Use of Alternative Materials in Pavement Frost Protection: Material Characteristics and Performance Modeling

GUY DORÉ, JEAN MARIE KONRAD, MARIUS ROY, AND NELSON RIOUX

With freezing indexes ranging from 1,200°C to over 2,000°C day and frost penetration reaching 3 mm under pavement surface, frost action has always been a major concern for pavement engineers in Québec, Canada. The province's ministry of transportation has thus undertaken a study on frost action in pavements with two main objectives. The first is to revisit the whole approach of pavement design in severe frost conditions and develop a rational pavement design method to mitigate efficiently the effects of frost action. The second objective is to evaluate alternative techniques that might protect pavement against the detrimental effects of frost action. To gather the data needed to evaluate the performance of different pavement designs in support of those objectives, a specific pavement monitoring program was developed. The modeling and the laboratory work carried out to define the characteristics of the main test site constructed during summer 1994 are described. Mechanical and thermal simulations using ELSYM 5 and a finite element model developed at Laval University have led to an optimal pavement structure for the test site. The benefit of thermal insulation was weighed against the detrimental effect of incorporating a soft layer within the pavement structure to determine the best combination of thickness and depth for the insulation layer. Alternative insulation materials were identified and characterized through a comprehensive laboratory testing program. Based on criteria such as local availability, mechanical and thermal performance, cost, and environmental considerations, three promising materials were selected for the field testing. Saw dust, tire chips, and plastic crumbs were tested and compared with conventional insulated (expanded and extruded polystyrene) and uninsulated pavements.

Frost action on pavements has always been a major concern for engineers in the province of Québec. Recent surveys show that between 10 and 20 percent of the 30 000-km provincial network exhibit distresses associated with frost action. Moreover, the rate of degradation on these affected pavements in terms of change in roughness with time (]IRI/year) is, on average, twice that of non-affected pavements. Based on these numbers, efforts to correct the frost problem in the provincial network can be estimated at more than $100 million (Canadian), excluding additional construction costs to build frost-resistant pavements, user costs, and indirect costs such as those related to the decline in transportation productivity during the period when spring load restrictions are in place.

It is generally believed that more can be done to better understand and control pavement performance in severe frost conditions. Existing methods, typically based on empirical models if not simply on rules of thumb, cannot support performance prediction and are not sensitive to specific site conditions. Moreover, it is believed that methods that take only thaw weakening into consideration cannot properly address frost problem in Québec's severe climatic context.

The Québec ministry of transportation has undertaken a major study with the following two objectives:

- Revisit the whole approach to pavement design in frost conditions and develop a rational method that specifically deals with freezing and thawing of pavement structures; and
- Review and assess the performance of all mitigation methods with a special emphasis on the evaluation of alternative insulation materials such as plastic, rubber, and wood residues.

A work plan was prepared, illustrated in Figure 1, which presents the concept of the proposed design approach (white boxes) and the research required to achieve the objectives (grey boxes).

The project is planned over a 4-year period. Until now, most of the efforts have been directed toward the preparation of the main test site. The work done includes site selection, mechanical and thermal simulation, design of pavement structures, laboratory characterization of alternative insulation materials, and the development of an instrumentation plan.

TEST SITE SELECTION

To achieve the maximum benefit from the large investment required for pavement monitoring, test sites must be rigorously selected and designed. Guidelines for site selection were based on the international state of knowledge on pavement monitoring and the experience of the Strategic Highway Research Program (SHRP).

The selected site, in St. Martyrs Canadiens, 50 km south of Victoriaville, involved the rehabilitation of a provincial road affected by frost action. Moderately aggressive climatic and traffic conditions characterized the site, where one control section and four sections insulated with different materials were built and instrumented.

The design of the test sections was based on mechanistic modeling and on a specific program of laboratory testing on potential insulation materials.

MODELING OF ST. MARTYRS CANADIENS TEST SITE

The two main objectives of the test site were to provide high quality, real-time information on pavement response and performance in frost conditions, and assess the performance of alternative frost protection

---

G. Doré and N. Rioux, Québec Ministry of Transportation, 200 Dorchester Sud, 3rd Floor, Québec, Qc., Canada G1K 7P4. J. M. Konrad and M. Roy, Civil Engineering Department, Laval University, Québec, Qc., Canada G1K 7P4.

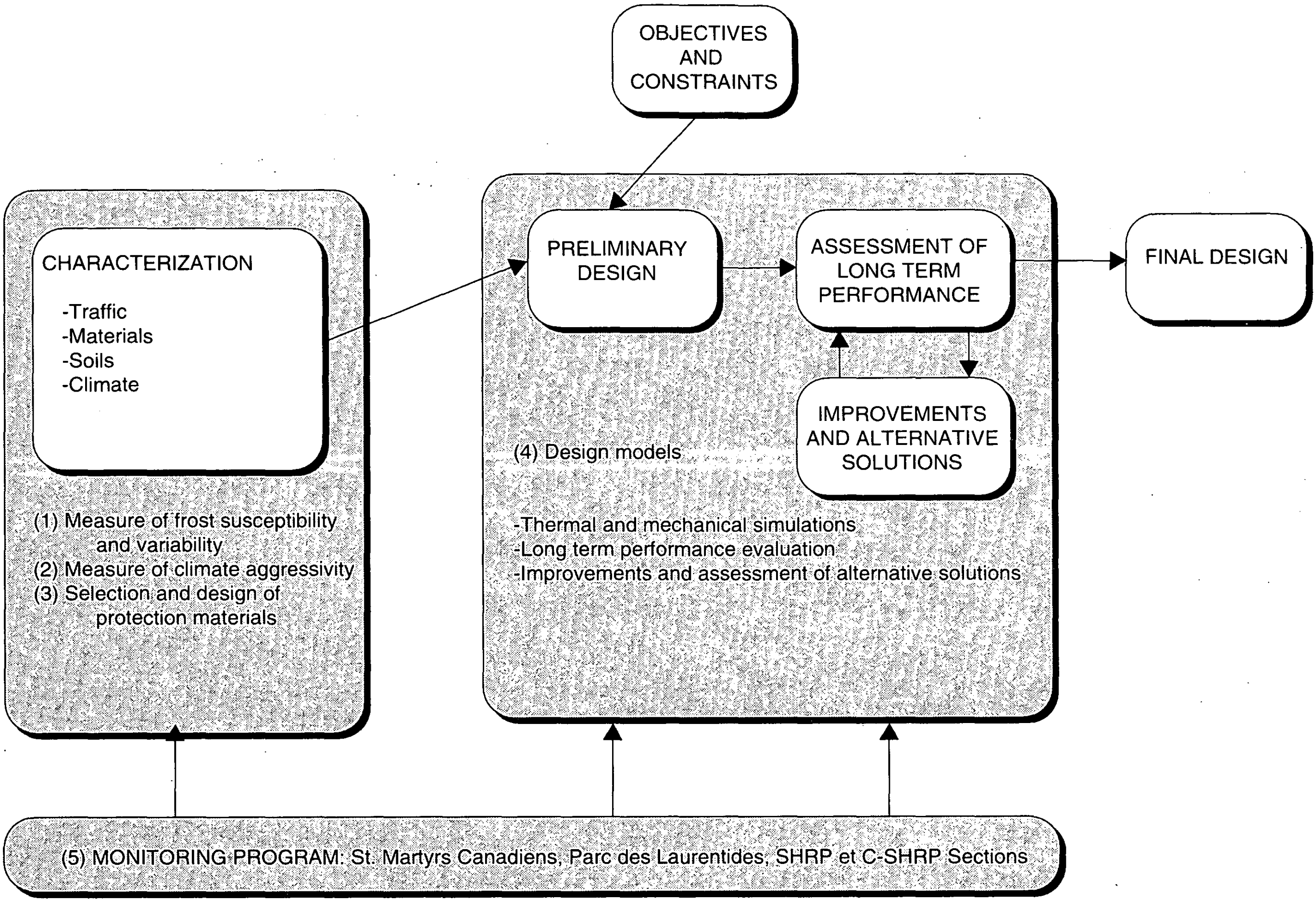

FIGURE 1 **Pavement design in frost conditions: concept of proposed method and research required.**

materials in pavements. Because the site was located on a provincial highway, it also was important to make sure that the test sections provided satisfactory service at a reasonable cost to travelers. The structural design of the test pavements was therefore critical.

It is expected that introducing a relatively soft insulation layer to the pavement system will improve its thermal performance. However, its mechanical performance will likely be significantly affected. Thus, a design approach was adopted that allowed the best possible compromise between the benefit due to the insulation and the associated structural loss. The 12 sections illustrated in Figure 2, characterized by different depths and thicknesses of the insulation layer, were analyzed using a mechanical and a thermal model. The results of the simulations were then combined in an attempt to assess the overall performance of the different pavement structures.

Three types of bulk insulation materials were initially considered in the study: wood residues, tire chips, and plastic crumbs.

Mechanical Simulation

The principle of mechanical simulation is to calculate stresses, strains, and displacements at critical locations in the pavement structure under a static load. These values are then used to estimate the life of the pavement structure using fatigue models. The simulation was done using ELSYM 5. Based on the linear elastic theory applied to multi layer systems, the system calculates the idealized response of the specified pavement structure at a given location under the specified load.

Performance modeling was needed for project preparation and had to be done before any specific laboratory and field information was available. The mechanical and thermal properties of the materials considered were thus extracted or estimated from available data in the literature. The characteristics used are presented in Table 1. Because no information was available on plastic crumbs at the time of the simulation, only the wood residues and the tire chips were used in the analysis.

The results of the mechanical simulation are shown in Figures 3 and 4. As expected, the total deflection of the pavement (Figure 3) and the strain at the bottom of the asphalt layer (Figure 4) grow with increasing thickness and decreasing depth of the insulation layer. These figures also illustrate the large difference in the response of the structures insulated with crumb rubber compared with the reference structures (no insulation) or the structures insulated with wood residues.

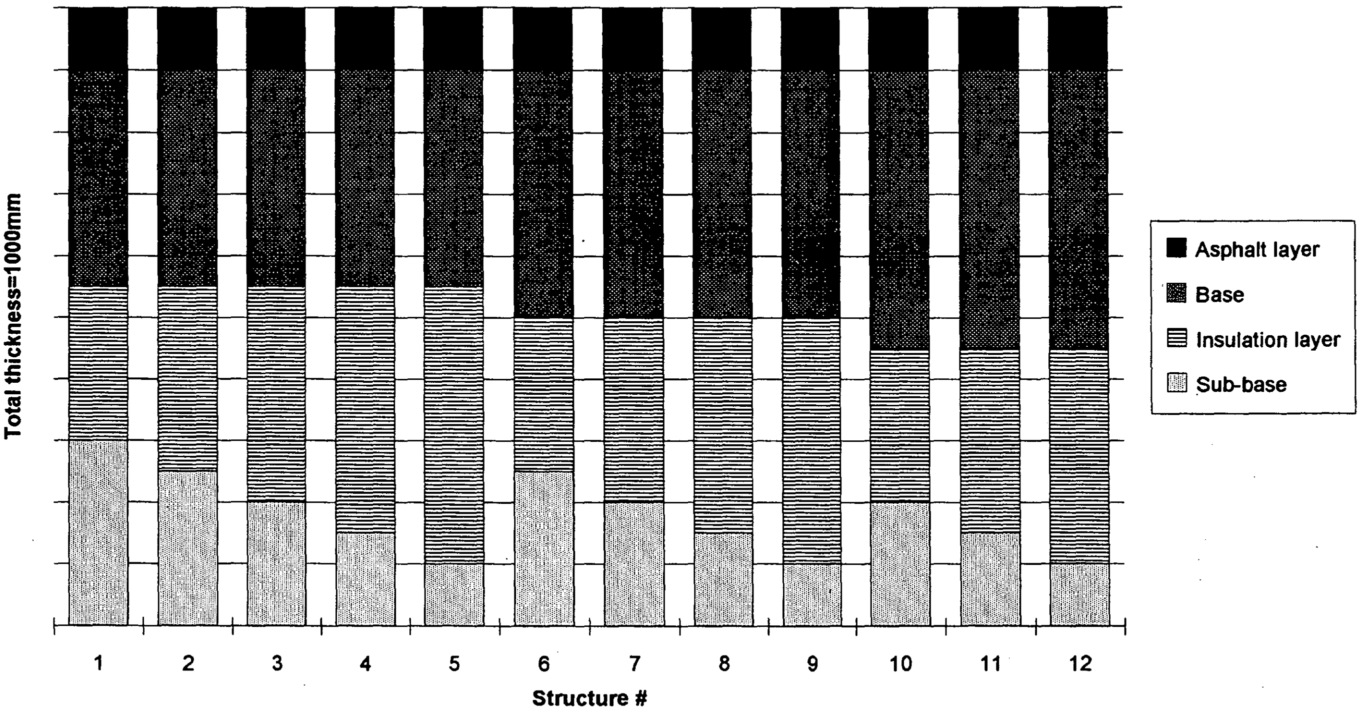

FIGURE 2 Pavement structures analyzed.

TABLE 1 Working Assumptions: Materials Characteristics, Highway 161, St. Martyrs Canadiens

	Asphalt layer	Base	Tire chips	Wood residues	Sub-base	Natural soil
	MB	GW-GC	CP	CB	SC	Cl
Thermal cond.k (W/m°C)	1.5 (a)	2.0 (a)	0.25 (1)	0.25 (1)(d)	2.3 (a)	1.5 (a)
Thermal cap. Cm (kJ/m^3°C)	2300 (a)	2700 (a)	600 (1)	440 (1)(a)	2800 (a)	3000 (a)
W (%)	***	6.0 (1)			15.0 (1)	25.0
Dry dens. (kg/m^3)	2500 (a)	2200 (a)	500 (b)	160 (f)	2000 (a)	1900 (a)
Initial temperat. cond.(°C)	4.5	4.5	4.5	4.5	4.5	4.5
Freezing index (°C.j)	1226	1226	1226	1226	1226	1226
Segregat. Potent. (mm^2/°C.h)	***	50 (1)	***	***	125 (1)	175 (1)
Plate Modulus M_E (Mpa)		300 (a)	1.55(1) (b)(c)	95 (1)(b)	60 (a)	15 (a)
Elastic Modulus E (Mpa)	3100 (g)	200 (b)(g)	1.1 (c)	70 (b)	83 (g)	48 (g)
Poisson coeff.	0.35	0.30	0.45 (b)	0.26 (b)	0.35	0.45

(a) Dysli [10]
(b) Newcomb/Drescher [11]
(c) Humphrey [12]
(d) Ladanyi [13]
(f) Johnson [14]
(g) MTQ [15]

(1) Estimated

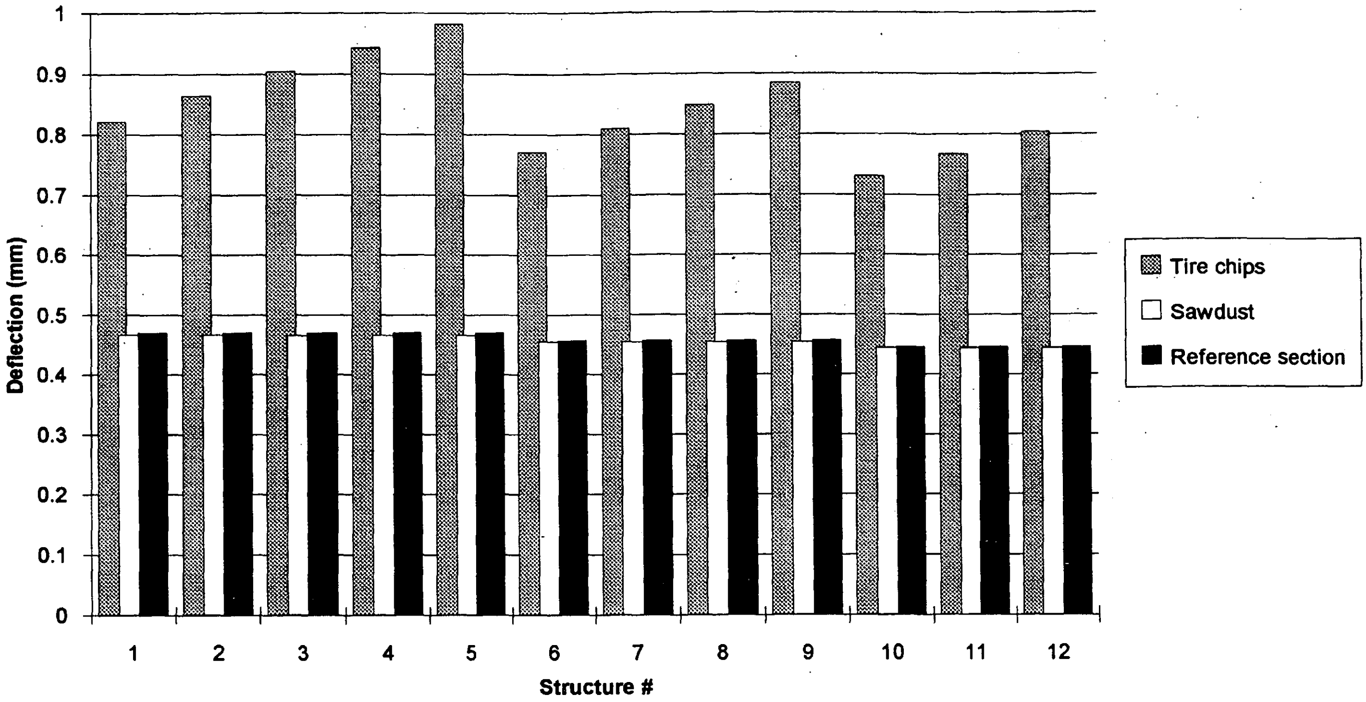

FIGURE 3 Calculated deflection at surface of pavement.

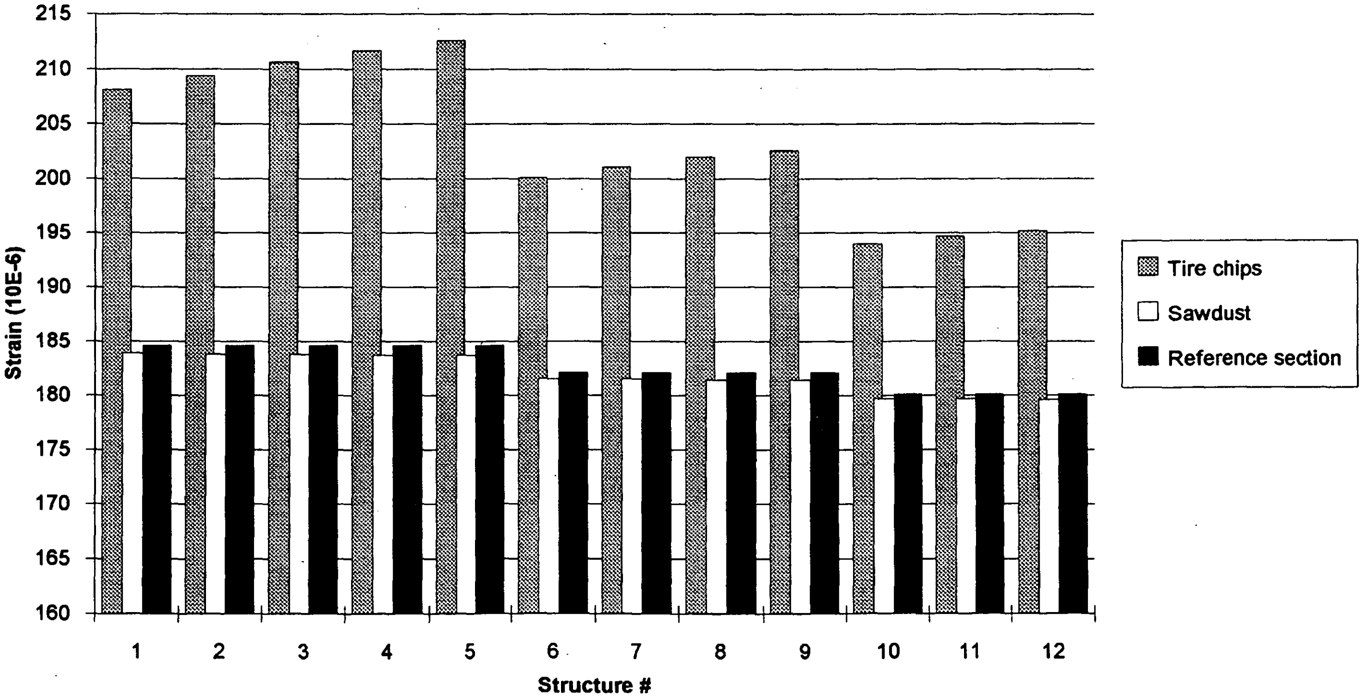

FIGURE 4 Calculated horizontal strain at base of asphalt layer.

Thermal Simulation

Thermal simulation was used to estimate vertical movements resulting from frost action beneath the pavement. The same 12 structures illustrated in Figure 2 and the same three bulk insulation materials were modeled using a numerical bi-dimensional model developed at Laval University (*1*). The model estimates heat and mass transfer as well as the resulting distribution of water and vertical movements of the pavement structure using the segregation potential concept developed elsewhere (*2,3*).

The use of wood residues is relatively well-documented in the literature (*4*). However, it is difficult to find relevant literature on the use of tire chips or plastic crumbs. In two recent experiments, tire chips were used as insulation material in a pavement structure (*5,6*). Although no specific measurement of thermal conductivity was done on the material, the experiments still provided useful information on the thermal behavior of tire chips.

Based on the literature search and on the judgment of frost experts from Laval University and the Canadian National Research Council, it was assumed for the first simulation iteration that all three materials had equivalent thermal conductivities as shown in Table 1.

The results of the thermal simulation for average winter conditions (FI = 1,226°C.d) are shown in Figures 5 and 6. Figure 5 shows that for all structures modeled, the insulation layer was sufficient to keep the freezing front within the pavement structure (1000 mm), thus reducing the expected total heave to less than 28 percent of the expected heave for the reference section.

Combined Performance

Given the working assumptions and the results of the simulations, it is generally observed that increasing thermal performance leads to decreases in mechanical performance, and unless each component is analyzed for its specific contribution to the overall performance of the pavement, the selection of the optimal pavement structure is very difficult.

Because they are the weakest of the three materials considered, the tire chips constitute a critical case and will be used in an attempt to combine the thermal and the mechanical performances to identify the optimal pavement structure for the test site. To make the analysis possible, it was necessary to assume that the serviceability loss associated with frost action was equal to the serviceability loss due to traffic. Based on the AASHTO model (*7*) (which predicts that the maximum serviceability loss ($]PSI$) due to frost action is between 1,5 and 2,0 and the total expected serviceability loss should be about 3,0), it appears that this assumption is realistic in the context of the St. Martyrs Canadiens test site.

The performance has been analyzed relatively to the reference section using fatigue and performance models. These models are empirical transfer functions linking mechanistic model outputs to observed pavement performance. To evaluate pavement performance as it relates to frost action, the AASHTO model (*7*) has been used. As Equation 1 shows, the model links the heaving rate to the Pavement Serviceability Index (PSI):

$$]PSI_{sg} = 0.01\,P_f\,]PSI_{\max}\,[1 - e^{-(0.02\phi t)}] \tag{1}$$

where

$]PSI_{sg}$ = loss of serviceability of pavement associated with frost action,
P_f = proportion of pavement surface subjected to frost action,
$]PSI_{\max}$ = maximum serviceability loss due to frost action,
ϕ = heaving rate, and
t = time.

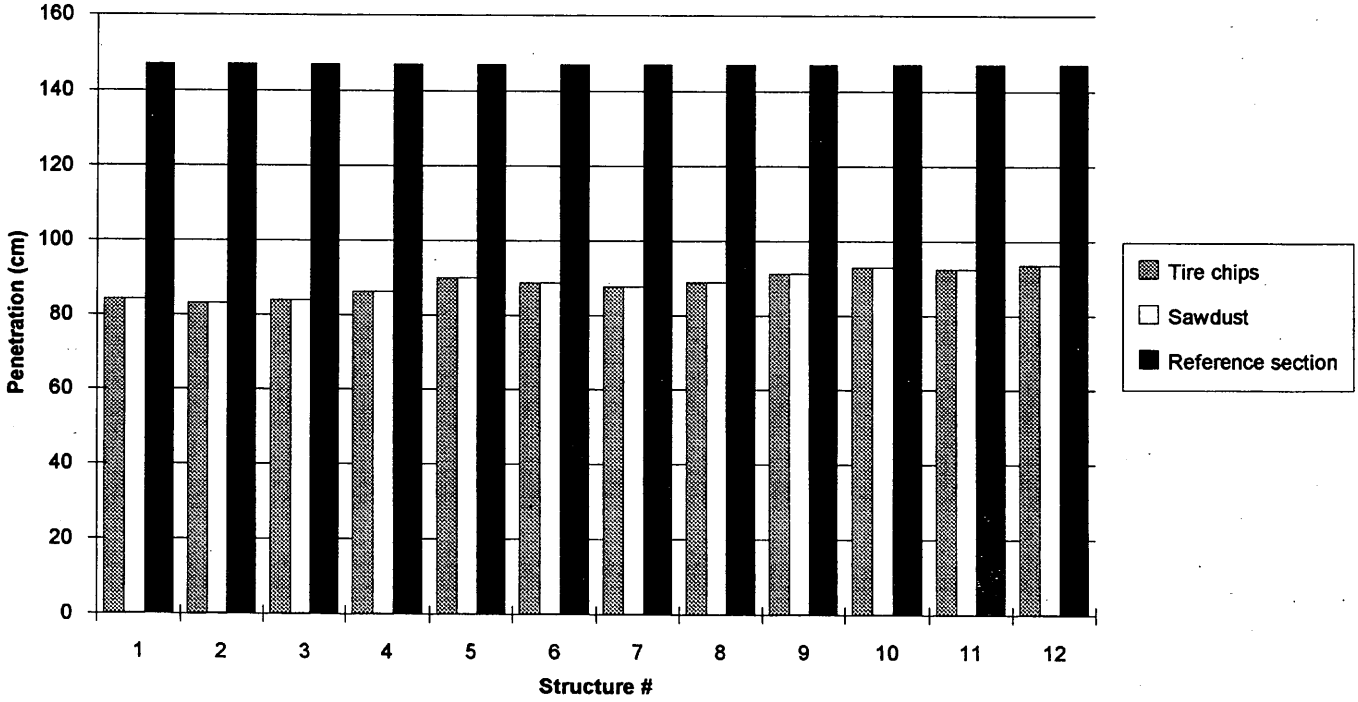

FIGURE 5 Calculated frost penetration (average winter, FI = 1,226°C.d).

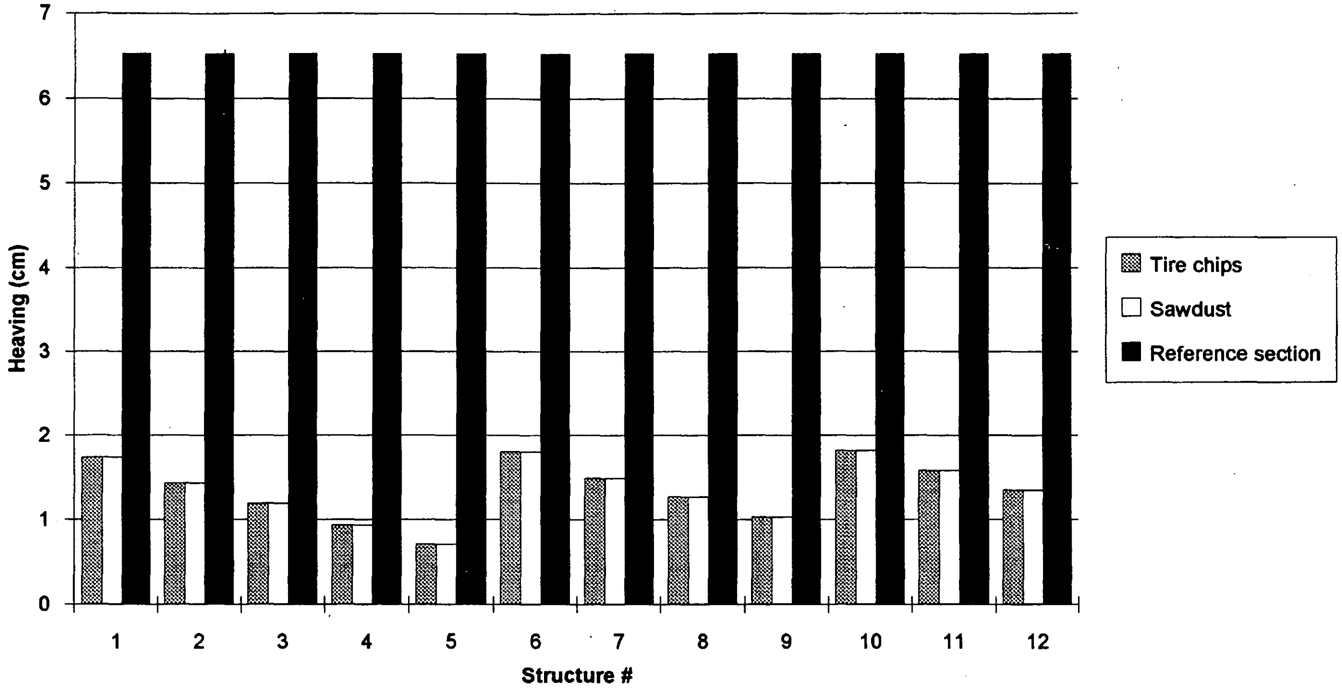

FIGURE 6 Calculated maximum heaving (average winter, FI = 1,226°C.d).

Pavement performance associated with traffic was evaluated using the following model reported elsewhere (*8*):

$$I = 0.5\,(E_t/X)^{4.27}N \qquad (2)$$

where

I = cumulative damage to pavement,
E_t = strain at bottom of asphalt structure,
X = reference strain value, and
N = number of load cycles.

The relative performance (Pr) related to traffic (Pr_t) or frost action (pr_f) is defined as follows:

$$Pr = \frac{\text{performance of insulated structure}}{\text{performance of reference structure}} \qquad (3)$$

The resulting combined performance is thus

$$P = (Pr_f - 1) + (Pr_t - 1) \qquad (4)$$

The results of the analysis of the combined performance are given in Figure 7. The analysis shows that the combined performance improves as depth and thickness of the insulation layer increase. However, it is more sensitive to depth than thickness. Based on the working assumptions and considering the limitations of the method, it is believed that a properly designed pavement, including a layer of bulk insulation material, can significantly outperform a conventional pavement despite the low rigidity of the layer. Because it is expected that construction cost will increase with the thickness and depth of the insulation layer, and because there is not a major difference in the combined performance for Sections 8 to 12, Section 10 was selected as the optimal pavement structure for the test site.

LABORATORY TESTS

The three material types used in the simulation were selected on the basis of cost, local availability of materials, and potential benefit to the thermal performance of the pavement. However, there were major concerns about the mechanical performance of these materials. The calculated performance of modeled structures, based on material characteristics extracted from the literature or simply estimated, showed interesting potential for the insulation materials considered and led to the structural design of the test site. The next step was to validate and, if possible, improve material properties through an extensive laboratory program.

The materials tested included the following:

- Wood residues: sawdust, wood chips, and combinations of both;
- Recuperated rubber: tire chips, ground tires (powder), combinations of both, and combinations of chips with sawdust and sand; and
- Recuperated plastics: plastics from domestic recuperation and plastics from the recycling of electric wires.

To assess the best-performing materials within the three generic groups and properly characterize them, the following tests were performed on the 17 different combinations of materials described in Table 2: one-dimensional compression, shearing, California Bearing Ratio (CBR), permeability, and thermal conductivity.

Mechanical Properties

Except for a series of thermal conductivity tests conducted on dry materials, all tests were conducted on saturated materials under a

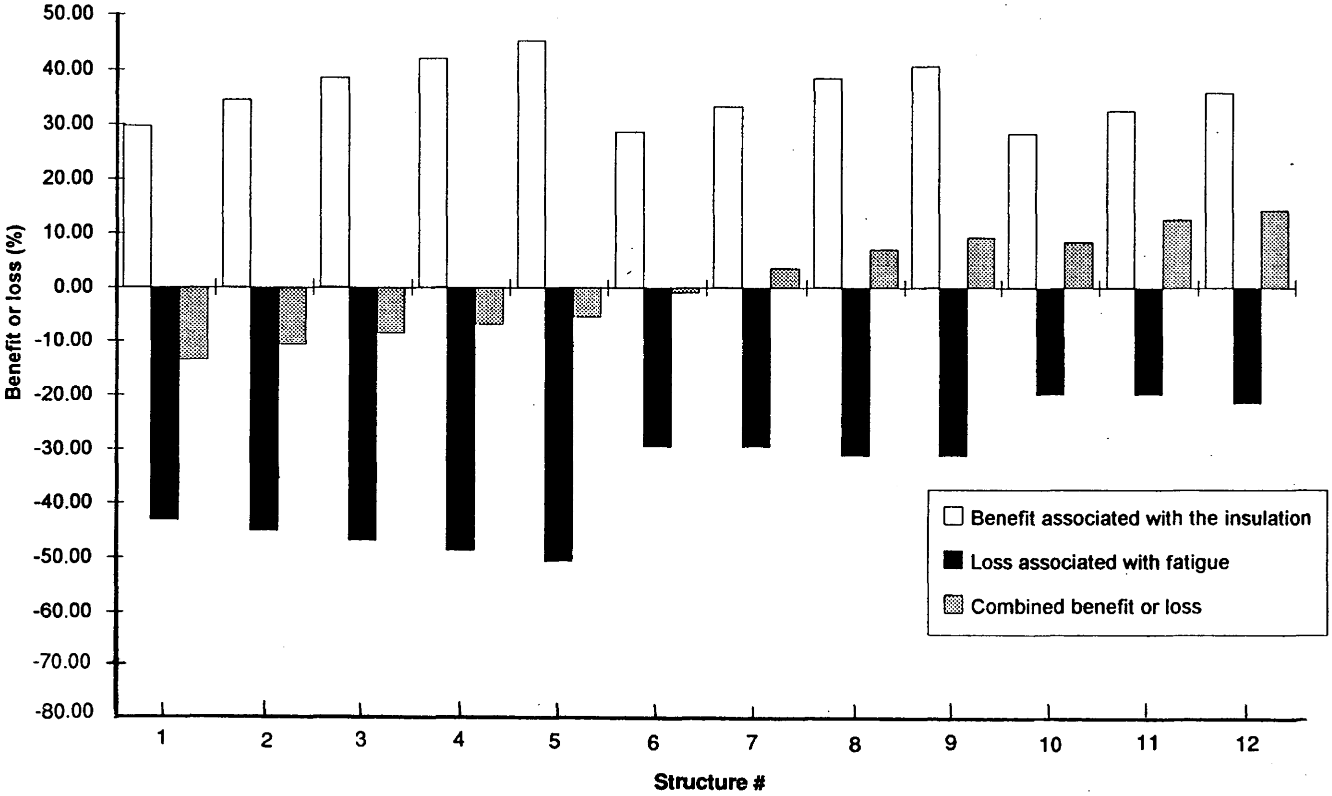

FIGURE 7 Anticipated combined performance.

TABLE 2 Materials Descriptions and Laboratory Tests Results

Material description	Maximum density (kg/m3)	Compression modulus (MPa)	Shear modulus (kPa)	CBR (%)	Hydraulic conductivity (cm/sec)	Dry thermal conductivity (W/mC)
Crushed stone (CS): 20-0mm	2250.00	150.00	23.10			
Sand (S): Poorly graded class A	1817.00	100.00	16.87	27.17		
Ground tire (GT): 1-4mm	698.00	0.82	3.00	0.56		0.32
Tire chips (TC): 20-40mm, steel and polyester not removed	667.00	1.02	2.70	0.55		0.38
Sawdust (SD): 1-4mm	201.00	6.67	13.59	2.60	0.0013	0.16
Wood Chips (WC): 20-40mm	234.00	6.81	15.46	3.07		
Plastics from domestic recuperation (RP): 8-12mm, polyethylene	506.00	5.83	9.06	0.36	0.0024	
Plastics from electric wire recycling (TP): 5-10mm, thermoplastic	492.00	3.82	7.71	0.67		0.28
Mixes (Volumetric proportions)						
GT(30)/TC(70)	807.00	1.22	3.75	0.79		
GT(50)/TC(50)	819.00	1.53	4.05	1.06	0.0013	0.34
GT(70)/TC(30)	765.00	1.55	3.81	0.89		
S(30)/TC(70)	1222.00	3.27	4.87	3.52		
S(50)/TC(50)	1519.00	28.36	15.08	9.93		
SD(50)/TC(50)	553.00	2.83	6.46	1.48		
SD(30)/WC(70)	315.00	6.92	14.79	3.20		
SD(50)/WC(50)	271.00	10.67	15.78	3.47		
SD(70)/WC(30)	348.00	6.54	13.20	3.61		

surcharge of 20 kPa. For the one-dimensional compression test, a tangent modulus at the beginning of the second loading cycle (first reloading) was used. The shear test was done using a large shear box (250 × 250 × 150 mm). In an attempt to better represent strain conditions in a pavement structure, a secant modulus at 1 mm displacement was used, although it does not allow for the full mobilization of the strength of the material.

The results of the mechanical tests for the best performing materials among each class are given in Table 2, and illustrated in Figures 8, 9, and 10. Figures 11 and 12 illustrate the effect of combining different proportions of ground tires and sand with tire chips.

The tests used to characterize mechanical properties of alternative insulation materials have obvious limitations. As static tests they do not represent the dynamic stress conditions experienced by the insulation materials in a pavement structure very well. It is believed that the simple compression test provides the best overall evaluation of the stress-strain characteristics of the materials. However, material properties can also be related to CBR values. In all cases within this study, the real benefit of mechanical tests is obtained when the results are analyzed relative to known materials (sand and crushed stone).

Thermal Properties

Two techniques were used to determine thermal conductivity. The first, based on the principle of a linear source of unsteady state heat, has been used by the National Research Council of Canada (*9*). The second approach was developed at Laval University and uses the steady state heat flow conditions at the interface of two materials to derive their relative thermal conductivity. If one of the materials is a calibrated material of known properties, thermal conductivity of the tested material is readily inferred.

The results of the thermal conductivity tests for dry, saturated unfrozen, and saturated frozen materials are given in Table 2 and illustrated in Figure 13.

The tests procedures used should yield reliable results. It should be noted, however, that these results were obtained for set conditions of saturation (dry and saturated), which are not necessarily representative of actual filed conditions.

Hydraulic Conductivity

Hydraulic conductivity of the three types of material selected for the test site was tested using the falling head procedure. In all cases, the tests showed that the materials had adequate draining capacity because of their use in pavements.

DISCUSSION OF RESULTS

As expected, all three types of materials showed weak mechanical properties, but promising thermal characteristics. Of all the tire mixes the material made of 50 percent tire chips and 50 percent ground tire performed best and showed properties comparable to the ones used in the mechanical simulation. However, the production of such a mix might not be economically feasible and, even if it were, the mechanical properties remain weak and would limit its use to low-volume roads. The possibility of using a tire chips-sand mix will be explored further.

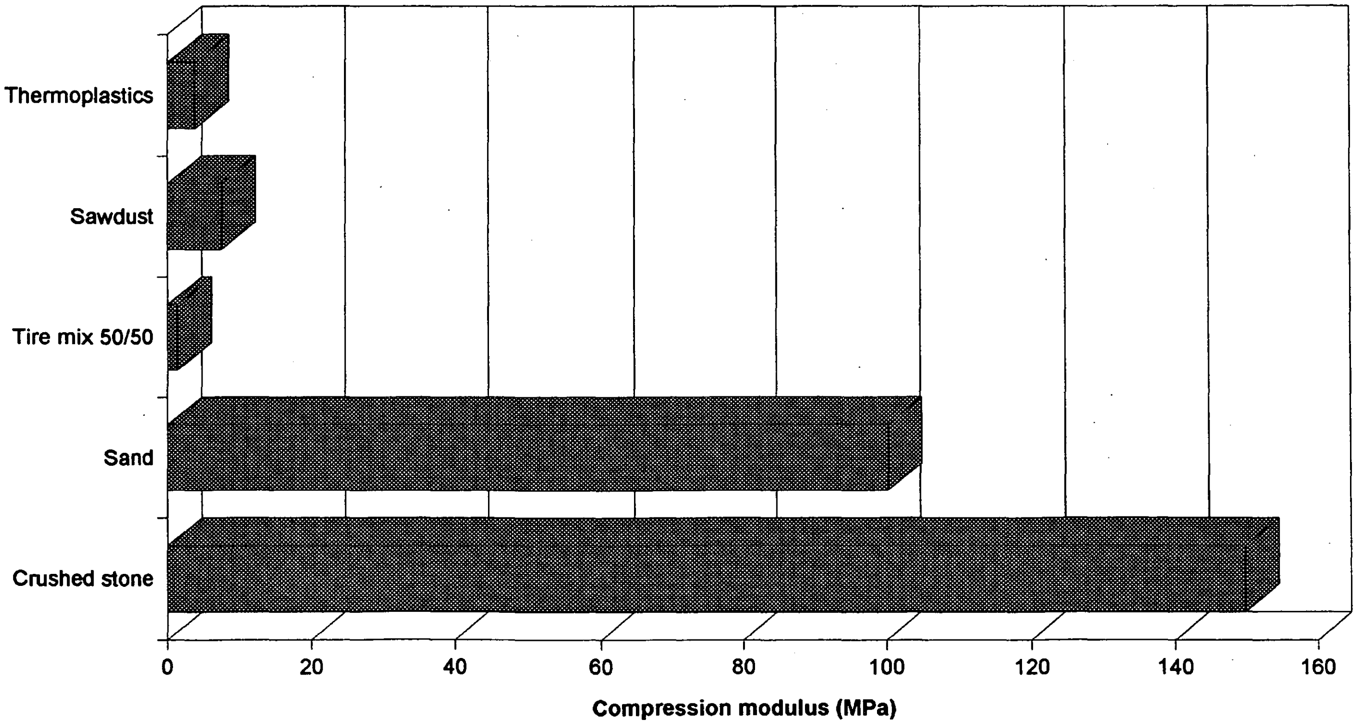

FIGURE 8 Results of simple compression tests on selected materials.

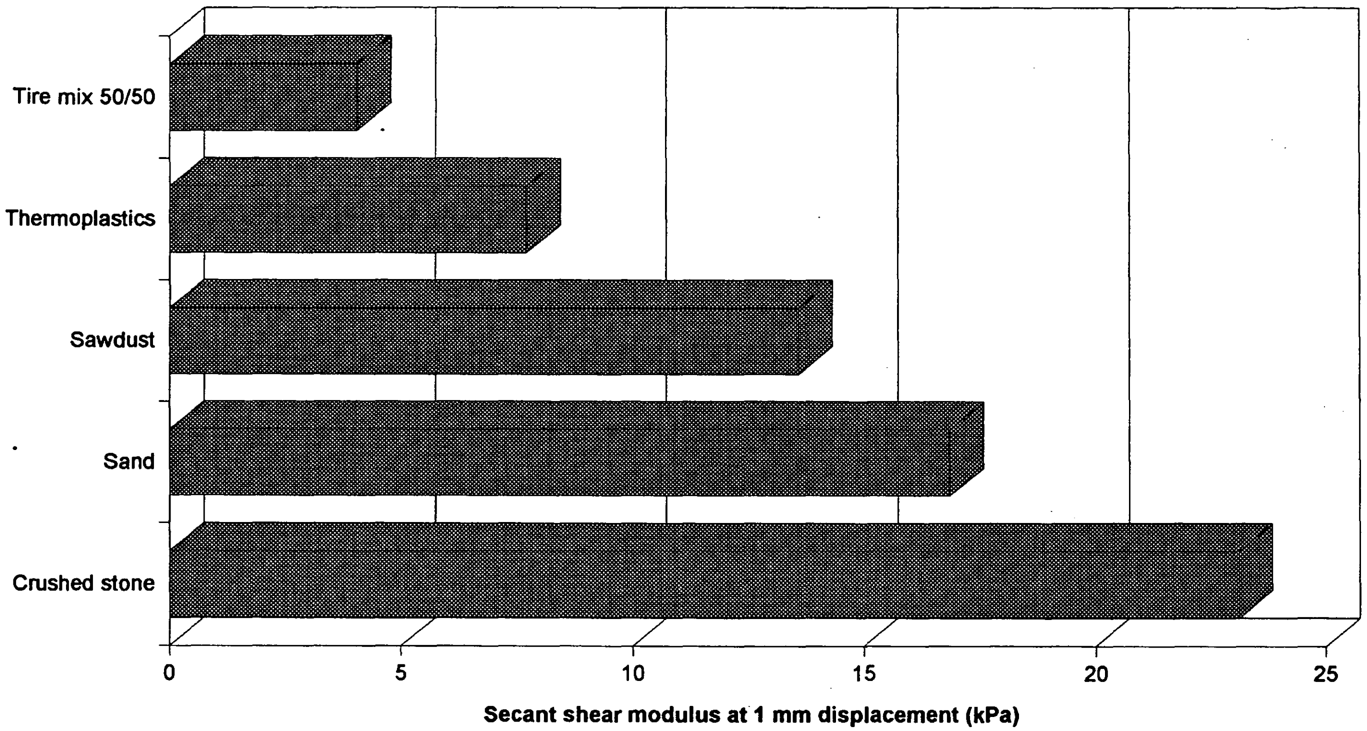

FIGURE 9 Results of shear resistance tests on selected materials.

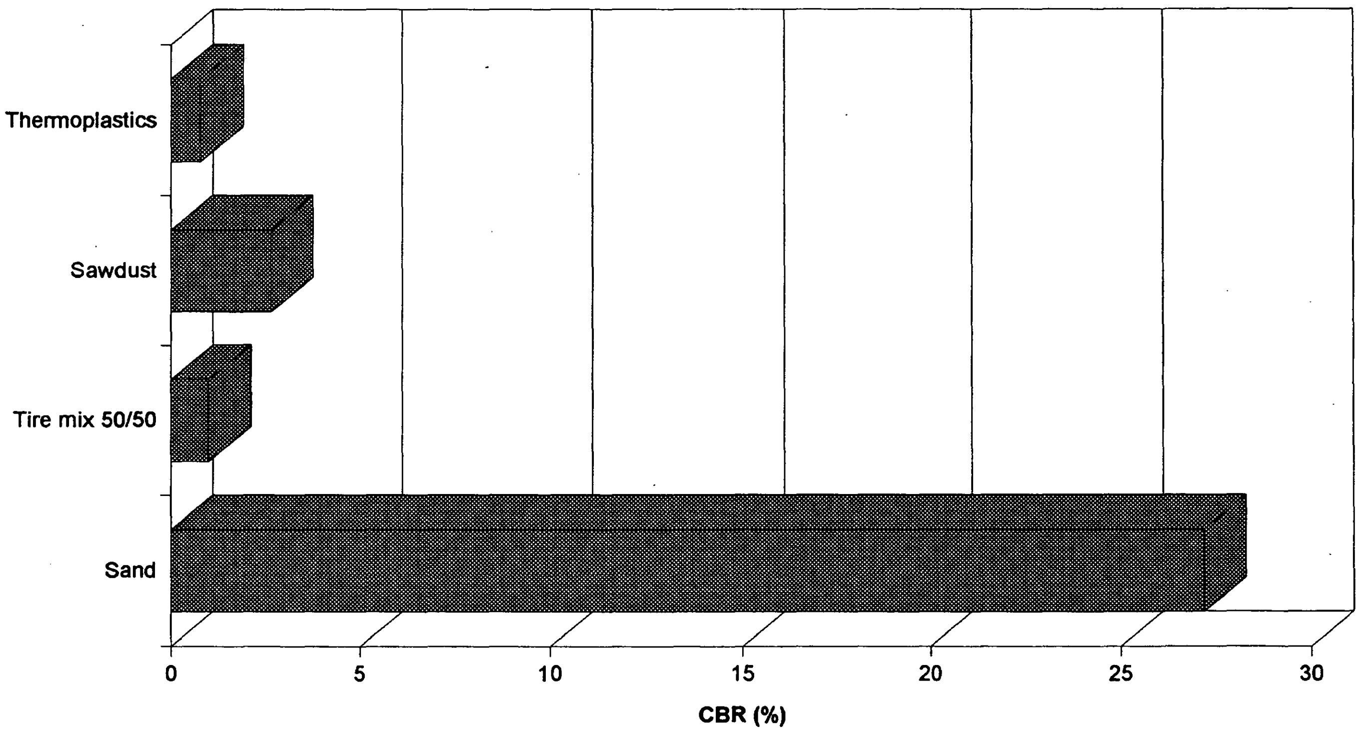

FIGURE 10 Results of CBR tests on selected materials.

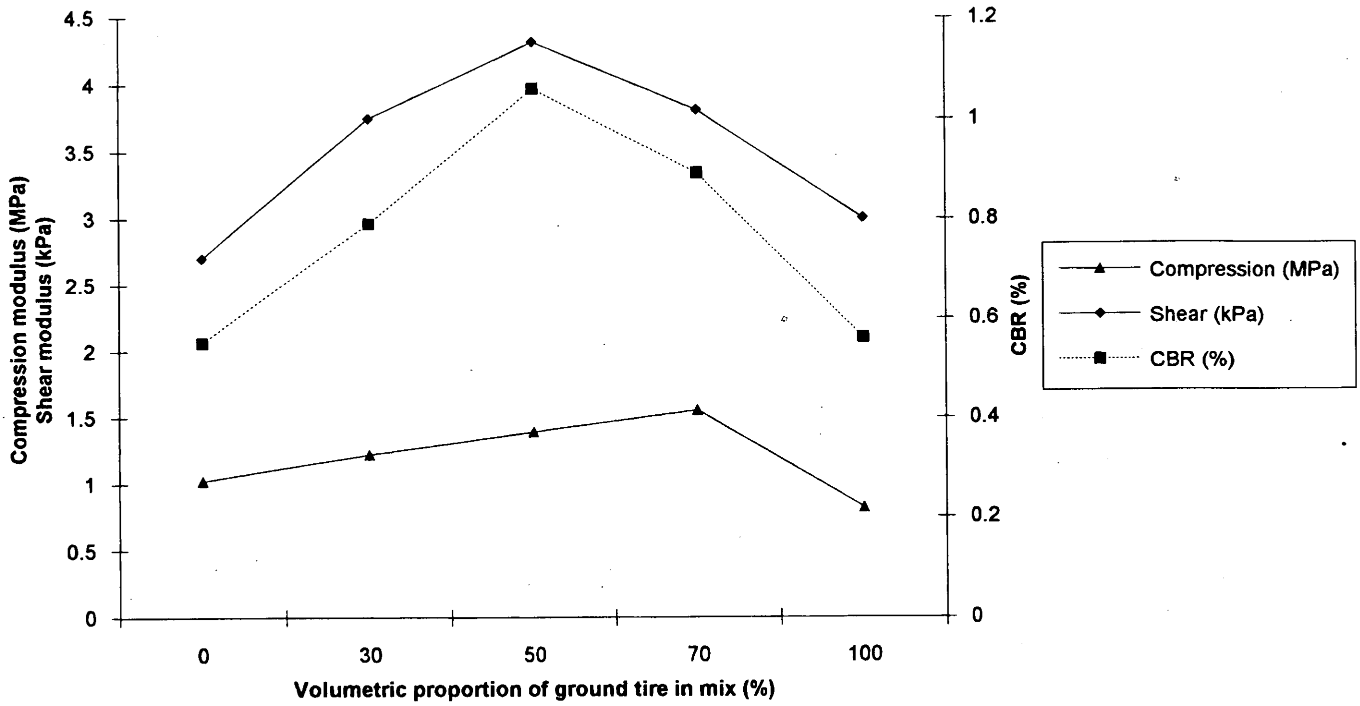

FIGURE 11 Mechanical properties for tire chips–ground tire mixes.

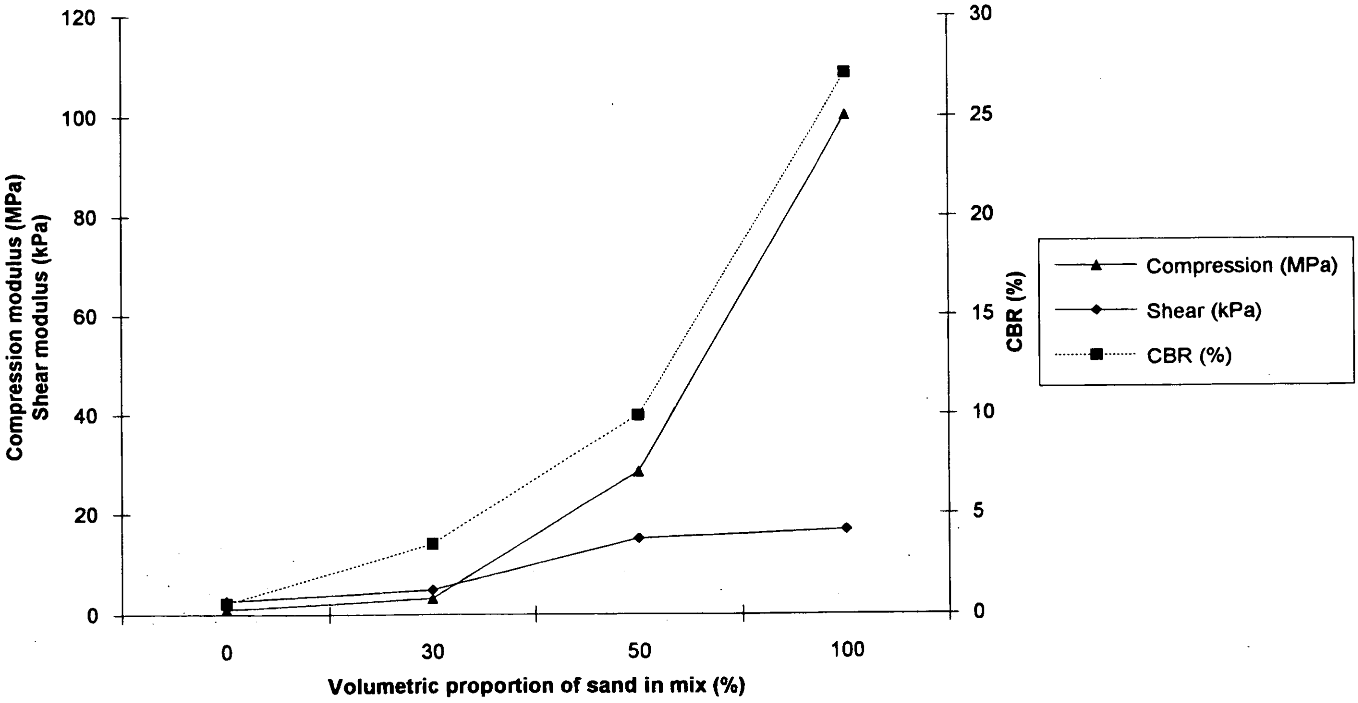

FIGURE 12 Mechanical properties for tire chips–sand mixes.

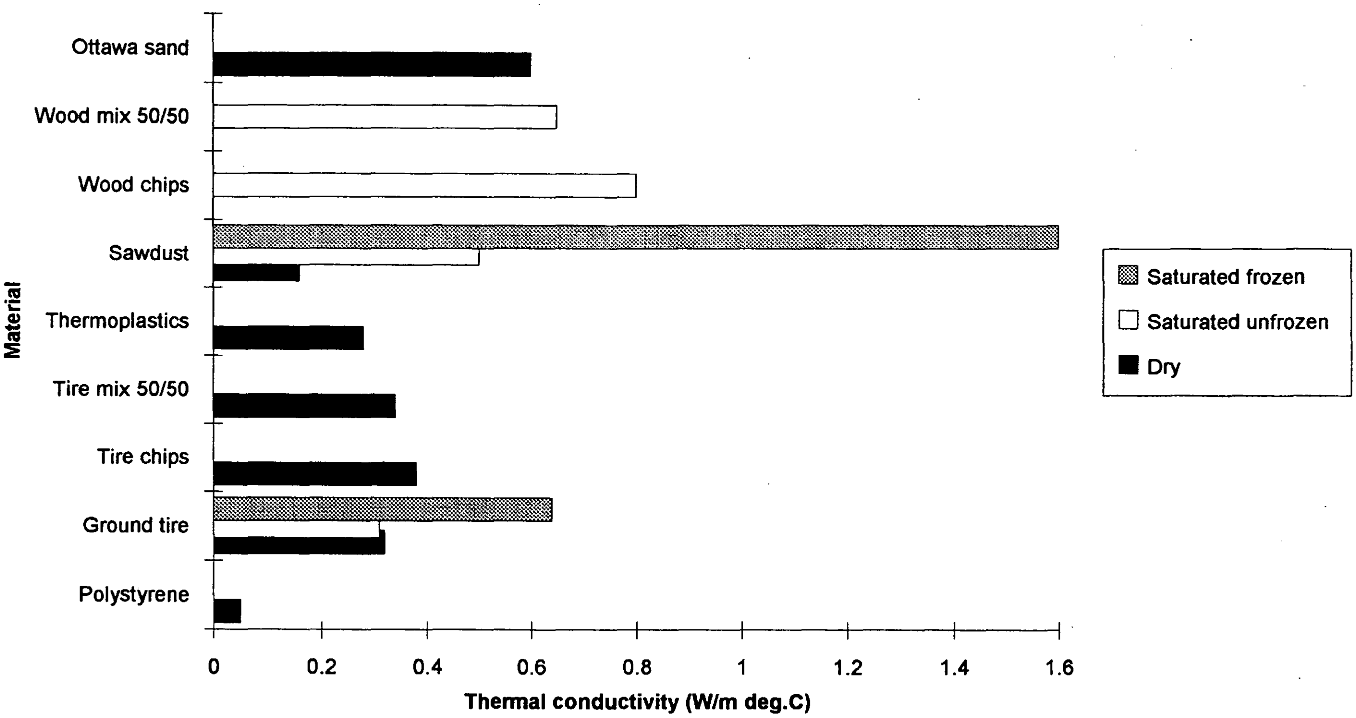

FIGURE 13 Results of thermal conductivity tests.

Among the wood residues, the sawdust showed the best combination of mechanical and thermal properties. The mechanical properties of the sawdust, however, were much lower than the ones used in the mechanical modeling but still much higher than the tire mix, which was used as the critical material for the optimization of the pavement design.

The thermal characteristics of sawdust are sensitive to moisture content and precautions should be taken at the design stage to prevent water from flowing into the layer through shoulders or cracked surface layers. The plastic recuperated from electric wires showed better potential performance than the one from domestic recuperation as well as a fairly good overall performance.

CONCLUSIONS

A major study on design and protection of pavements against frost action has been undertaken in the province of Québec. The study, designed to develop a rational design method and assess alternative frost protection materials, relies heavily on the long-term monitoring of eight pavement test sections to be constructed in 1994 and 1995. Most of the effort so far has been invested in the site preparation to allow for the longest monitoring period possible. Work done includes site selection, pavement design through mechanical and thermal modeling, material characterization, and preparation of the instrumentation plan.

Although the results reported in this paper were obtained at an early stage in the project, they provide useful information on the potential use of bulk insulation materials for frost mitigation in pavements. The following conclusions may be made based on this first phase of the research:

- The structural design of an insulated test section has been optimized using thermal (Laval model based on the segregation potential concept) and mechanical (ELSYM 5) simulations. By combining the expected mechanical performance with the expected thermal performance, it has been possible to determine that, if the pavement is properly designed, the expected loss in performance resulting from the addition of a soft layer is advantageously counterbalanced by the benefit associated with its insulating properties.
- Laboratory tests have significantly improved knowledge of the thermal, mechanical, and hydraulic characteristics of potential insulation materials, including recycled tires and plastics, as well as wood residues. Materials have been combined to maximize their performance. Pavement design must take into consideration the low rigidity and the fairly low thermal conductivity of these materials. Both aspects must be taken into account concurrently in the overall analysis of the performance.

The project will now focus on test site construction; instrumentation and monitoring; and model development. Relevant SHRP and C-SHRP long-term monitoring data will be incorporated in the study, and the C-SHRP BSTAT analysis package will be used in the development of the first-generation performance models.

REFERENCES

1. Konrad, J. M. Analyse Numérique des Chaussées Soumises à l'Action du Gel, du Dégel et du Trafic. *Colloque International Géotechnique et Informatique.* Paris, France, 1992.
2. Konrad, J. M., and N. R. Morgernstern. A Mechanistic Theory of Ice Formation in Fine-Grained Soils. *Canadian Geotechnical Journal,* Vol. 17, No. 4, 1980, pp. 473–486.

3. Konrad, J. M., and N. R. Morgernstern. Frost Heave Prediction of Chilled Pipelines Buried in Unfrozen Soils. *Canadian Geotechnical Journal,* Vol. 21, No. 1, 1984, pp. 100–115.
4. Gandhal, R. Bark as Road Building Material in Sweden. *Frost I Jord,* NR.5-, Dec. 1971.
5. Humphrey, D. N., and R. A. Eaton. Tire Chips as Insulation Beneath Gravel Surfaced Roads. *Frost in Geotechnical Engineering,* 1993.
6. Rioux, N. La Réutilisation des Pneux dans les Techniques de Protection contre le Gel. *Congrès de 1994 de la Fédération Routière Internationale,* 1994.
7. AASHTO. *Design of Pavement Structures.* Washington, D.C., 1985.
8. Ullidtz, P. *Pavement Analysis.* Elsevier, Amsterdam, the Netherlands, 1987.
9. Daigle, L. D., S. McDonald, L. E. Goodrich, and T. H. W. Baker. *Mesure de la Conductivité Thermique en Laboratoire de Différents Matériaux Recyclés* Saturés. Laboratoire d'infrastructures, Institut de recherche en construction, CNRC, Report H-7017.1, l'Université Laval, Canada, 1995.
10. Dysli, M. *Le Gel et son Action sur les Sols et les Fondations.* Complément au Traité de Génie Civil de l'École Polytechnique Fédérale de Lausanne, Switzerland, 1991.
11. Newcomb, D. E., and A. Drescher. Engineering Properties of Shredded Tires in Lightweight Fill Applications. Presented at the 73rd Annual Meeting of the Transportation Research Board, 1994.
12. Humphrey, D. N., T. C., Sandford, M. M., Cribbs, and W. P. Manion. Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill. In *Transportation Research Record 1422,* TRB, National Research Council, Washington, D.C., 1993.
13. Ladanyi, B. *Guide sur la Conception et la Réhabilitation des Infrastructures de Transport en Régions Nordiques.* Ministry of Transportation, Québec, Canada, 1991.
14. Johnson, G. H. *Permafrost Engineering Design and Construction.* J. Wiley and Sons, 1981.
15. *Norme pour la Conception des Chaussées.* Ministry of Transportation, Québec, Canada, 1994.

Publication of this paper sponsored by Committee on Frost Action.