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PERFORMANCE OF A ROAD BASE CONSTRUCTED WITH SHREDDED RUBBER TIRES

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ABSTRACT: Waste tires have recently proved to be an ecological and financial burden in many regions of the world. In Canada, an equivalent of one waste tire per capita is added to the stockpiles annually. The road construction can utilize a large quantity of scrap tires but there is a shortage of technical data on design and performance. Given this lack of technical data, a gravel-surfaced lightweight road embankment was constructed in Manitoba on a soft ground using large size (300 mm) tire shreds in the base layer.

This paper reports the performance-monitoring program of the road and development of a layered elastic-isotropic deflection model based on one-dimensional constrained compression laboratory tests on three sizes of the tire shreds. Design guidelines for roads constructed using shredded rubber tires are presented based on the laboratory testing, numerical model and field performance of the road.

1. INTRODUCTION

In Canada and the United States, an equivalent of one waste tire per capita is added to the stockpiles annually. Two environmental and health hazards associated with tire stockpiles are catastrophic fires and insect breeding. Such impacts of environmental constraints compelled researchers to seek an innovative use of scrap tires. Hence the major markets for scrap tires are Tire Derived Fuel, rubber products and civil engineering applications. Civil engineering applications of scrap tires benefit from their lightweight and thermal insulation properties, and hydraulic conductivity. But there is a shortage of technical data on design and performance. Given this lack of technical data, a gravel-surfaced lightweight road embankment was constructed in Manitoba on a soft ground using large size (300 mm) tire shreds in the base layer. The objectives were to monitor the performance of the road, examine the thermal and mechanical behaviour of the tire shreds and develop design guidelines for the construction of roads using tire shreds in the base layer.

2. PROJECT BACKGROUND

2.1 Site Description

The project site is located 5 Km North-East of Winnipeg, Manitoba, near the intersection of PR 213 and PR 207. A new road is to provide access to an active gravel pit. The topography of the site is flat to undulating. During the spring melt; the topography leads to poor drainage and areas of standing water.

Hence the site is mostly a swampy area with an influx of surface water flowing from an adjacent golf course.

2.2 Geotechnical Investigation

A soil investigation was carried out by the University of Manitoba to assess the subsoil conditions of the site. From geotechnical investigation, it was evident that the soil was not a suitable subgrade for conventional construction. There were three possible alternatives to improve the subgrade soil prior to construction of a road embankment. These included: (a) stabilizing the soft subgrade (b) replacing the existing subgrade with a compacted borrow that is better suited for use as a subgrade; and (c) constructing a lightweight road embankment.

2.3 Road Base Construction

The 300 m long road embankment was constructed in July 1999. Initially five layers of the whole tire sidewalls were manually placed on the subgrade in overlapping pattern to provide a clear working surface and to elevate tire shreds above the ground water table. Then 300 mm tire shreds were hauled to the site unloaded directly over the sidewalls and were spread to the desired thickness of 1500 mm with the backhoe in layers. The tire shreds were compacted with five passes of small bulldozer, with passes perpendicular and parallel to the road, and were finally covered with 450 mm thick gravel fill. The construction sequence of the 2.15 m high road is shown in Figure 1.

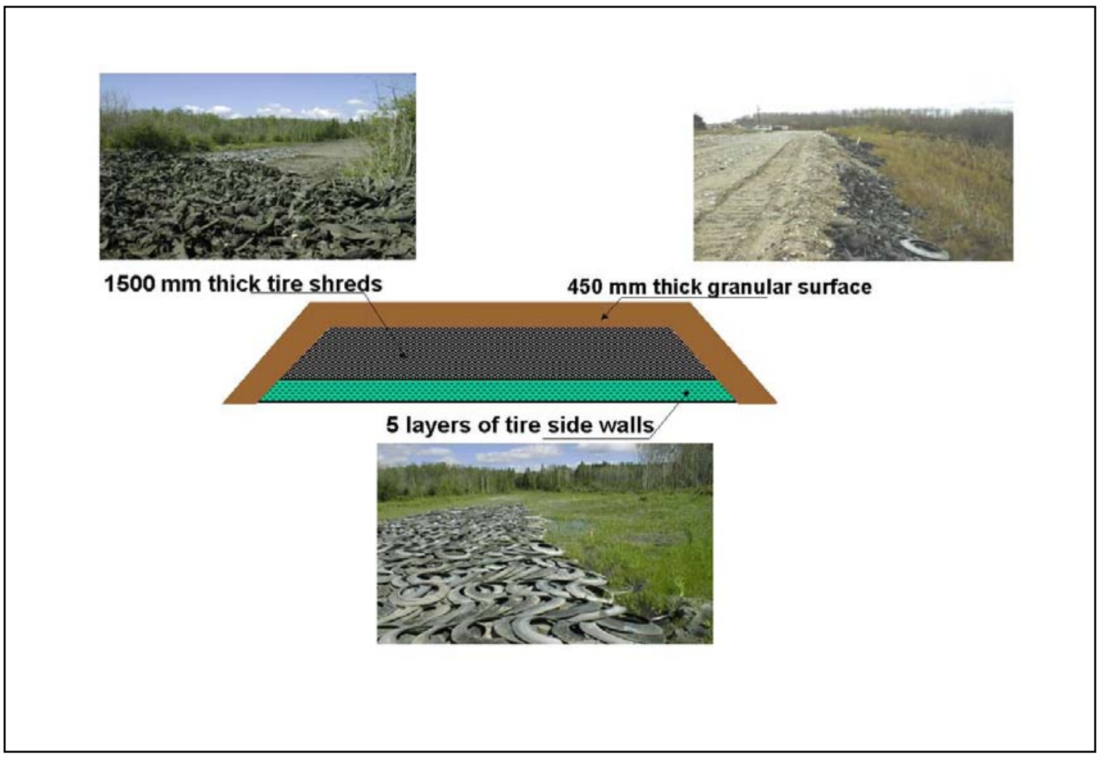

Figure 1. Construction of road base with shredded rubber tires

3. AUTOMATED TEMPERATURE MEASUREMENT AND GROUND WATER QUALITY TESTING

3.1 Automated Temperature Measurement

Soil thermal properties are of great importance in many engineering projects and other situations where heat transfer takes place in soils. Heat transfer in tire shreds plays an important role in roads construction over frost susceptible soils. An understanding of the thermal behaviour of tire shreds helps on deal with this problem. For this purpose an extensive field-monitoring program was put in place by the University of Manitoba to monitor ground thermal regime and develop the thermal behaviour of tire shreds.

3.1.1 Road instrumentation

Thirty-two copper constantan twenty-gauge thermocouples in four 50 mm PVC pipe casing were used in this program. Strings of thermocouples were attached to pipe casings for the evaluation of the thermal behaviour of tire shreds. Nine and seven thermocouples were placed in the tire shred embankment and in the natural ground adjacent to the embankment respectively. The sensors were placed at a uniform spacing of 343 mm in tires section and 457 mm in the adjacent roadside. Thermocouples were connected to the data acquisition system, placed in a heated and insulated data collection box.

3.1.2 Data collection

The temperature-monitoring program was started in November 2000. The DAQ system recorded a temperature reading for each sensor every hour. Temperature measurement was performed for the winter and spring seasons, Dec 2000-May 2001. Periodically a monitor was connected to the computer in the data collection box on site and the data was collected manually by transferring it to disks for subsequent analysis.

3.1.3 Data analysis

The climate or environment in which a road structure is to establish has an important influence on the behaviour and performance of the various materials in the road structure. Probably the two climatic factors of major significance are temperature and moisture (Wright and Paquette, 1987). One of the special climate related problems of interest in many regions of the world is that of damage caused to pavement structure by the freezing and thawing of subgrade and bases during winter and spring seasons. This phenomenon is called frost action. To investigate such effects for tire shred embankment a temperature-monitoring program was started and data was collected for winter/spring seasons, December 2000-May 2001. From this data, the average depth of frost penetration is summarized in Figure 2, which shows that frost penetrated deeper in the tire shred embankment compared to the natural ground which can be explained by the low water content and high void ratio in the tire shreds compared to the natural ground and the presence of a snow blanket on the natural ground (Shalaby and Khan, 2001).

Thermal conductivity governs steady state conditions and can be estimated through steady state method and the linear steady state equation (Farouki, 1986). For steady state conditions, a constant thermal gradient exists through each layer of uniform material and the heat flow through each layer of soil is assumed to be equal. Hence the ratio of thermal conductivity of soil and tires is inversely proportional to the ratio of their thermal gradients. Therefore the thermal conductivity of tire chips can be estimated from the thermal conductivity of underlying soil (Humphrey, 1997). Steady state method was used to determine the thermal conductivity from the subsurface temperature measurements, Figure 3. The thermal conductivity of tire shreds was found from the steady state conditions, to be 0.2832 W/m·°C which is five times lower than thermal conductivity of clay for dry density of 1500 Kg/m^3 and moisture content of 25 percent (Shalaby and Khan, 2001).

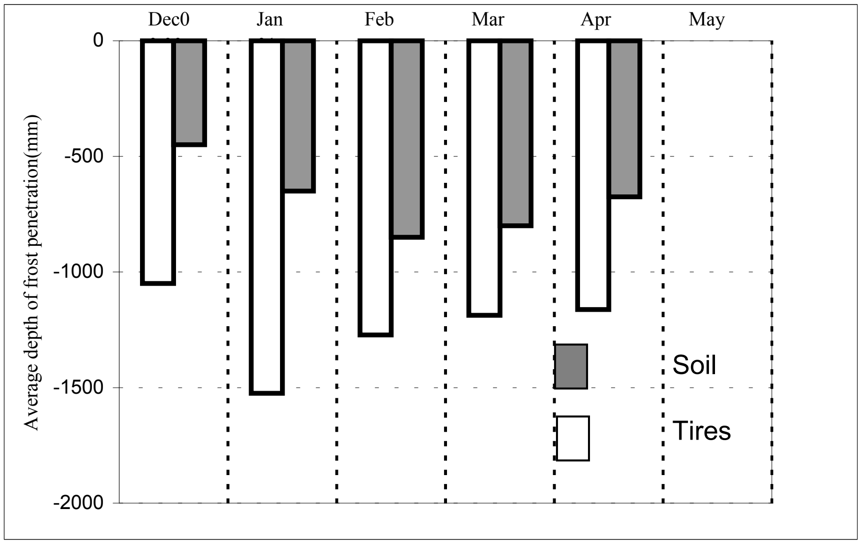

Figure 2. Average depth of frost penetration in natural ground and tire shred embankment, Dec 2000-May 2001

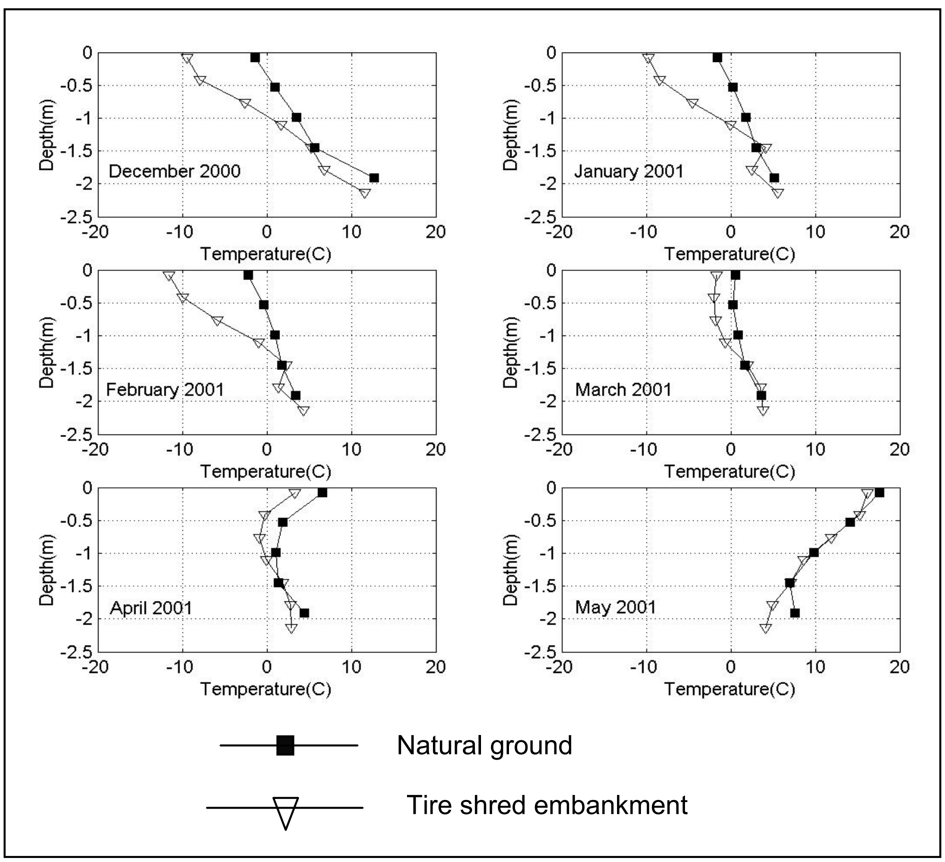

Figure 3. Thermal gradients of the natural ground and the tire shred embankment

3.2 Ground Water Quality Testing

To investigate the effect of tire shreds on water quality, inorganic and organic water quality tests were performed for the tire shred embankment on 15/03/001 and 20/04/001(Khan and Shalaby, 2001). The inorganic water quality results, as shown in table 1, are compared with the Canadian Council of Ministers of the Environment (CCME) Environmental Quality Guidelines (EQGs), (CCME, 1999). These results showed that concentrations of Aluminium, Iron and Manganese are higher than the recommended values but are of less concern, as these are secondary parameters in the EQGs. The organic water testing was performed for total extractable and purgeable hydrocarbons including Benzene, Toluene, Ethyl benzene, Xylenes (BTEX). The results showed that the level of organics is below the test method detection limits.

Table 2. Inorganic Water Quality Analysis

Analyte	Detection Limit [1] (mg/L)	Canadian Limit [2] (mg/L)	As tested on 15/03/01 (mg/L)	As tested on 20/04/01 (mg/L)
Aluminium	0.009	0.2	1.53	0.055
Barium	0.0002	1	0.0780	0.0454
Calcium	0.2	1000	120	83.2
Chromium	0.0009	0.05	0.0024	< .0009
Iron	0.003	0.3	5.75	0.159
Magnesium	0.06	No Limit	54.7	31.3
Manganese	0.0002	0.05	0.714	0.033
Sodium	0.4	200	11.5	5.5
Zinc	0.0007	5	0.0868	0.0098

1. APHA Standard Methods for Examination of Water and Wastewater (1998)
2. CCME Environmental Quality Guidelines (1999)

4. DEFLECTION MEASUREMENT

A reliable and economic design of road embankment using tire shreds in the base layer depends on several factors, among which a proper characterization of load-deformation response of tire shreds is very important. Base or subbase materials undergo deflections when subjected to repeated loads from moving vehicular traffic. Each time a load passes a road structure, the materials rebounds less than it had deflected under the load. After repeated loading and unloading sequences, each layer in a road structure accumulates only a very small amount of permanent deformations and most deformation is recoverable or resilient deformation (Tian, 1998). To explain this behaviour, researchers have used the concept of resilient modulus; M_R, which defines the recoverable deformation response of road materials under repetitive loading corresponding to given state of stress (Bosscher, 1994). A satisfactory tire shred embankment design can be achieved by use of appropriate resilient moduli for tire shreds. The standard resilient modulus test cannot be run on pure tire shreds and the elastic modulus can be estimated from the repetitive constrained modulus tests (Bosscher, 1994). But limited work has been reported on the resilience response of tire shreds. To investigate the mechanical behaviour of three sizes of tire shreds and to develop design parameters for tire shred embankments, field and laboratory deflection tests were performed, assessing the resilience response of the tire shreds to various stress level and measuring the deflection of the tire shred embankment.

4.1 Field Deflection Measurement

Metal settlement plates (500 x 500 mm) were placed at several locations flush with the surface of the road to measure the compressibility of the tire shred embankment. Then a rod and level survey was performed to quantitatively evaluate the performance of the embankment under traffic loads. Initially, the as built elevations of the settlement plates were recorded. Then the settlement plates were loaded by a stationary 21,000 Kg dual-tandem axle load and the elevations were recorded. A final elevation was recorded after the removal of the load. The deflection of the road was obtained from the difference of initial elevation and the elevation under load. The rebound was measured from the difference of final and loaded elevations. Two loading and unloading passes were performed. An average of 15 mm and maximum of 25 mm deflection under the load was recorded. This deflection is not of great concern for unsurfaced roads. An average instantaneous rebound of 11 mm and an average irrecoverable displacement of 7 mm were also recorded after two passes of the loaded truck.

4.2 Laboratory Deflection Measurement

4.2.1 Test materials

Three sizes of the tire shreds, minus 300 mm, minus 150 mm and minus 50 mm, were examined for laboratory compressibility testing. These tire shreds were generally curved, irregular shaped and many had sharp, tangled and twisted steel reinforcing fibers protruding from their cut edges. These tire shreds were from a mixture of steel and glass-belted tires. The uncompacted density of these tire shreds was determined in the laboratory by first weighing an empty container and then weighing the container filled with tire shreds. The uncompacted density was obtained from the difference of final and initial readings and was found to be 343 Kg/m^3, 355 Kg/m^3 and 534 Kg/m^3 for minus 300 mm, minus 150 mm and minus 50 mm tire shreds, respectively. The compacted density was also obtained by monitoring the compressibility of the shred sample during the application of the load.

4.2.2 Test apparatus

Several laboratory tests have been performed to determine the response of the tire shreds to cyclic loading. To investigate the behaviour of large size tire shreds and to address the resilience of the material for high stress level, cyclic loading/unloading constrained compression tests were performed using a servo hydraulic loading frame connected to a data acquisition system. The constrained tests were performed in a 0.622 m^3 straight wall cylindrical steel container. The inside dimensions of the container were 900 mm in diameter and 1000 mm in height. The steel loading plate, which was 875 mm in diameter and 200 mm thick was attached to the actuator, was slightly smaller than the inside diameter of container to prevent jamming.

4.2.3 Testing methodology

As per ASTM D 6270 (ASTM, 1998) placing the tire shreds in a rigid cylinder with diameter several times greater than the largest particle size and then measuring the vertical strain caused by an increasing vertical stress computed the deflection of the tire shreds. The inside of the cylinder was lubricated, ASTM D 6270, to reduce the portion of the applied load that is transmitted by side friction from the tire shreds to the walls of the cylinder. It should be stressed that in tests where higher level of accuracy is required both top and bottom stresses should be measured to compute the average vertical stress. The tire shreds were placed in a loose state in the cylinder upto a depth of 800 mm. The load was applied to the tire shreds at a constant rate of displacement of 10-mm/min. Repeated loading and unloading cycles were made. The tire shreds were unloaded at the same rate. The tire shreds were subjected to 20 cycles of loading. In each case, computer directed the actuator to perform programmed test procedure. Throughout the test the values of load and vertical displacement were collected in a data file after a specified time increment.

4.2.4 Experimental results

Figure 4 shows the stress-strain response of the three sizes of the tire shreds after the deduction of the irrecoverable displacement caused by placing the shreds in a loose state in the cylinder. Irrespective of the shred size, initial compaction takes place in the first cycle of loading and stiffness of the tire shreds increases. A portion of this compression is irrecoverable and a significant rebound (resilience) occurs upon unloading. The subsequent loading-unloading cycles tend to have similar stress-strain response however with less resilience response than the first cycle. These test results were characterized in terms of the maximum strain obtained at 600 KPa stress level in the first cycle of loading. At this stress level, the strain was about 36.5, 38.5 and 41 percent for 50 mm, 150 mm and 300 mm tire shreds respectively indicating that the deflection of large size tire shreds (300 mm) is about 2.5 percent higher than small size tire shreds (150 mm). The direct labour and material costs for large size tire shreds were $12 per ton compared to $30-$65 per ton for small size tire shreds (Graham et al, 2001), suggesting that the large size tire shreds can be a feasible economical alternative compared to small size tire shreds.

4.2.5 Deflection analysis

Multilayer computer software, KENLAYER, was used to model the deflection of the tire shred embankment based on the laboratory test data (Huang, 1993). Construction equipment used for field compaction can have a contact pressure of 35 KPa for wide-track bulldozer (Humphrey, 1996) and 56.5 KPa for crawler type tractor (Hager et al, 1998). A total of field compaction stress and tire contact pressure of 695 KPa and a gravel surcharge stress of 8.82 KPa was assumed for this analysis. Most of the deflections observed in the laboratory and field deflection tests were recoverable under the repeated applications of loads. Because only minor irrecoverable displacements are observed after several load/unload cycles, tire shreds exhibit non-linear elastic behaviour after few initial cycles of load application (Edil and Bosscher, 1992). Linear and non-linear deflection analysis of the tire shred embankment was performed using a seven-layer elastic isotropic system based on elastic layer theory. In this analysis the subgrade, the lowest layer, was assumed to be infinite in horizontal and vertical directions while the other layers of the road embankment were assumed to have infinite extent in horizontal directions only. Load was expressed as a tire contact pressure, field compaction stress, exerted by construction machinery in the field, and gravel surcharge on top of the tire layer in the tire shred embankment. The determination of the required deflection is based on the effective resilient modulus values obtained from laboratory tests data.

In the linear analysis the embankment was assumed to be a linear homogenous mass having an elastic modulus of the tire shreds independent of the level of stress and constant for all five layers of the tire shreds. It was therefore possible to select approximate elastic moduli for the three sizes of the tire shreds from Figure 5 commensurate with the 704 KPa stress level.

Using non-linear analysis it is evident that the stress-strain response of the tire shreds obtained from laboratory tests is dependent on the stress levels, Figure 5, showing that the resilient modulus of the tire shreds increases with increase in bulk density. The vertical stress due to the surface loading at mid-depth of each layer beneath the surface of the road was determined by the Boussineq's equation for distributed loads (Huang, 1993). The surface deflections were calculated by KENLAYER using the elastic moduli of the tire shreds obtained from Figure 5 for the respective stress levels. Coefficient of earth pressure at rest for the tire shreds was assumed to be 0.4 (Humphrey and Sandford, 1993) as an input parameter in KENLAYER for the non-linear elastic analysis.

It was observed that the primary variables that influence the resilient response of tire shreds are stress level and the density of the tire shreds. It was noted that the deflections of the road based on linear elastic analysis are approximately 40 percent smaller than when the fill is analyzed as non-linear elastic system. This means that the non-linear assumption in deflection prediction, based on material properties determined from a one-dimensional constrained compression test, gave a safe estimate of the deflection of the tire shred embankment compared to the linear elastic assumption. However it should be stressed that this conclusion is derived from analyzing limited combination of elastic input parameters and a simplified model of layered materials.

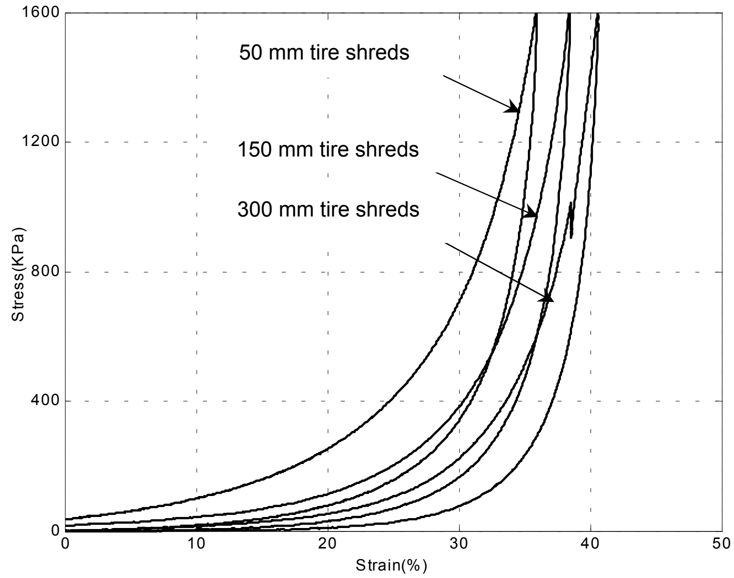

Figure 4. Constrained stress-strain responses of three sizes of tire shreds

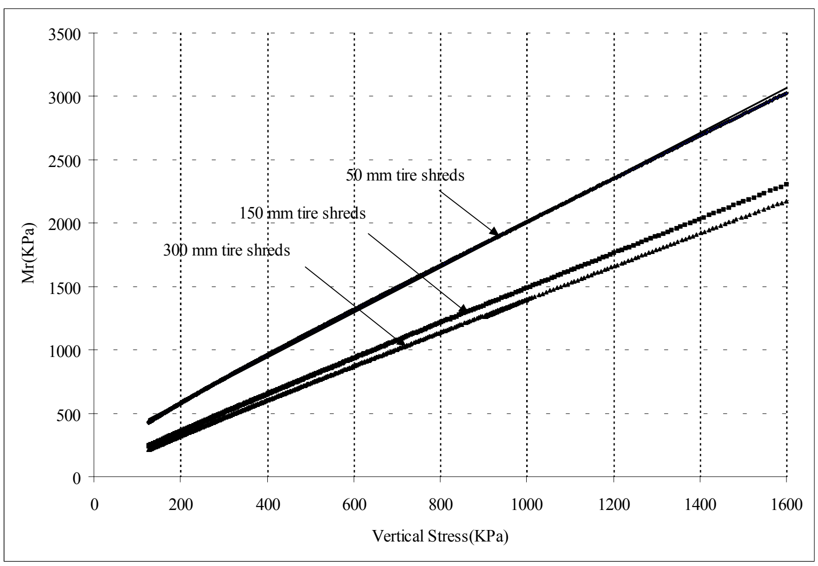

Figure 5. Resilience response of three sizes of tire shreds obtained from laboratory testing

5. PRACTICAL APPLICATIONS OF RESULTS

Presumably, limiting the depth of frost into the subgrade soil limits, adequately, the potential for frost heave and thaw weakening. One of the implications of the preceding calculation of depth of frost penetration is that the total depth of road structure in the frost-affected areas can be influenced by such results. Hence the depth of frost penetration can be used in the road design process. Most state highway agencies in the United States use an empirical rule of thumb that the total pavement structure should be at least 50 percent of the expected depth of frost penetration in frost-affected areas (WSDOT, 1995). Hence the depth of frost penetration obtained in this study can be used in the design of tire shred embankments in frost affected areas by taking the total thickness of pavement structure as half of the expected depth of frost penetration which comes out to be 765 mm from this monitoring program. This number can give an expected minimum range of the thickness of tire shred embankments for practitioners and researchers.

Numerical values of various constants permit mathematical checks of various heat transfer problems in connection with frost action in soils. The numerical values of thermal gradient, thermal conductivity and depth of frost penetration presented in this research are offered for use in such calculations. The value of thermal conductivity of tire shreds obtained from this analysis can also be used in theoretical calculations of the depth of frost or thaw, which relies on reasonably accurate values of thermal conductivity. Theoretical depth of frost penetration can be found out by using Stefan formula or modified Berggren formula (WSDOT, 1995) knowing the thermal conductivity value of the tire shreds. It is hoped that the use of values presented and additional research may lead to corrections and improvements in the stated values.

The design of tire shred embankments can be characterized by the resilient moduli of tire shreds. However due to the complexity of the shape of tire shreds and equipment requirement, it is desirable to develop an approximate method for the estimation of resilient modulus of the tire shreds and hence deflection prediction of the tire shred embankment. A non-linear layered elastic isotropic model developed in this research relates the resilient modulus of the tire shreds with the applied stress at the top of the embankment and predict the deflections. This model, developed by studying the resilient and irrecoverable strain of three sizes of tire shreds under the load/unload cycles in the laboratory and field, provides an estimation of the resilient modulus of tire shreds and deflections of the tire shred embankment. Using this approximate procedure, deflections of the tire shred embankments can be predicted and a satisfactory road design can be achieved using large size tire shreds in the base layer.

6. CONCLUSIONS

Following are the conclusions and observations drawn from the research.

- The thermal gradient in tires, natural ground and gravel is approximately 10°C /m, 2°C /m and 1.5 °C /m respectively.
- The thermal conductivity of the tire shreds is five times lower than the thermal conductivity of clay with a dry density of 1500 Kg/m^3 and moisture content of 25 percent.
- Frost penetration in the tire shred embankment is larger than in the natural ground because of the low water content and presence of large voids in tire shreds and the difference in snow cover.
- The observed surface deflection of the tire shred embankment is 15 to 25 mm, under 21000 Kg dual-tandem axle load. An average rebound of 11 mm and irrecoverable displacement of 7 mm were recorded after two passes of load.
- The elastic modulus of the tire shreds is proportional to the bulk density of the shreds.
- Non-linear elastic isotropic analysis gives a conservative estimate of the deflection of the tire shred embankments compared to the linear elastic analysis. The design of road embankments with large-size tire shred layers can be made using the non-linear elastic analysis model presented in this paper.
- Large size tire shreds can be an economical alternative compared to the small size tire shreds in the construction of the tire shred embankment.

7. ACKNOWLEDGEMENTS

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