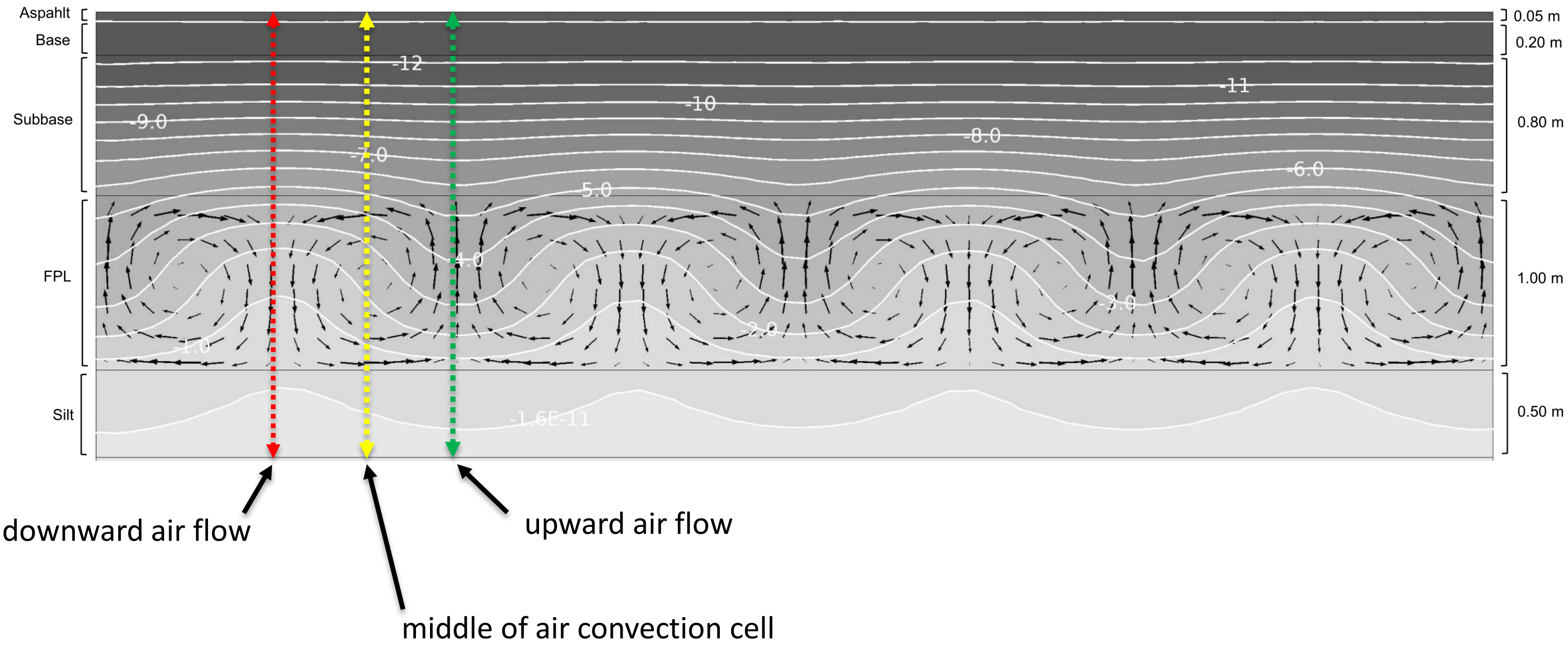
Road section Ro1



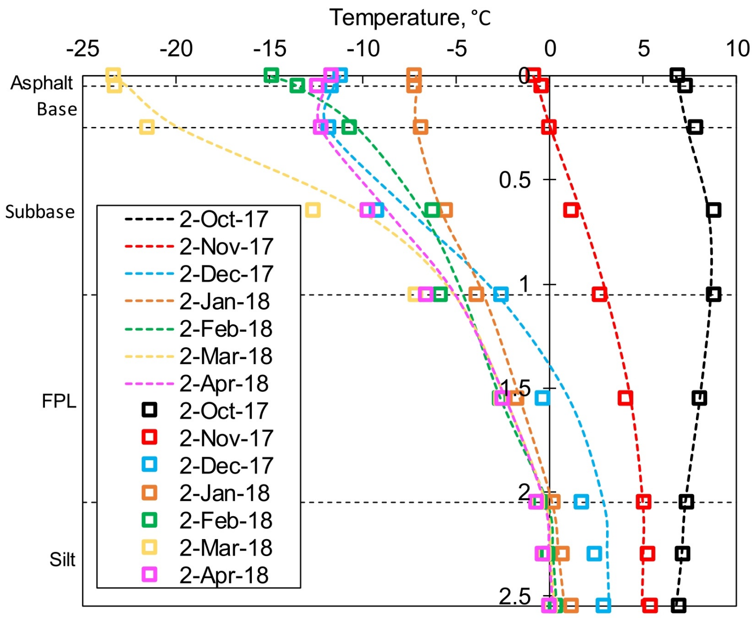
Road section Ro6



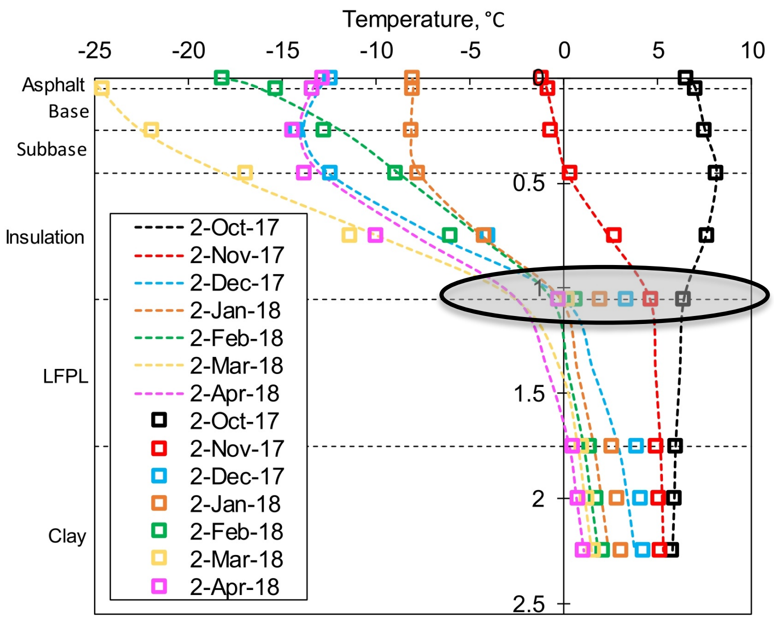
Road section Ro1



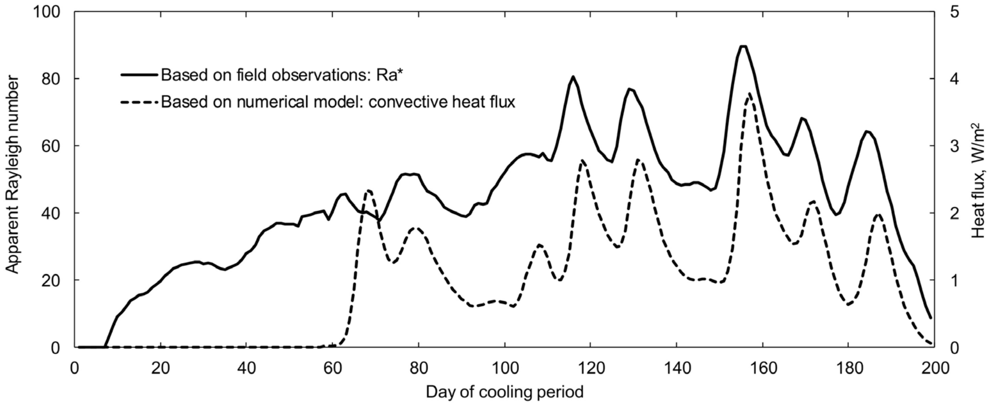
Road section Ro1



Road section Ro6

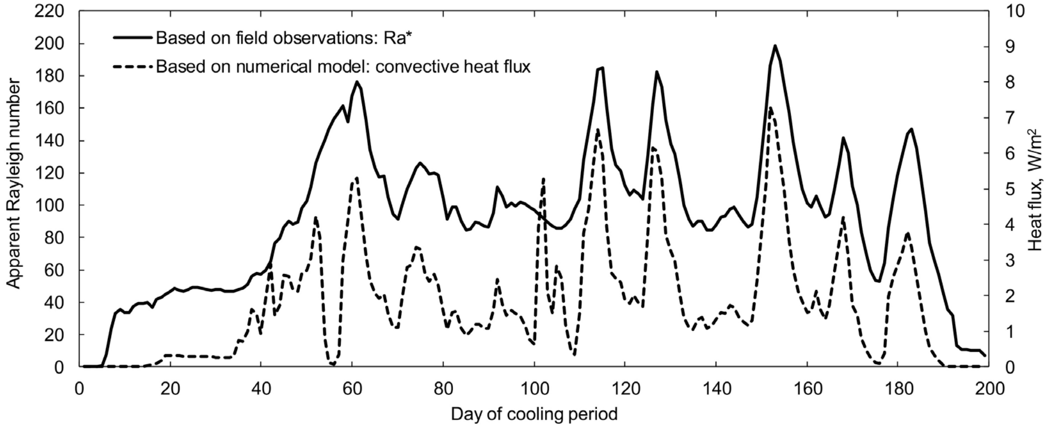


Road section Ro1



Convection in frost protection layer

Road section Ro6

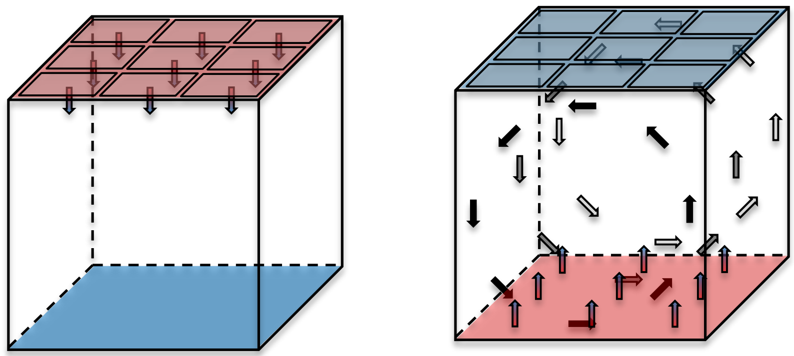


Convection in foam glass layer

Conclusion:

- Measurements of coarse-materials;
- Modelling;
- Frost protection layer – crushed rock materials;
- Coarse-subbase;
- Lightweight aggregates.

Thank you!



Glasopor

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