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Extruded polystyrene (XPS) foam frost insulation boards in railway structures

Les feuilles de mousse de polystyrène extrudées en structures ferroviaires

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ABSTRACT
The use of extruded polystyrene foam boards in track structures requires that high thermal resistance is retained in the harsh loading environment of the track. To retain low thermal conductivity, the frost insulation board must be able to resist the absorption of water despite minor mechanical damage. The replacement of the blowing agent used in board production over the last 15 years, due to environmental concerns, has also decreased the thermal resistance of the board. This paper discusses the field and laboratory studies conducted to evaluate the sustained performance of XPS boards. As a result of the project, the dimensioning value for the thermal conductivity of XPS frost insulation boards was changed to 0.050 W/Km and stricter compressive strength requirements for the boards under high axle loads were introduced.

RÉSUMÉ
L'usage des feuilles de mousse de polystyrène extrudées en structures ferroviaires exige la conservation d'une bonne résistance thermique des feuilles dans les sévères conditions de charge qu'on a dans les structures ferroviaires. La qualité essentielle pour la conservation d'une basse conductivité thermique est la capacité de la feuille isolante à s'opposer à l'infiltration de l'eau également malgré légers dommages méchaniques. Le changement qu'on a eu pendant les quinze deriners ans pour raisons environnementales dans les gaz propulseurs de la fabrication des feuilles a diminué la résistance thermique des feuilles. Dans ce papier nous examinons les recherches sur place et en laboratoire que nous avons fait pour évaluer la fonctionnalité de longue durée des feuilles XPS. Le résultat du projet est que nous avons changé la valeur assignée à la conductivité thermique de la feuille isolante et nous avons augmenté les exigences sur la résistance à la compression de la feuille quand la charge par essieu est élevée. La nouvelle valeur assignée à la conductivité thermique de la feuille isolante est 0.050 W/Km.

1 INTRODUCTION

The frost protection of a track structure is based on making the structure frost resistant using, in the case of the most important rail lines, a dimensioning frost sum of air that is statistically likely to occur once every 50 years (Fig. 1). When laying new tracks, frost protection is mainly achieved by making the structural layers of non-frost-susceptible soil material thick enough to prevent frost from reaching the frost-susceptible subsoil. On the other hand, in the renovation of existing tracks, increasing the thickness of the structure is usually not possible due to the boundary conditions of track geometry or stability problems. In such instances, frost protection is usually improved by adding frost insulation boards under the ballast layer in connection with ballast cleaning. The installation of the boards during ballast cleaning (Fig. 2) makes it possible to work even during fairly short interruptions in train traffic. However, then the insulation board must be installed immediately under the support layer, which leaves the top surface of the board exposed to angular ballast grains.

Extruded polystyrene (XPS) foam boards have been used in railway structures in Finland since the 1970s. In the 1970s, expanded polystyrene (EPS) foam was also used in the frost insulation of tracks, but its use was discontinued in 1980 because of the bad experiences regarding its moisture resistance. Since 1981, only extruded polystyrene (XPS) boards have been used in Finland for the frost insulation of tracks.

Frost insulation materials are subjected to a very severe loading environment in a track structure due to train loading cycles recurring tens of millions of times. This sets special requirements for their load-bearing capacity. The boards must be able to retain their high thermal resistance under the harsh conditions of the track structure.

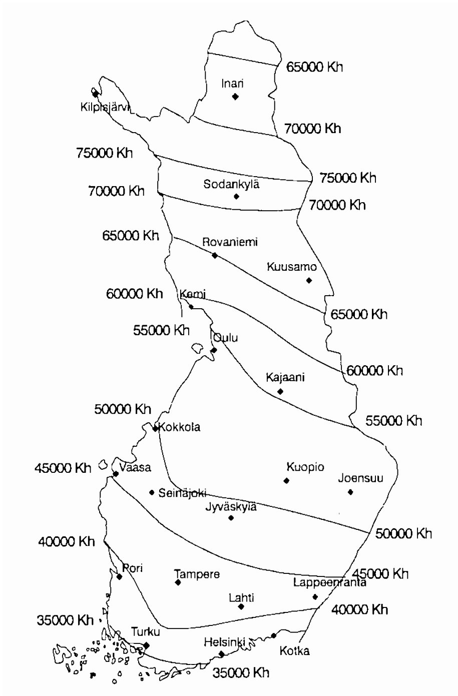

Figure 1. Frost sum of air with the statistical probability of occurring once in 50 years in Finland, F_{50}.

The research project concerning the frost protection of track structures and the long-term durability of frost insulation boards of polystyrene was commissioned by the Finnish Rail

Administration and realised at the Laboratory of Foundation and Earth Structures, TUT, in 2000-2002. The objective was to determine the ability of the insulation boards to retain their performance during the required service life of 40 years at present (max 225 kN) and possibly increased axle loads (Nurmikolu & Kolisoja, 2001). The results were used to revise the dimensioning guidelines for the frost protection of track structures (Nurmikolu & Kolisoja, 2002)

Figure 2. Installation of frost insulation boards under the ballast layer during ballast cleaning.

2 XPS MATERIAL

Environmental regulations have necessitated replacing the blowing agents used in the manufacture of XPS boards over a period of 15 years from heavy-molecule CFC gases through intermediary stages (mainly HCFC) to the present carbon dioxide. The blowing agent used in the manufacture of boards stays in the closed cell structure, and its thermal conductivity (Table 1) thus has a major impact on the thermal conductivity of the board itself. The change of blowing agent has increased the thermal conductivity of XPS board markedly, a fact that has often been largely overlooked. This is actually due to the acceleration of the cell gas diffusion process, known as the board ageing phenomenon. The diffusion of the earlier used heavy-molecule gases of low thermal conductivity from the cell structure of the board was a rather slow process that took decades (Table 1). By contrast, the diffusion of carbon dioxide takes place mainly during the first few months following manufacture, after which the pores of the board are filled with air of higher thermal conductivity than blowing agents.

Table 1. Thermal conductivities, comparative ecological values and the rates of the ageing processes of some blowing agents. (Nieminen & Järvelä, 1999)

Blowing agent	λ_{10} [W/Km]	Ozone depletion	Green house effect	Half-life [a] 50 mm board	100 mm board
CFC 12	0.010	1.0	7300	24	95
HCFC 22	0.011	0.05	1500	0.3	1
HCFC 142b	0.011	0.06	1600	21	84
HFC 134a	0.013	0	1200	1.9	7.6
HFC 152a	0.013	0	140	0.1	0.7
CO_2	0.016	0	1	0.01	0.1
Air	0.025				

Besides increasing thermal conductivity, the diffusion of the cell gas also affects the strength properties of the board. The compressive strength of boards blown with carbon dioxide increases considerably during the first few months following manufacture. The obvious reason is that the diffusion of carbon dioxide from the cell structure is very quick while the penetration of air into the pores is slower. Initially this causes an underpressure in the cell structure, and when the pressure later stabilises, the strength of the board increases.

The sustained performance of polystyrene boards requires retaining high thermal resistance in the loading environment of the track structure. However, thermal resistance gradually decreases due to 1) the diffusion of the blowing agent in the pores, 2) mechanical damage to the board, and 3) absorption of water. The research project examined the role of these factors in the degradation of the performance of frost insulation boards in a track structure.

3 PERFORMANCE OF INSULATION BOARDS AT PRESENT AXLE LOADS

3.1 *Mechanical damage*

The present condition of XPS boards installed in track structures in the 1980s and 1990s was examined in the project. Specimens were taken from the boards of all three manufacturers of XPS boards used in Finland, from production lots of different years and from different track sections.

The specimens divided into two distinct groups on the basis of their condition. The boards made by one manufacturer in 1989-90 were clearly inferior to all the others: specimens taken from them were more or less damaged but all were highly wetted. In the worst case the part of the insulation under a sleeper had been largely destroyed (see Fig. 3, top right). Even specimens that seemed to be in relatively good condition were found to be highly wetted based on their weight. These problem boards came from the problematic production lots made during the process of changing blowing agents (CFC → HCFC).

All other specimens had withstood loads of 5-10 years relatively well (e.g. Fig. 3, left). The top surfaces of all specimens showed indentations caused by the penetration of ballast grains, but as a rule they were less than 10 mm deep. Almost all specimens also had indentations on the bottom surface (Fig. 4) from the ballast grains left under the boards in installation. Another form of damage besides indentations were cracks on the bottom surfaces of the boards running in the direction of or perpendicular to the rail (e.g. Fig. 3, bottom right). Half of the specimens from better kept boards had also cracked to some extent, but even the worst cracks did not reach all the way through. The part of the boards under the rail was observed to have bent slightly more than the end section due to the traffic load.

Figure 3. Mechanical damage in XPS frost insulation boards, generally (left), and in the problematic production lot (top right). An example of cracks in the bottom surface of a board, bottom right.

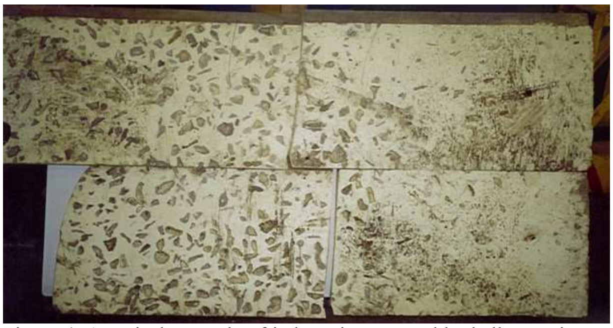

Figure 4. A typical example of indentations caused by ballast grains on the bottom surface of an XPS board.

3.2 *Water absorption and thermal conductivity*

The specimens could be divided into two groups by moisture content measurements, which could be expected on the basis of the above-mentioned visual inspection. The moisture contents of the boards in poor condition that had been installed in 1989-90 varied from 7.6-21.8 vol.%. The thermal conductivity measured even from the driest specimen (7.6 vol.%), at an average temperature of -5 ºC, was 0.074 W/Km, that is, twice the dimensioning value. All specimens, except those from the problematic production lot, had resisted the moisture absorption rather well. Their moisture contents varied between 0.9-3.4 vol.%. In relation to their service life, the moisture content of the boards had increased on average by 0.36 vol.% per year (variation 0.21-0.57 vol.% per year). Despite the slight wetting, the thermal conductivity values measured from the specimens were very low, which is attributable to the low thermal conductivity of the HCFC gas still contained in the cell structure. Figure 5 shows the results of these thermal conductivity measurements together with values measured from boards manufactured using CO_2 as a blowing agent and moisturised artificially. It is worth noting that boards manufactured with the new technology using CO_2 as a blowing agent have a higher thermal conductivity, even as new, than boards made using HCFC gas in the 1990s.

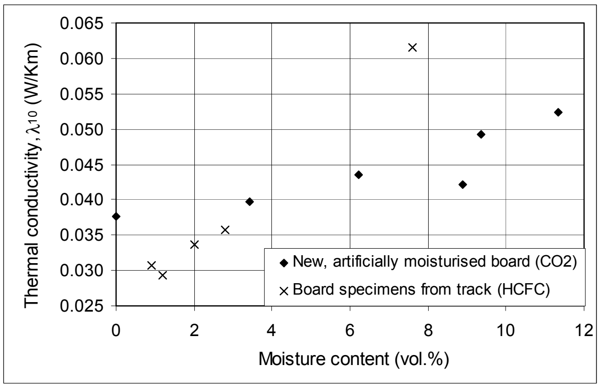

Figure 5. Results of thermal conductivity measurements (λ_{10}) on XPS boards removed from a track structure representing the earlier technology where HCFC was used as a blowing agent and boards made using CO_2 as a blowing agent (Styrodur C-RHS) and moisturised artificially.

Based on the moisture absorption of the specimens taken from a track, the present XPS boards were estimated to attain a maximum moisture content of about 10-12 vol.% during their expected service life of 40 years. This naturally only applies to problem-free production lots. With a view to the original (dry) thermal conductivity of presently used XPS boards expanded with CO_2, and the estimated moisture content of 10-12 vol.%, it was decided to use 0.050 W/Km as the dimensioning thermal conductivity of XPS frost insulation boards instead of the previously used 0.037 W/Km. The mechanical damage caused by ballast grains is taken into account in dimensioning by increasing insulation thickness by 10 mm. An example of frost dimensioning curves for track structures based on these values is shown in Figure 6.

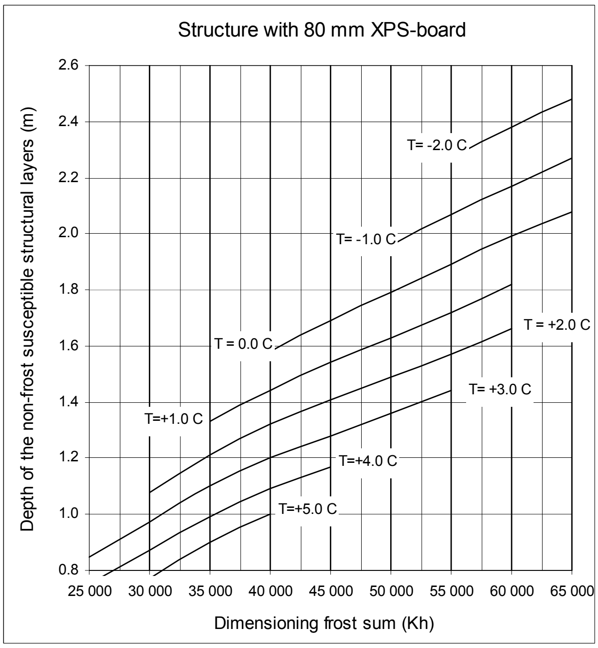

Figure 6. Track frost dimensioning curves based on the 0.050 W/Km dimensioning value of the XPS insulation board with an insulation thickness of 80 mm. T stands for the annual average temperature of air in the region. (Nurmikolu & Kolisoja, 2002)

4 EFFECT OF INCREASING AXLE LOADS ON THE PERFORMANCE OF INSULATION BOARDS

The mechanical behaviour of unused XPS frost insulation boards was analysed by extensive sets of cyclic loading tests (SP Method 2687) and static compression tests (EN 826). In the cyclic loading test (Fig. 7) a board specimen is loaded cyclically while measuring the compression of the board. The permanent compressive deformation of an XPS frost insulation board suitable for use in a track structure must not exceed 5 % in the cyclic loading test, where a loading pulse of 200 kPa is repeated $2x10^6$ times.

Figure 7. A regular cyclic loading test setting (left) and a setting where the loading is applied to the insulation board through a ballast layer (right).

As part of a project concerning the possibilities of increasing axle loads, the effects of a possible increase were also assessed in terms of damage to frost insulation boards. The effects were studied by varying the loading level used in sustained cyclic loading tests. The number of loading pulses was varied depending on the loading level to maintain a constant cumulative loading throughout the test series. A total loading corresponding to a train loading of 300 million tons was used, which is equivalent to the service life of average-strength track ballast in Finland. The loading level was found to affect the compressive deformation of an XPS board produced in the cyclic loading test as shown in Figure 8. The effect of the loading level was analysed by comparing the used loading level to the compressive strength of the board. The figure reveals that the compressive deformation caused by cyclic loading increases exponentially with increasing loading levels, despite the fact that the number of loading pulses is smaller at higher loading levels. In the light of quality control tests of XPS frost insulation boards conducted at TUT over several years, compressive strength is a highly significant factor affecting the behaviour of the board in cyclic loading test.

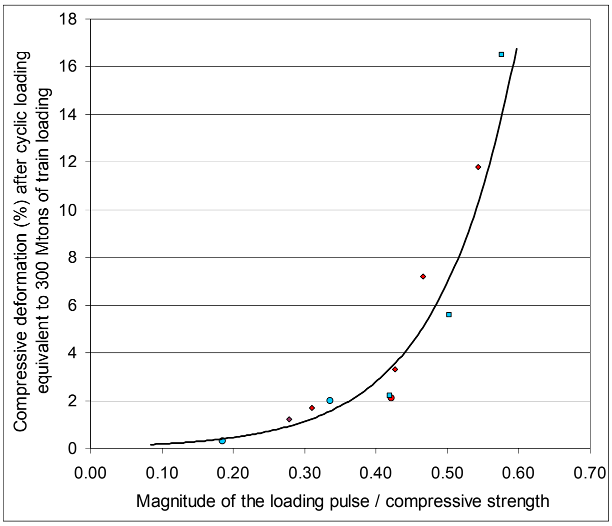

Figure 8. Effect of the magnitude of the loading pulse compared to the compressive strength of board on the compressive deformation of XPS frost insulation boards in a cyclic loading test corresponding to a train loading of 300 million tons.

In the light of the results, increasing axle loads with XPS boards meeting the current compressive strength requirement of 450 kPa would increase compressive deformation by 25-45 % if the present axle load of 225 kN were increased to 250 kN, or by 80-130 %, if the axle load were increased from 225 kN to 300 kN. The variation in the value results from the variation in the safety factor used in the calculations, or, in practice, the assumed level of loading directed to the board at an axle load of 225 kN. The present compression level, which has proven adequate in field tests, can be maintained by increasing the compressive strength requirement for boards to 500 kPa with a maximum permissible axle load of 250 kN, and to 600 kPa with a maximum permissible axle load of 300 kN, as has been done in Finland. It should, however, be noted that present compressive deformations are so small that a slight increase in them would hardly lead to significant degradation of the thermal resistance of the board. The compressive deformation of 7 % attained in the cyclic loading test did not affect the thermal conductivity of a dry board. On the other hand, water absorption may increase radically due to the breaking of the closed cell structure as a result of mechanical damage.

The results of the research project were used to define technical terms of delivery for XPS frost insulation boards for the Finnish railways that comply with the European standard (EN 13164).

5 SUMMARY AND CONCLUSIONS

Extruded XPS frost insulation boards are used in the frost protection of the track structure mainly in connection with renovation. The good strength properties of XPS boards and their high resistance to water absorption make them a very suitable insulation material for the harsh environment of track structures. To retain its performance, the insulation must be able to resist absorption of water despite minor mechanical damage.

The replacement of the blowing agent used in board manufacture due to environmental concerns has increased the thermal conductivity of the new board. With the presently used carbon dioxide the diffusion of the blowing agent from the cell structure of the board is much faster than with the previously used CFC and HCFC gases.

On the basis of the field and laboratory tests made, XPS boards are estimated to absorb 10-12 vol.% moisture during their 40 year service life in the track structure, which is why the dimensioning thermal conductivity of present XPS boards expanded with CO_2 has been changed to 0.050 W/Km. During the transition to new production methods, some problematic production lots were released into the market by one manufacturer and were used in track structures; these lots were susceptible to mechanical damage and consequently lost their thermal resistance very rapidly.

On the basis of the conducted cyclic loading and static compression tests, increasing axle loads with XPS boards meeting current compressive strength requirement of 450 kPa would increase compressive deformation by 25-45 % if the present axle load of 225 kN were increased to 250 kN, or by 80-130 %, if the axle load were increased from 225 kN to 300 kN. The present compression level, which has proven adequate, can be maintained by increasing the compressive strength requirement for boards to 500 kPa with a maximum permissible axle load of 250 kN, and to 600 kPa with a maximum permissible axle load of 300 kN.

ACKNOWLEDGMENTS

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