Revision of the French reference document of frost design method for High Speed Railway Lines.

C. Mauduit, J. Livet & L. Peiffer
Laboratoire Régional des Ponts et Chaussées, Nancy, France.

A. Robinet
Société Nationale des Chemins de fers Français, Direction de l'Ingénierie, Paris, France

G. Lefebvre
Centre d'Etudes et de Recherches en Thermique, Environnement et Systèmes, Université Paris XII, France.

ABSTRACT **:** The revision of the project of typical railway structure s catalog has lead Société Nationale des Chemins de Fer français (SNCF) to consider a modernization of its "frost design method". In particular, high speed railways required very severe levelling margins. Very high speeds need perfect evenness to prevent any defect of lengthwise level, which would generate unballasting risk and vertical movement injurious for the lifetime of structures. A collaboration has been engaged with the Laboratoire Régional des Ponts et Chaussées (LRPC) de Nancy. The aim was to build a new technical SNCF reference document using the design pavement method developed by the network of Laboratoires des Ponts et Chaussées. during the past three decades. This approach is based on thermal modelling of structures and winter characterization through the freezing index concept.

The process followed for the realization of this document consisted in reproducing the scheme employed for the road frost design method, adjusting it to the railway problematic. Indeed, besides use' specifities, rain penetrates railway structures. Energy exchanges are enhanced with atmosphere, the water continuously modifying physical properties of railway components. Moreover, use of atypical materials for roads builders, such as ballast, obliged additional laboratory tests in order to know their physical properties and thermal behavior.

KEY WORDS **:** Frost design method, high speed railway track, thermal conductivity, ballast.

GLOSSARY :

IR : reference freezing index (°C.day)	Q_g : acceptable quantity of frost transmitted to frost susceptible layers (°C.day)
IAtm : atmospheric freezing index (°C.day)	Q_{ng} : thermal protection of the capping-layer ((°C.day)$^{1/2}$)
IA : acceptable atmospheric freezing index (°C.day)	A_n : thermal coefficient of the capping-layer (°C.days)$^{1/2}$/cm
IS : surface freezing index (°C.day)	h_n : thickness of the non-frost susceptible layer (m)
It : transmitted freezing index (°C.day)	Q_M : quantity of frost evaluated by mechanical analysis ((°C.day)$^{1/2}$)
p : slope of heaving frost test (mm/(°C.hour)$^{1/2}$)	Q_{PF} : quantity of frost acceptable at the capping-layer level ((°C.day)$^{1/2}$)
k : thermal conductivity (W/mK)	e : thickness of thawed soil (m)
l : samples thickness (m)	ΔT : temperature gradient (°C)
S : samples surface (m^2)	Φ : flux (W)
ku : unfrozen conductivity (W/mK)	n : porosity (%)
kf : frozen conductivity (W/mK)	ρd : dry density (kg/m^3)

1. INTRODUCTION

The SNCF reference document for track bed layers design takes into account frost protection. The existing frost design approach is based on the old road design methodology (SNCF, 1995). As part of the program of optimisation of the track bed layers, RFF (the owner of the French railways infrastructure) asked SNCF to create a new reference document and to study the adaptation of the new road methodology developed by the network of Laboratoires des Ponts et Chaussées to railways.

The target of this evolution is the optimisation of the track beds and the evaluation of the impact of new materials use in the layers such as asphalt, cement treated soils, etc.

A better knowledge of the thermal behaviour of the ballast is necessary to bring the project to a successful conclusion. SNCF has entrusted the Laboratoire Regional des Ponts et Chaussées de Nancy, specialised in the field of frost protection, with this study.

2. FROM ROADWAY DESIGN METHOD TO THE RAILWAY FIELD

2.1 French frost design method for pavements

The French pavement design approach is decomposed in two parts (LCPC-SETRA, 1998) :

- the first one consists in a mechanical calculation based on a combined approach between contributions of mathematic models, experimental data and the knowledge of the behavior of current pavements observed on test sections, or on accelerated pavement testing. This method adopts a probabilistic calculation approach by estimating the changes over time in the probability of failure of the pavement structure.
- the second part of the design method consists in a verification of the design pavement taking into account frost conditions. In this approach, the freeze-thaw verification of pavements only focuses on the assessment of thaw damage (frost heaving risk is neglected) due to the loss of bearing capacity of the thawed frost sensitive layers. This parameter is estimated by a frost heaving test according to a French standard (NF P 98-234.2).

In the freeze-thaw verification, a winter is chosen as a reference and is characterized by its freezing index. The harshness of this index depends on the policy followed by the road manager. The verification consists in the comparison between IR and IA, evaluated thanks to the structure and its frost susceptibility.

- If IR ≤ IA, frost testing is positive and the pavement structure is adopted.
- If IR > IA, frost testing is negative and the pavement has to be modified (increase in the thickness of the non-frost susceptible layers) until a positive frost testing is reached.

IR depends on the area climate and IA, function of the structure, is calculated in five steps :

- Step 1, examination of the frost susceptibility of the soil support : the quantity of frost Q_g is deduced from the slope of the heaving frost test (Table 1) and Q_{ng} is determined by the relation $Q_{ng}=A_n h_n^2/(h_n+10)$ with A_n values presented in Table 2.
- Step 2, mechanical analysis : the mechanical behavior verification in thaw periods is realised limiting to 5% the increase of stresses in the pavement, in relation to the normal situation. The thickness of thawed frost susceptible soil (e) is calculated by iteration with a capping-layer resilient modulus divided by 10. This thickness is transcribed in an additional quantity of frost accepted by the relationship Q_M = e/10.
- Step 3, determination of the quantity of frost acceptable at the capping-layer level : $Q_{PF} = Q_{ng} + Q_g + Q_M$.

- Step 4, study of the thermal protection provided by the pavement structure. A calculation thermal model forecasts the freezing index that will be transmitted from the surface to the bottom of the foundation layer. An equation, It = f (IS) is then established.
- Step 5, determination of IA, corresponding to IS and acceptable for the structure, by IA= IS/0.7+10, according to the relationships : $Q_{PF} = \sqrt{It}$, It = f(IS) and IS =0.7(IAtm-10). The ultimate equation has been fixed by experimental measurements on sampling of pavements in conditions of exposure representative of an average.

Table 1 : Values of Q_g

p (mm/(°C.hour)$^{1/2}$)	≤0.05	0.05<p≤0.25	0.25<p≤1	p>1
Q_g ((°C.day)$^{1/2}$)	∞	4	1/p	0

Table 2 : Values of the coefficients A_n

Materials	A[(1)]	B[(1)] et C[(1)]	D[(1)]	LTCC[(2)]	CV[(3)], SC[(4)],SL[(5)]
A_n (°C.days)$^{1/2}$/cm	0.15	0.13	0.12	0.14	0.17

[(1)] soil classes defined by standard (French standard : NF P 11-300)
[(2)] lime cement-treated silt, [(3)] fly-ash, [(4)] cement-stabilized sand, [(5)] slag-stabilized sand

2.2 Adjustments to the railways problematic

The process followed for the definition of this reference document consisted in reproducing the scheme employed for the road frost design method, but adjusted to railway problematic.

2.2.1 Different problematics between pavement and railway structures.

In the pavement field, a reasonable alteration of the structure is allowed by heaving during frost periods and loss of bearing capacity during thaw periods. This ageing is thought to be tolerable according to the lifetime of the road. Moreover, it is possible to add some materials, resulting in a mechanical compensation and a decrease of the probability of the frost front to reach frost susceptible layers. At the same time, the bituminous pavement has a watertightness which limits the impact of infiltration. Finally, in critical extreme freezing index situations, load restrictions (thaw barriers) can limit the deterioration of roads.

In the railway field, the problematic is different, as frost issues are rather estimated through the notion of the materials' heaving during frost periods, considering the necessity of a perfect evenness of the structure. Moreover, the railway approach has to take into account high speeds, where any defect of lengthwise level would damage the structures and then reduce their lifetime. Otherwise, railway structures can't integrate load restrictions or adjunction of material on the surface. Design method assumptions have therefore to be more severe. Lastly, contrary to pavements, rain penetrates railway structures and is continuously modifying physical properties of railway constituents.

2.2.2 Hypotheses for the reference document and complementary investigations

Based on these differences, some hypotheses have been taken into account for the application of the French reference document of frost design method to High Speed Railways Lines. These hypotheses were a simplification of the frost pavement design method. The first one considered that the permissible quantity of frost which can be transmitted to the frost susceptible layers as nil (Qg=0). The second one neglected step 2 about mechanical protection (no treated materials employed in this structure : (Q_M=0)).

As both fields differ on a few points, some interrogations have been raised and need to be solved by additional tests or studies. Among them, not presented in this paper : frost susceptibility of railway structure materials and the way of taking it into account (slope of heaving frost test or absolute heaving), geothermal gradient in the first forty meters of the ground, thermal exchanges on surface's structure (relationship between air and surface temperature and between corresponding indexes) and physical properties of ballast (equilibrium water content, emissivity and thermal conductivity) have been carried out (Mauduit C.& Livet J., 2003-2004). For the thermal behavior of ballast, one of the most important parameter for the definition of the frost design method (fundamental coefficient with a significant incidence in modelling), additional laboratory tests were conducted and are summed up below.

3. CHARACTERIZATION OF PHYSICAL PROPERTIES OF BALLAST MATERIAL

Physical properties and heat transfer in porous material such as ballast have been studied. Experimental measurements have been done to characterise thermal conductivity and water content. Theoretical modelling has been carried out to approach convective heat transfer which may occur in such highly porous materials.

3.1 Thermal conductivity measurements

Thermal conductivity of two distinct natures of ballast have been measured in dry conditions, a trapp (similar to basalt) and a rhyolite rock. Two sets of experimentation have been made :
- characterisation of the thermal conductivity of the rock (solid phase only).
- measurement of the thermal conductivity of the ballast porous medium (granular shape)

3.1.1 Thermal conductivity measurement at steady state on rocks samples.

The laboratory apparatus, presented in figure 1, uses two identical solid rock cylindrical samples (diameter 200 mm and 30 mm thick) sandwiched between two cylinders cooled by a cryogenic fluid and separated by a heater that provides an electric power proportional to the thermal one. Temperature probes, symmetrically placed on both sides of the tested samples, allow to calculate, when the steady state is reached, the conductivity of the rock tested, with a formula deduced from Fourier's law : $k = (\phi / S) * (l / (\Delta T))$.

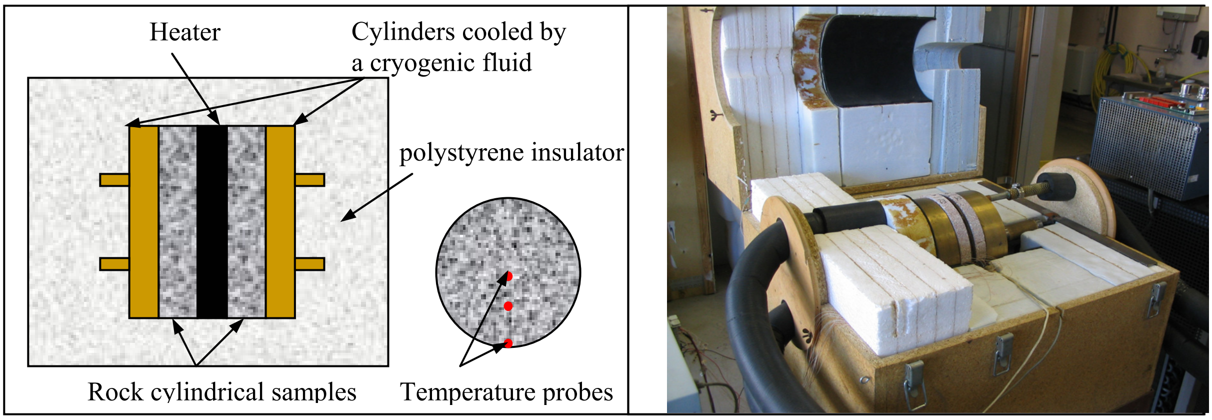


Figure 1 : Thermal conductivity test on rocks samples

The results, presented in Table 3, were in agreement with the literature, where conductivity of eruptive rocks with microlitic structure, such as trapp and rhyolite, ranged between 1.6 and 2.1 W/mK (Missenard, 1965). Among the different materials valid for high speed railway lines, conductivity values varied between 1.6 and 2.6 W/mK, except for quartzite, considered separately (k ≅ 4.5 W/mK). The hypothesis retained for the definition of the reference document were an average of 1.6 and 2.6 and another one of 4.5 W/mK.

Table 3 : Thermal conductivity measured on rocks samples (solid phase only)

Samples	Measured Thermal conductivity (W/mK)
Pyrex (standard sample : laboratoire national d'essais value : 1.12 W/mK)	1.10
Trapp	1.86 / 2.12
Rhyolite	1.59 / 1.67

3.1.2 Thermal conductivity measurement on ballast in its granular shape

The experimental apparatus (figure 2) consisted in a approximately $1m^3$ box. All box faces were insulated with polystyrene in order to minimise heat loss, and temperature gradient is generated using two circulating water baths at the top and bottom of the box.

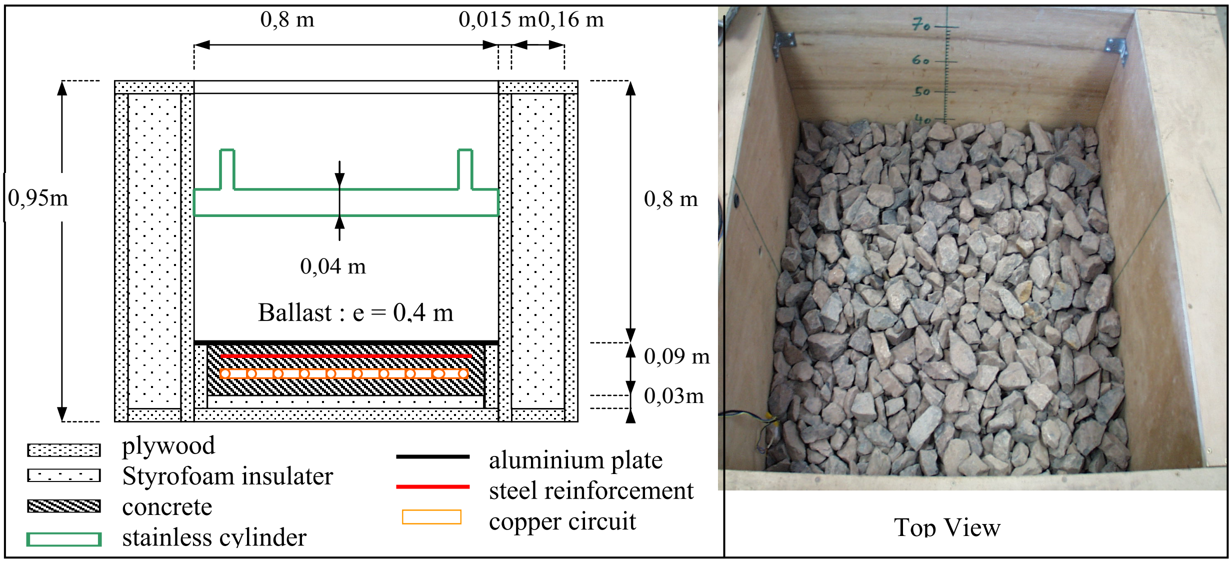


Figure 2 : Thermal conductivity test on ballast in its granular shape

Measurements were performed so that the average temperature in the box was close to the ambient one. The highest temperature was applied on the top of the box in order to avoid the development of convective heat transfer. The opposite configuration may induce, according to the geometry of the apparatus, convective heat transfer in the porosity (Goering, 2000).

The ballast was put into the box in 10 cm layers and lightly compacted to a level close to the one encountered on site (vibration and traffic solicitations). Two temperature probes were installed at the top of each layer and two fluxmeters (thickness 0.5 mm) were placed in contact with the warm surface. During the test, the temperatures were continuously monitored to ensure that the temperature profiles had reached a steady state.

For this experimentation, two configurations have been tested to simulate the evolution of the physical properties of ballast during his lifetime :

- a clean ballast with real grain size distribution (25/50 mm)
- a dirty one, polluted by its attrition's particles which fill up the air voids (12.5% of 1.6 mm)

Table 4 : Thermal conductivity measured on ballast in its granular shape

Samples	Thermal conductivity (W/mK)
Clean Trapp	0,49 (+/-0,16)
Dirty Trapp (artificial pollution)	0,60 (+/- 0,21)
Clean Rhyolite	0,42 (+/-0,12)
Dirty Rhyolite (natural pollution)	0,91 (+/-0,49)

Standard deviation not calculated according to conventional rules

Table 4 gives the results obtained with the four materials. The difference observed on clean ballast were in complete agreement with measurements conducted on rock sample, the thermal conductivity of trapp being lightly greater than the rhyolite one. For dirty materials, the difference observed on the results can be explained by artificial pollution particles (0-6mm) for trapp, not representative of the real contact between grains (development of thermal contact resistance).

3.2 Interdependence of parameters : Mickley modelling

Physical properties of ballast evolve during the lifetime of the structure due to combined effects of climate and mechanical solicitations. Intrinsic characteristics are directly linked with external factors : precipitations increase the water content of the ballast (temperature acting on the phase of this water) and traffic solicitations involve ballast's attrition and rising of particles from sublayers, increasing pore filling process and modifies its specific weight.

It is relatively known that the heat transfer characteristics of a composite medium as a porous one can be approximated by combining the ones of the different components. Very complex mathematical theories known as homogeneization methods (Bergman & al., 1985) may be used, but, in the geotechnical field, more comprehensive methods as the de Vries model (de Vries, 1963) or the Mickley model (Mickley, 1951) are usually used.

The Mickley model has first been used to make a cross-comparison between the results obtained, at a dry state, with both experiments (on rock samples and on ballast in its granular shape). This comparison has given satisfactory results, with differences of about 20%, considering a porosity of dirty ballast n=25%.

Then, the Mickley model has been used to determine thermal conductivities of dirty ballasts, at different level of water content, in order to determine the most restrictive couple water content / thermal conductivity, for frost penetration.

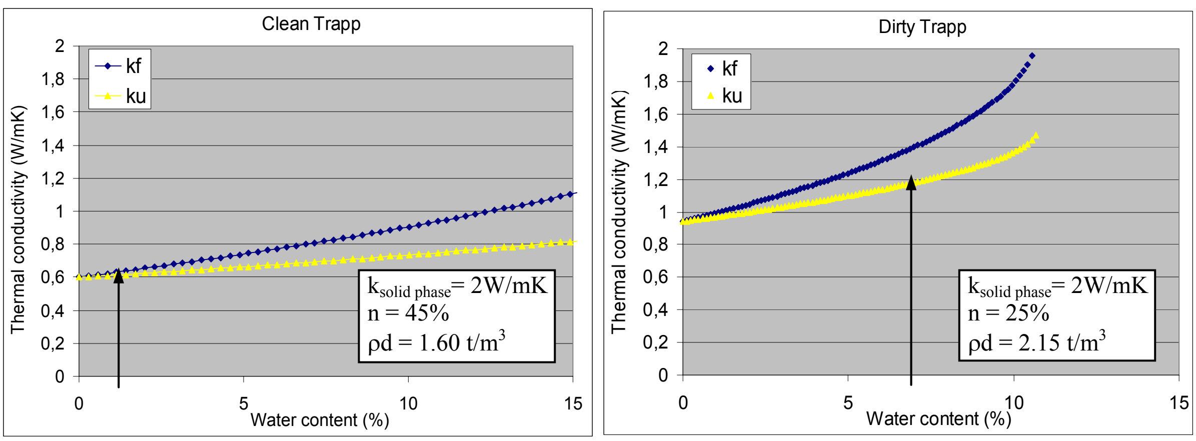


Figure 3 : Application of Mickley model on both configurations of trapp ballast.

The examples presented on Figure 3 show the conductivity values selected for clean or dirty trapp for reference water content (equilibrium water content laboratory tests have shown a reference value equal to 1% for clean ballast and a maximum value of roughly 7% for the dirty ballast). For a clean trapp, thermal conductivity values are ku=0,61W/mK and kf=0,63W/mK (water content 1%), and for a dirty trapp, ku=1,16 W/mK and kf =1,40 W/mK (water content 7%).

3.3 Theoretical works on convective heat transfer in porous materials

As the objective of the study was to extend to railways the frozen design method elaborated for roadways, it has been decided to use, the same reference modelling tool, Cesar-Gels (see 4.1). It was then necessary to be able to describe the heat transfer as a conductive one and to evaluate two effective heat conductivity values, one for the unfrozen and one for the frozen ballast.

In the case of energy transfer through a macro porous medium such as a railway embankment ballast, relatively small temperature gradient induces very low effect of the radiative exchanges, compared to conduction and convection (Techer, 2003). Some initial experiments and modelling work showed that the convection phenomena might be of first importance, fact that has been also pointed out by other researchers (Goering, 2000), (Lai Y. & al., 2004).

Different typical convective situations may occur. The observed ballast embankment may be open or close, the convection may be due to temperature gradient (natural convection) or due to pressure gradient (forced convection), the temperature gradient may be positive in the bottom-up or in the top-down direction, etc.

In order to design railway embankments in frozen conditions, the situations which must be evaluated are not ones which will certainly actually occur. The prediction needs not to be a realistic one, but may be in some sense a worse one ; we may assume that it will lead to a good design for more usual situation.

The idea is not then to take into account the heat convection phenomena in all possible configurations, but in few of them, where the convection will be taken into account as an increase of the heat conductivity value which is supposed to increase the freezing risk.

Three typical convective configurations could be evaluated for every embankment design problem : one without convection, one with relatively intensive natural convection and one when a huge forced convection occured. Convection phenomena may have effects in all directions or be orientated (for example, when a huge top-down air flow occurs, top temperature has an influence on the bottom part of the embankment, but the bottom temperature may have no influence on the top part of the embankment). Then it is proposed to describe a worse situation by including an isotropic increase of heat conduction corresponding to the highest possible contribution of convection among all possible direction and orientations. It is assumed that the frozen risk is a monotonal function of the effective conductivity of the embankment and that majorating the conductivity value increased the frozen risk. In order to limit the overcost which may be induced by the methodology, a moderation may be introduced by weighing the results corresponding to the three typical convective situations (the weighing factors being chosen by the railways manager in charge of the acceptable risk).

It remains to evaluate the air speed values and the corresponding effective heat conductivity values in some typical configuration, thanks to a detailed model currently elaborated. It will be necessary to evaluate the effective usefulness of the proposed methodology by modelling a relatively large configuration set.

4. IMPACT OF PHYSICAL PROPERTIES OF BALLASTS ON FROST PENETRATION

4.1 Numerical model CESAR-GELS

CESAR-GELS is a CESAR-LCPC general software module using the finite elements method.
This software solves the well-known Stefan problem in which the freezing-thawing phenomena in a porous medium is described as a set of two solid parts (frozen and unfrozen) separated by a moving frontier where the phase change occurs (described as an enthalpy term in the energy balance equation of the frontier). Only heat transfer by conduction (described by Fourier's law) may occur in each solid part. The unknown factors are temperatures and frost front propagation speed. Each layer is characterized by its dry density, its water content, its thermal capacity, its frozen and unfrozen thermal conductivity.

4.2 Geometry, initial and bordered conditions and physical properties of materials

All the possibilities of assembling layers of high speed railway structures, in nature and thickness, are currently tested. The structure' geometry has been chosen in relation to real dimensions of railway tracks. Three configurations of capping-layer thickness were defined as : 0 cm, 35 cm (example on Figure 4) or 50 cm, from mechanical considerations.

Three types of bordered conditions were defined : a flow nil on the model's borders, an imposed temperature of 14°C at the bottom of the model and a temperature profile at the top. It represented a surface freezing index of about 400°C.days. Initial conditions of temperature have been fixed in relation to measurements made on several deep cores (Mauduit, 2003).

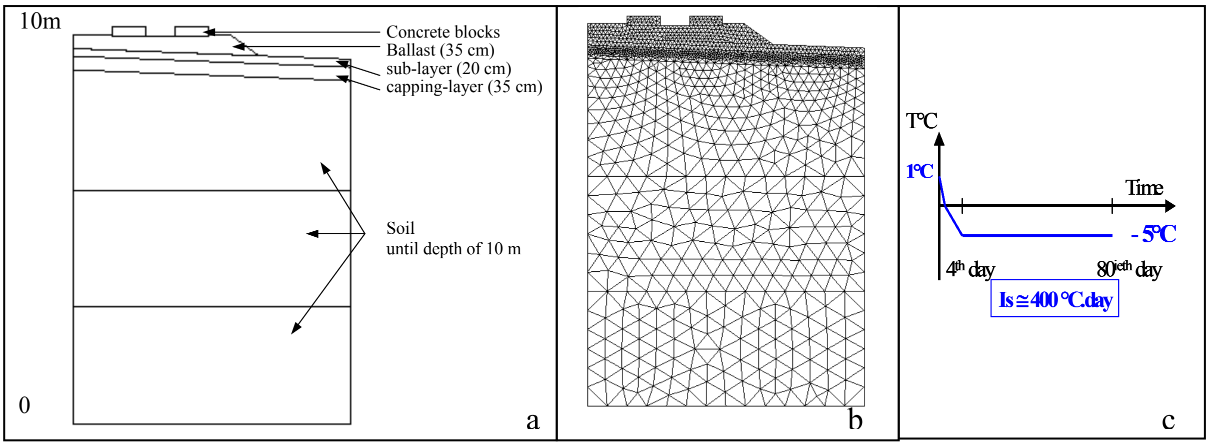


Figure 4 : Geometry (a), mesh of the structure (b) and surface temperature profile (c).

Simulations have been carried out with constant properties of layers underneath ballast, fixed in relation to properties usually used for pavement materials. As there are several origins and natures of ballast and there is no management for the track building and maintenance, an "average" ballast has been considered for the sake of the calculation (a greater management of its supply of the ballast would allow an accurate evaluation of its properties). Two ballasts, in their clean and dirty conditions, have been kept to simulate their influence on frost penetration; their properties have been determined by Mickley model :

- an intermediate ballast, with a thermal conductivity of its solid phase of 2.1 W/mK.
- the more restricting ballast, quartzite one, with a thermal conductivity of 4.5 W/mK.

No increase coefficient have been taken into account to simulate convection in the porous medium of the ballasts, in the examples presented in Table 5.

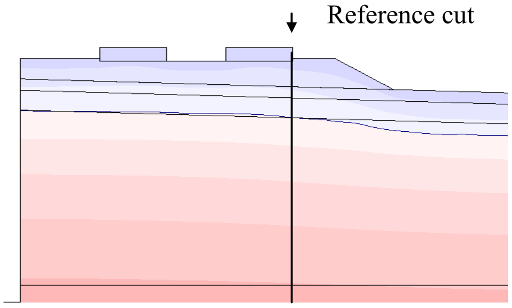
Table 5 : Selected physical properties of the different layers

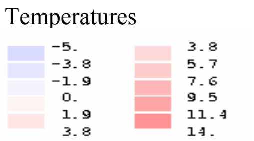
Materials	thickness (m)	Dry Density ($kg.m^{-3}$)	Water content (%)	Specific calorific capacity ($J.kg^{-1}.K^{-1}$)	Unfrozen thermal conductivity ($W.m^{-1}.K^{-1}$)	Frozen thermal conductivity ($W.m^{-1}.K^{-1}$)
Concrete blocks	0.25	2400	1	1100	2.0	2.1
Sub-layer	0.20	2150	6	836	1.8	2.1
Capping-layer	0.35	2200	5	836	1.7	2.0
Soil	until 10m	1300	32	836	1.1	1.8
Clean intermediate	0.35	1500	1	836	0.64	0.66
Dirty intermediate	0.35	2060	7	836	1.19	1.43
Clean quartzite	0.35	1500	1	836	1.32	1.34
Dirty quartzite	0.35	2060	7	836	2.33	2.74

4.3 Results and impact on frost design method

Modeling has allowed to determine the acceptable surface freezing index for the four hypotheses of ballast. These indexes are determined so as the frost front will reach the top of the frost susceptible soil. In a first approach, the acceptable atmospheric index has been deduced from the relationship established for roads : IA=IS/0.7+10. Additional measurements are planned on railway lines, where radiative exchanges are very different from the ones on pavements, to determine a more realistic relationship.

The asymmetry of the structure has shown some differences in frost penetration (figure 5). This has involved a choice of a restrictive reference cut, which was located in the axle of the exterior rail supporting concrete block.





Ballast	IS (°C.day)	IA (°C.day)
Clean intermediate	433	629
Dirty intermediate	238	351
Clean quartzite	218	322
Dirty quartzite	148	222

Figure 5 : Example of frost front penetration and results of acceptable indexes values.

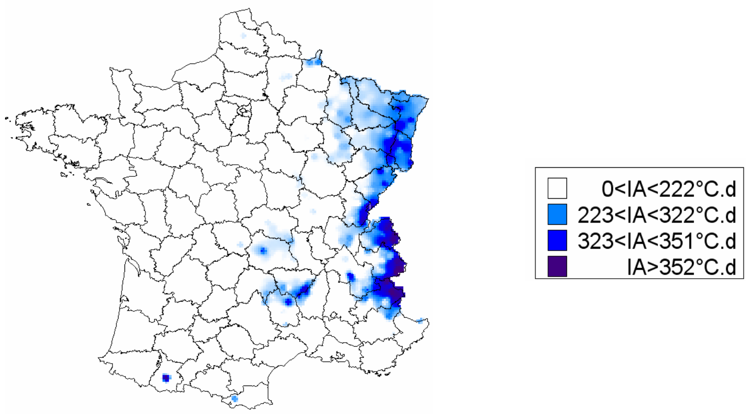


Figure 6 : Areas where the different ballasts can be employed on this structure of 35 cm of capping-layer without any risk of damage.

The map of exceptional frost indexes, presented in the previous figure 6, indicates areas where the four structures could be employed, without any risk of frost deterioration, according to this reference index. The dirty quartzite structure acceptable until IA=222°C.day, will be invalid in areas colored in blue. In these areas, it could be built either the same structure with a less conductive ballast or a thicker one with the same nature of ballast. The fundamental impact of hypothesis on ballast physical properties (owner of French railway lines choice) for the definition of the new frost reference document, is pointed out here.

5. CONCLUSION

Work engaged on revision of the frost design method for High Speed Railway Lines has shown that the transfer from pavement method is delicate. The different problematics have raised some interrogations on which works are still currently conducted. Preliminary studies have shown the considerable influence of ballast physical properties on frost penetration and then on permissive areas for building the different structures. This reference document, focused first on high speed lines, aims to be extended in the future to classic railway tracks.

REFERENCES

Bergman, D. et al., 1985. *Les méthodes de l'homogénéisation : théorie et application en physique*, École d'été d'analyse numérique, Coll. DER-EDF, Eyrolles éd., Paris.

De Vries, D.A. 1963. *Thermal properties of soils*. Physics of plant environment, John Wiley and Sons, Inc., New York, p. 210–235, In W.R. van Wijk (ed.).

LCPC-SETRA, 1998. *Catalogue des structures types de chaussées neuves, réseau routier national.* Ministère de l'Equipement des Transports et du Tourisme.

Goering et al., 2000. *Convective heat transfer in railway embankment ballast.* Ground freezing 2000, communication. Rotterdam. p31-36.

Mickley A.S., 1951. *The thermal conductivity of moist soil*. Am. Inst. Elec. Eng. Trans.

Missenard, A., 1965. *Conductivité thermique des solides, liquides gaz et de leurs mélanges*. Editions Eyrolles.

Mauduit, C., Livet, J., 2003-2004. *Analyse du fichier national des essais de gonflement au gel. Caractérisation et étude de sensibilité des propriétés physiques de quelques ballasts. Influence de la température dans les 40 premiers mètres du massif sur le dimensionnement au gel des structures.* Rapport de recherche pour le LCPC.

SNCF, Direction de l'infrastructure, 1995. *ST N°590 B. Spécification technique pour la fourniture des granulats utilisés pour la réalisation et l'entretien des voies ferrées*.

Techer, L., Lefebvre, G., 2003. *Modélisation du transfert thermique au sein des ballasts de voies ferrées*. Mémoire de DEA - Mécanique Energétique, Université Paris XII.

Lai, Y. et al., 2004. *Adjusting temperature distribution under the south and north slopes of embankment in permafrost regions by the ripped-rock revetment.* Cold Regions S&T, 39:1.