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THERMAL CONDUCTIVITY OF RECYCLED TIRE RUBBER TO BE USED AS INSULATING FILL BENEATH ROADWAYS

by

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16. Abstract
Under the present federal highway funding act, Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, used tires in all states must be either combined with highway pavements or recycled as consumer products in increasing amounts. One possible use of tires in Alaska is to shred, chop or grind tires into small particles and use this material as an insulating fill to reduce thaw or freeze penetration beneath roads. This study presents the results of measuring thermal conductivities of frozen and unfrozen ground and shredded tire rubber of various sizes and at three compactions. Thermal conductivities ranged from 0.059 to 0.096 BTU/hr-ft-F° for crumb rubber, 0.056 to 0.080 BTU/hr-ft-F° for rubber buffings, and 0.071 to 0.10 BTU/hr-ft-F° for rubber chips. Resilient moduli of the two smaller types of rubber samples were also measured in a triaxial test cell. Values ranged from 94 psi at a confining pressure of 5 psi up to 215 psi at a confining pressure of 15 psi.

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Thermal Conductivity of Recycled Tire Rubber to be Used as Insulating Fill Beneath Roadways

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ABSTRACT

Under the present federal highway funding act, Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, used tires in all states must be either combined with highway pavements or recycled as consumer products in increasing amounts. One possible use of tires in Alaska is to shred, chop or grind tires into small particles and use this material as an insulating fill to reduce thaw or freeze penetration beneath roads. This study presents the results of measuring thermal conductivities of frozen and unfrozen ground and shredded tire rubber of various sizes and at three compactions. Thermal conductivities ranged from 0.059 to 0.096 BTU/hr-ft-F° for crumb rubber, 0.056 to 0.080 BTU/hr-ft-F° for rubber buffings, and 0.071 to 0.10 BTU/hr-ft-F° for rubber chips. Resilient moduli of the two smaller types of rubber samples were also measured in a triaxial test cell. Values ranged from 94 psi at a confining pressure of 5 psi up to 215 psi at a confining pressure of 15 psi.

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1. INTRODUCTION

Ground tire rubber has been used as an additive in bituminous concrete for highway pavement construction since the mid-1960s. Early use of particulate tire rubber in bituminous concrete was employed as a means to improve its performance while simultaneously eliminating a waste product. Although the technology for tire-rubber-modified asphalt has been available for more than 20 years, only recently has the waste tire problem become so acute that the ISTEA includes a schedule of minimum requirements for using recycled tire rubber in asphalt pavements, starting in 1994.

Each year the United States discards approximately 285 million tires, more than one tire per person per year. Of that figure, 33 million tires are retreaded and 22 million tires are reused (resold). Another 42 million are diverted to various other alternative uses. The remaining 188 million tires are added to stockpiles, landfills, or illegal dumps across the country. In many cases these piles are a serious fire hazard, a prolific breeding ground for mosquitoes, and an ugly scar on the landscape. The Environmental Protection Agency estimates that 2 to 3 billion tires is the present size of the scrap tire stockpile problem.

Under the present federal highway funding act, Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), used tires in Alaska must be either combined with highway pavements or recycled as consumer products in increasing amounts. Beginning in 1994, about 250 tons per year must be recycled, increasing to 1,000 tons per year by 1997. The only alternatives to using tires as 5% to 20% of pavement mixes is consuming them in other recycling procedures. In Alaska, there are few recycling opportunities to utilize discarded tires available.

Although in the past the Alaska Department of Transportation and Public Facilities (AKDOT & PF) has experimented with using rubber modified asphalt, the use of ground or shredded rubber from used tires as an insulating layer has not been investigated. Tire rubber would serve as a substitute for the rigid foam plastic insulation used in the past within roadway fills to reduce frost heave and thaw degradation of permafrost.

The objective of this project is to measure and report thermal conductivities of ground and shredded tire rubber of various particle sizes. These data will allow engineers to evaluate the potential of using recycled tire rubber as an insulating material.

2. LITERATURE REVIEW

By 1991, 44 states had drafted, introduced, regulated or enacted laws to control the scrap tire problem. In recent years, a growing number of state departments of transportation and municipalities have investigated potential uses of recycled tire rubber. However, a preliminary literature search has revealed no data regarding thermal conductivities or thermal resistance data on shredded or granulated tire rubber.

There have been mainly two usages of recycled tire rubber in highway construction. One is to add ground tire rubber to the asphaltic paving mixture, modifying pavements in hopes of improving their performance. In Virginia, Maupin (1992), investigated the characteristics of an asphaltic mixture with crumb tire rubber. Test results indicated the asphalt rubber mixtures were more susceptible to permanent deformation than the same mixtures without. However, mixtures with asphalt rubber displayed less stripping. In Florida, Page, Ruth and West (1992) reported on the use of ground rubber as an additive mixture to improve the performance of the friction course. These results indicated field construction operations with the rubber-modified mixtures were essentially the same as those with conventional friction course mixtures. It is also believed that the rubber provides an improved elasticity to the binder and therefore greater resilience, and it should allow recovery from high pavement strains at intersections. In Alaska, as early as 1980, Esch (1984) used rubberized asphalt in a test road section to improve traction and reduce wintertime stopping distances under icy and frosty road surface conditions. It appeared that ground rubber asphalt mixtures improved ice-removal effects in higher traffic and higher speed areas.

The other application of used tire rubber is as a lightweight fill layer or as a layer of insulating material in roadway construction. Humphrey (1993) conducted a full scale field trial using tire chips as an insulating layer beneath a gravel surfaced road in Maine. The test sections had two different thicknesses of tire chips (152 and 305 mm) and three different thicknesses of overlying gravel cover (305, 457 and 610 mm). The test sections were designed to reduce penetration of frost in the underlying soil and thereby reduce the thickness of gravel cover needed to provide a stable road surface. The test data indicated the tire chip layer reduced the depth of frost penetration. A secondary benefit was that tire chips have a very high permeability, and therefore provided excellent drainage to remove excess water from the road substructure.

3. INVESTIGATION OF THERMAL CONDUCTIVITY VALUES

The thermal conductivity of solid rubber is listed as 0.08 ~ 0.10 BTU/hr-ft-F°, Mills (1992). Granulated rubber should have an even lower thermal conductivity, due to the air trapped in the voids, making it a good insulating material. Both frozen and thawed thermal conductivities (below and above 32°F) of granulated and shredded tire rubber were measured in this study. Variations in density and moisture content of the rubber samples were included in the test program.

3.1 Description of Materials

Three different types of ground tire rubber, as produced by different tire processing machines, were tested in this study. They included rubber buffings, granulated or crumb rubber, and rubber chips. Appendix A describes the apparatus and procedure used to measure sizes of the ground tire rubber tested. The rubber buffings, with more than 80% passing through a #10 sieve, were the finest among the three materials. The granulated rubber varied in size from 1/4-inch to the #50 sieve size. The nominal two-inch rubber chips produced by the shredder were the coarsest, with more than 80% passing through a 1-inch sieve, but only a few percent passing a 1/4-inch sieve. All these products were made from processing passenger car tires.

Therefore test materials consisted of not only rubber but also some traces of steel belting and tire cord. Sources and size ranges for the samples are listed in Table 1 (see appendix for detail data).

Table 1. Sources of Materials

	Rubber Buffings	Granulated Rubber	Rubber Chips
Particle Sizes	80% passing #10 sieve	90% passing 1/4" sieve	80% passing 1" sieve
Source	Mobat Tire	Rubber Granulators	Waste Recovery,Ltd
City & State	Fairbanks, Alaska	Everett, Washington	Portland, Oregon
Processing Method	Re-Tread Buffing Machine	Granulator	Shredder

3.2 Description of Conductivity Test Method and Equipment

Bankvall (1974) described steady-state as well as nonsteady-state methods for measuring thermal conductivity. The steady-state method, used in this project, has been standardized, and measurements in a guarded hot plate can be regarded as the basic method of measuring thermal conductivity of low thermal conductivity insulations. The principle of the guarded hot plate, or the so-called Poengen apparatus, is simple. It is based on the steady-state heat transfer between a warm and cold plate. A drawback of the conventional guarded hot plate is the length of time required to establish steady-state conditions, and the potential for moisture transport during the test.

In this investigation, two different guarded hot plate measuring systems were used: Dynatech Model TCFGM and Anacon Model 88. The advantages and disadvantages of these devices are listed in Table 2.

Table 2. Characteristics of Dynatech Model TCFGM and Anacon Model 88 Thermal Conductivity Analyzers

	Dynatech Model TCFGM	Anacon Model 88
Advantage	used to test both thawed and frozen materia materials	less time to reach equilibrium
Disadvantage	increased time to reach the equilibrium point	only used to test thawed materials

The Dynatech Model TCFGM was used to measure the thermal conductivity of tire rubber in a frozen state and the Anacon Model 88 was used to measure the thermal conductivity for tire rubber in the thawed state based on the reasons noted in Table 2.

3.2.1 Dynatech Model TCFGM

The Dynatech Model TCFGM guarded hot plate thermal conductivity measuring system is used for determining thermal performance of insulations and other materials of relatively low thermal conductance. The Model TCFGM requires two identical samples of the material, which are placed on the top and bottom sides of a horizontal flat plate heater assembly, creating a sandwich. The heater consists of a four-inch (10 cm) diameter inner (main) heater surrounded by an annular eight-inch (20 cm) diameter, separately controlled, guard heater. The function of the guard heater is to eliminate radial heat flow to or from the main heater, thereby forcing all heat from the main heater to be one dimensional through the test samples. Liquid cooled heat sinks are placed in contact with the samples, producing a uniform and constant temperature on the far sides. Figure 1 is the schematic layout of Model TCFGM.

The Model TCFGM conforms to ASTM C177 and ISO 2582 specifications. Test specimens must be 8 inches (20 cm) in diameter, with a maximum thickness of 2 inches (5 cm). Because of the exceptional versatility of the TCFGM, this equipment is ideally suited for determining the thermal conductivity of a variety of materials over a very broad range of

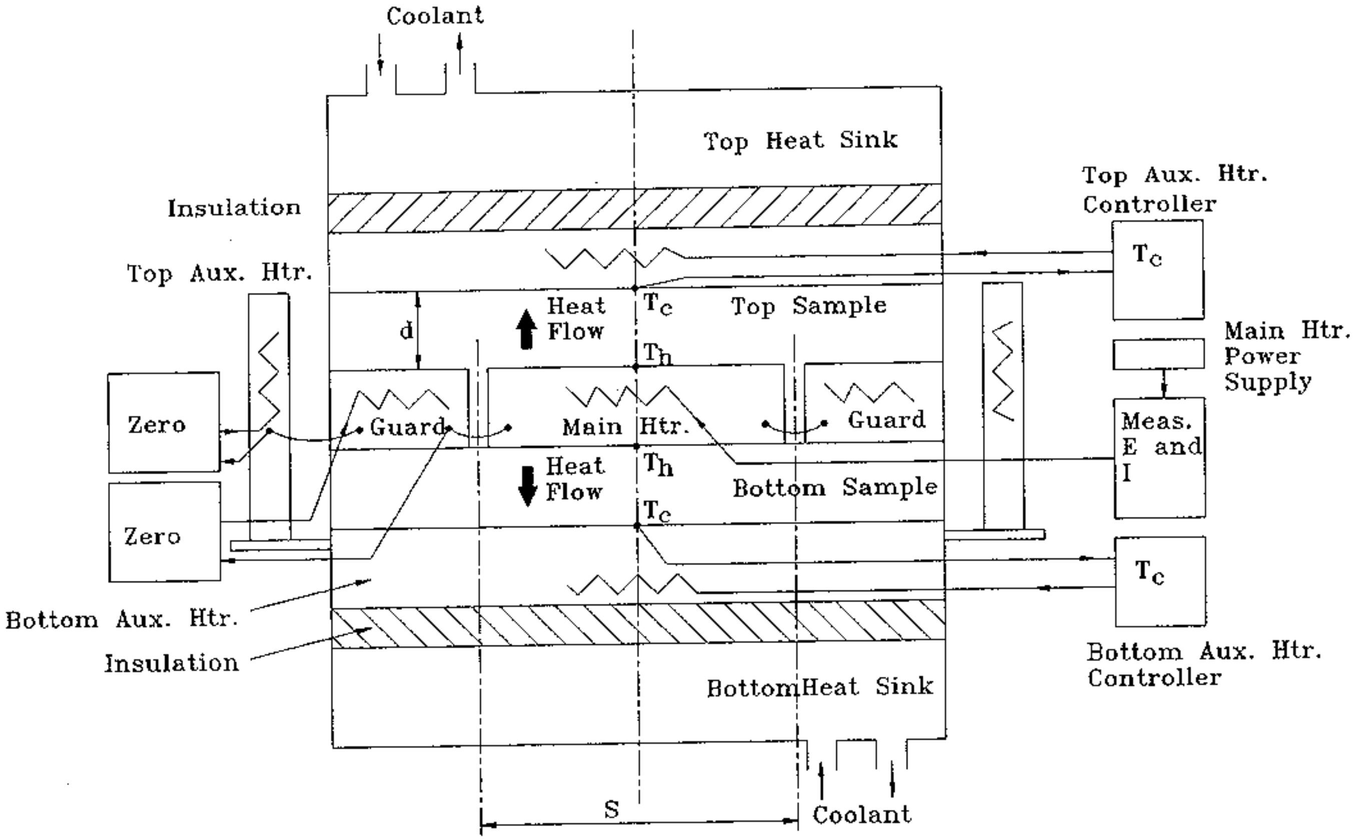


Figure 1. Schematic Layout of Model TCFGM Guarded Hot Plate Thermal Conductivity Instrument

temperature and environmental conditions. Materials that can be tested in the TCFGM include honeycomb systems, mineral fiber batt, cellular plastics, ceramic boards, rubbers, wood products and many others. In a typical test, from five to ten hours may be necessary before achieving thermal equilibrium in the test section. The required time depends on the total mass of the specimens and the operating temperature.

Fixed power input to the main heater is provided by a regulated DC power supply. The side of the sample next to the heater increases in temperature until thermal equilibrium is reached, thus establishing a steady temperature gradient through the sample. The final temperature of the guarded hot plate depends on the power input to the heater, the thermal conductivity of the test samples and the temperature of the heat sink (the cold face of the sample). In nearly all test applications, the test sandwich assembly is surrounded by loose fill insulation contained in a cylindrical shroud to minimize heat loss to the surroundings.

The effective thermal conductivity of the test samples is calculated based on the measurements of the final surface temperatures, the power input to the main heater and the thickness of the test samples, as follows:

$$k=\frac{E\times I}{S}\times\left[\frac{1}{(\Delta T_1/d_1)+(\Delta T_2/d_2)}\right]$$

where E×I = main heater input power

S = main heater surface area

ΔT = temperature difference across the sample

d = sample thickness

(Subscripts 1 and 2 refer to the two test samples.)

The temperature difference across the samples, $T_H - T_C = \Delta T$, is determined using chromel-alumel thermocouples. A total of eight thermocouples are used to measure surface temperatures of the hot and cold plates. Locations of these thermocouples are illustrated in Figure 2. These eight thermocouples are installed in grooves in the heater surfaces. Figure 2

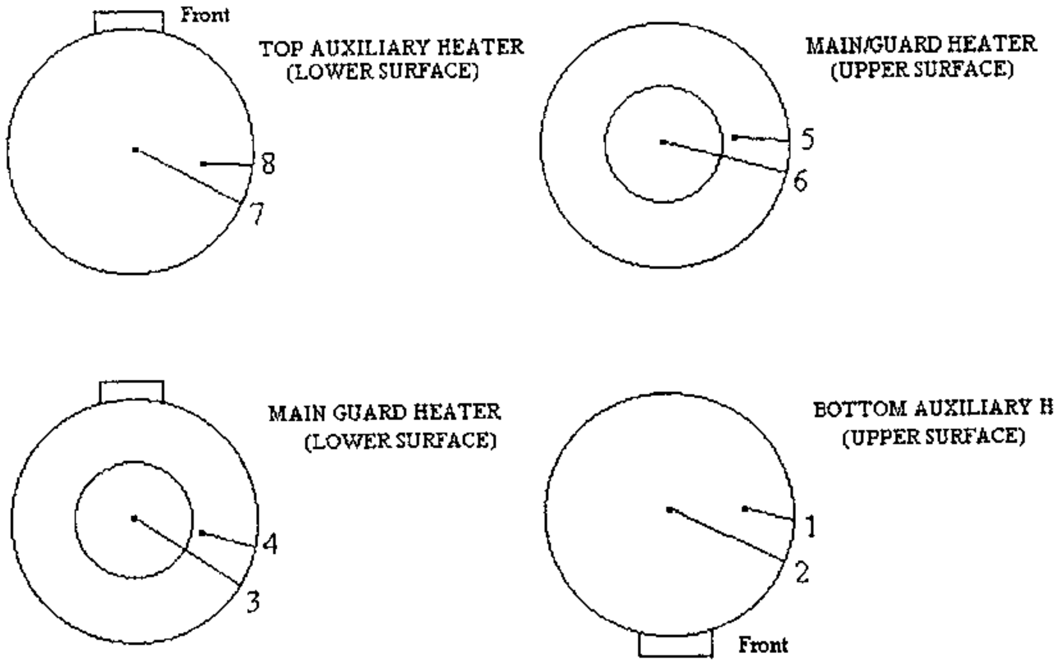


Figure 2. Layout of Thermocouples in the Heaters

shows that both faces of the heater contain two thermocouples, one with its measuring junction in the center of a four-inch circular area, and one in the surrounding guard area.

The main heater input power is determined by measuring steady DC voltage across and current flow through the main heater. The current flow through the main heater is determined by the voltage drop across a 0.01 ohm precision resistor in series with the heater. The voltage and current are also displayed on the digital millivoltmeter of the Model TCFGM.

3.2.2 Anacon Model 88

The Anacon Model 88 is also based on the standard guarded hot plate method. The apparatus (illustrated in Figure 3) is the standard Anacon Model 88 K-Factor instrument. An opening in the front panel (left side of instrument) is provided to accommodate an eight-inch by eight-inch square test sample up to 2 inches thick. The digital display is selected by a multi-push button selector switch located on the front panel.

As shown in Figure 4, the hot plate assembly consists of a four-inch diameter copper plate which is 1/8 inch thick. The heater disc (4 inches in diameter) is located on the top surface of the assembly. The heat flow sensors are located on the bottom surface of the hot plate. The complete assembly is insulated and all surfaces are sealed with a thermal compound.

The cold plate dimensions are identical to those given for the hot plate. The only difference between the two assemblies is the substitution of thermoelectric cooling. Using heat sink compound on the samples assures good thermal bonding.

The hot plate assembly is supported by a threaded stud. The supporting stud is attached to the assembly so that a vertical downward force can be applied to the heater plate, causing a uniform pressure over the entire sample surface. The heater plate is also mechanically

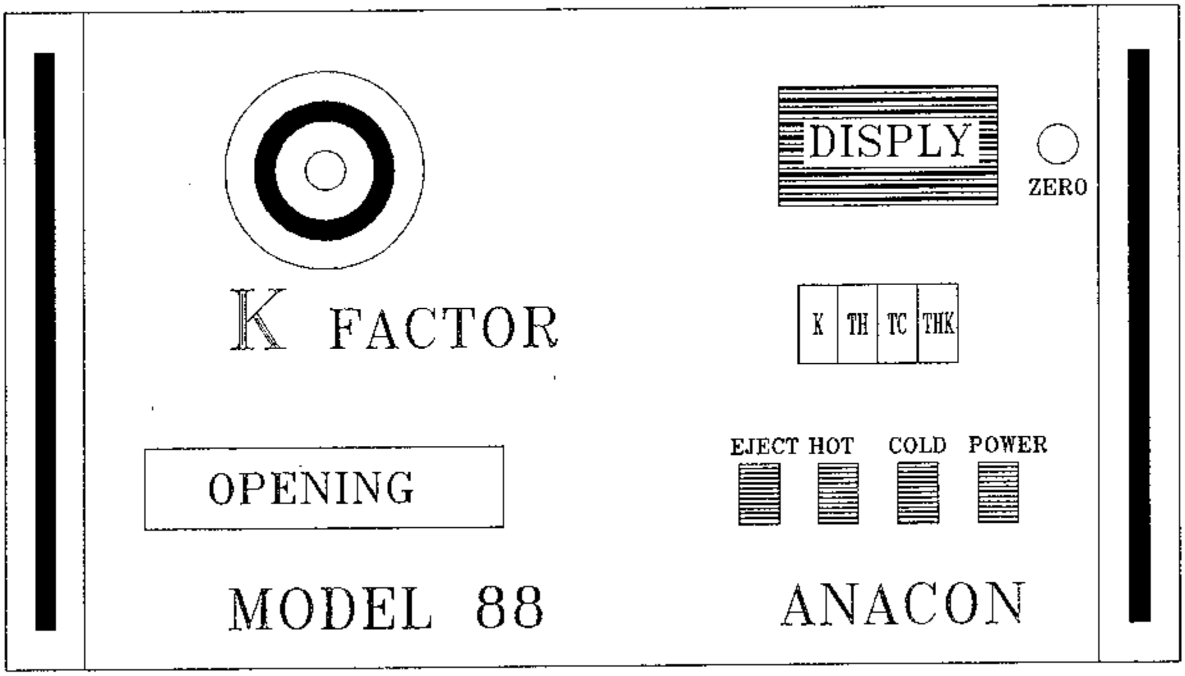


Figure 3. Configuration of Anacon Model 88

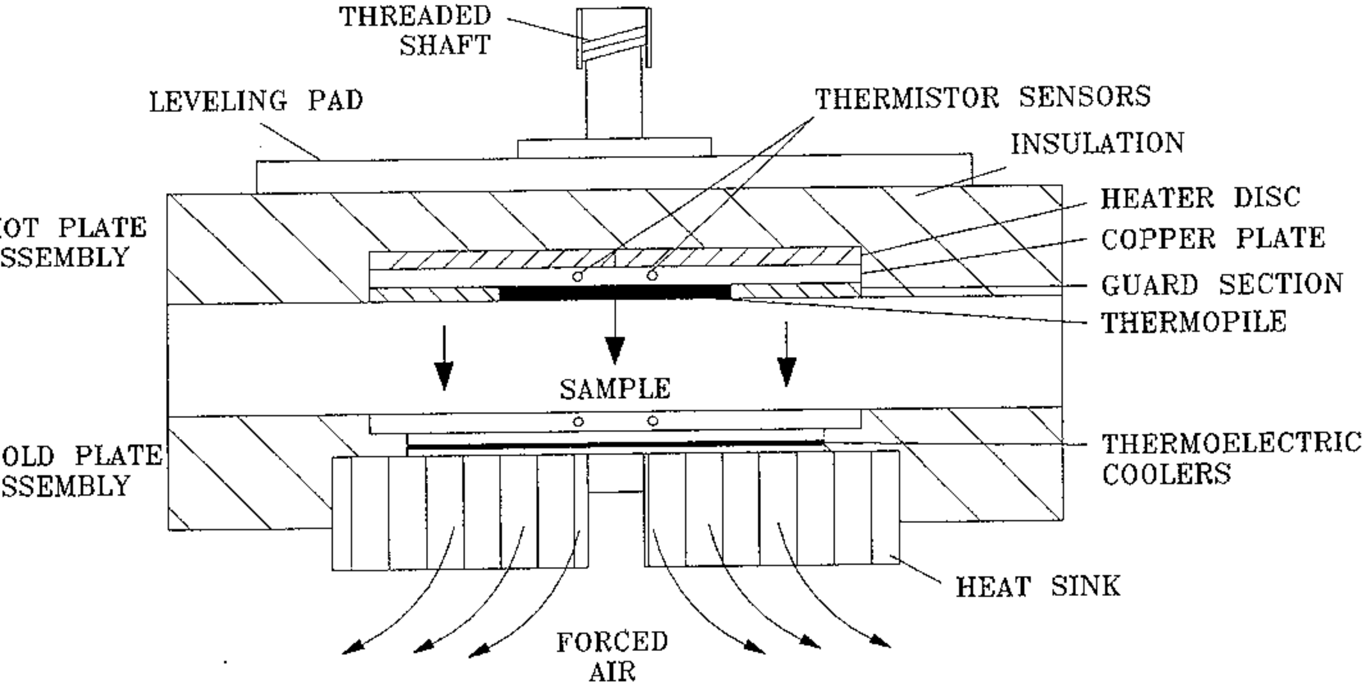


Figure 4. Measuring Assembly Block Diagram of Anacon Model 88

coupled to a potentiometer from which the sample thickness analog signal is derived. Pressure applied to the sample and the mechanical linkage between the plate assembly and the analog thickness signal are critical control parameters.

The standard Model 88 temperature settings for the hot and cold plates are 100°F and 50°F. The readout unit displays temperatures of hot and cold plates in degrees Fahrenheit, sample thickness in inches, and thermal conductivity in Btu-inch/hr-ft^2-F°.

3.2.3 Design of Sample Containers

Two sets of sample containers were designed and fabricated. Set #1 was designed for tests using the Dynatech Model TCFGM, and Set #2 for tests using the Anacon Model 88. Set #1 consists of two identical cylindrical sample containers. The sample containers were made from PVC plastic pipe with 7-7/8-inch inner diameter, 8.62-inch outer diameter and 1.73-inch thickness. Set #2 consisted of only one cylindrical sample container. This sample container was made from PVC plastic pipe with 6.62-inch inner diameter, 7.25-inch outer diameter and 1.77-inch thickness. The dimensions of the sample containers are presented in Table 3.

PVC plastic was chosen as a container material because it has a low thermal conductivity, 0.092 W/m-K (0.053 Btu/hr-ft-F°), Mills (1992). The thermal conductivity value of PVC being lower than the thermal conductivity value for rubber, reduces edge heat losses.

Each sample container has two circular galvanized steel end plates 0.04 inches thick. The bottom plate was glued to the container, and the top plate was removable. The thermal conductivity value of galvanized steel is listed as about 50 W/m-K (29 Btu/hr-ft-F°), Mills (1992), which is much higher than the expected thermal conductivity value for rubber. The thermal resistance of metal plate is 0.0001 hr-ft^2-F°/Btu in comparison to the thermal resistance of a rubber sample at 1.85 hr-ft^2-F°/Btu. Therefore, the thermal resistance of the metal plate and the temperature difference across the plates are negligible. Thus the temperature difference between the hot and the cold plates can be assumed to equal the temperature difference across the samples.

Set #1 containers were made from nominal eight-inch diameter, SDR 26 PVC pipe. The actual measured inner diameter was 7-7/8-inch instead of 8 inches. Eight-inch inner diameter plastic pipe, required for Dynatech Model TCFGM instrument, was not available. From a theoretical point of view, any sample (thickness less than 2 inches) with diameter greater than 4 inches and less than 8 inches can be tested in the Dynatech Model TCFGM instrument, because all the heat from the main heater should pass through the sample.

Table 3. Dimensions of Sample Containers

	Set #1		Set #2
	Container #1	Container #2	Container #3
Thickness (inch)	1.73	1.73	1.77
Outer Dia. (inch)	8-5/8	8-5/8	7-1/4
Inner Dia. (inch)	7-7/8	7-7/8	6-5/8

To compress the samples, two accessories, a compressing pipe and a circular compressing plate, were made for each sample container set. The inner and outer diameters of the compressing pipe are the same as those of the sample container with which it is associated. The compressing plate was made from steel. The diameter of the compressing plate is the same as the inner diameter of the sample container. The outside portion of the container wall and inside portion of the compressing pipe wall were reduced, using a lathe, so that the compressing pipe could be set upon the sample container. After the rubber had been placed in the assembly of a sample container and compressing pipe, the compressing plate was used to compress the sample. The configurations of sample containers and accessories are illustrated in Figure 5.

3.3 Test Procedures

Thermal conductivities of the frozen samples were measured using the Dynatech Model TCFGM, and for thawed samples, the Anacon Model 88 was used.

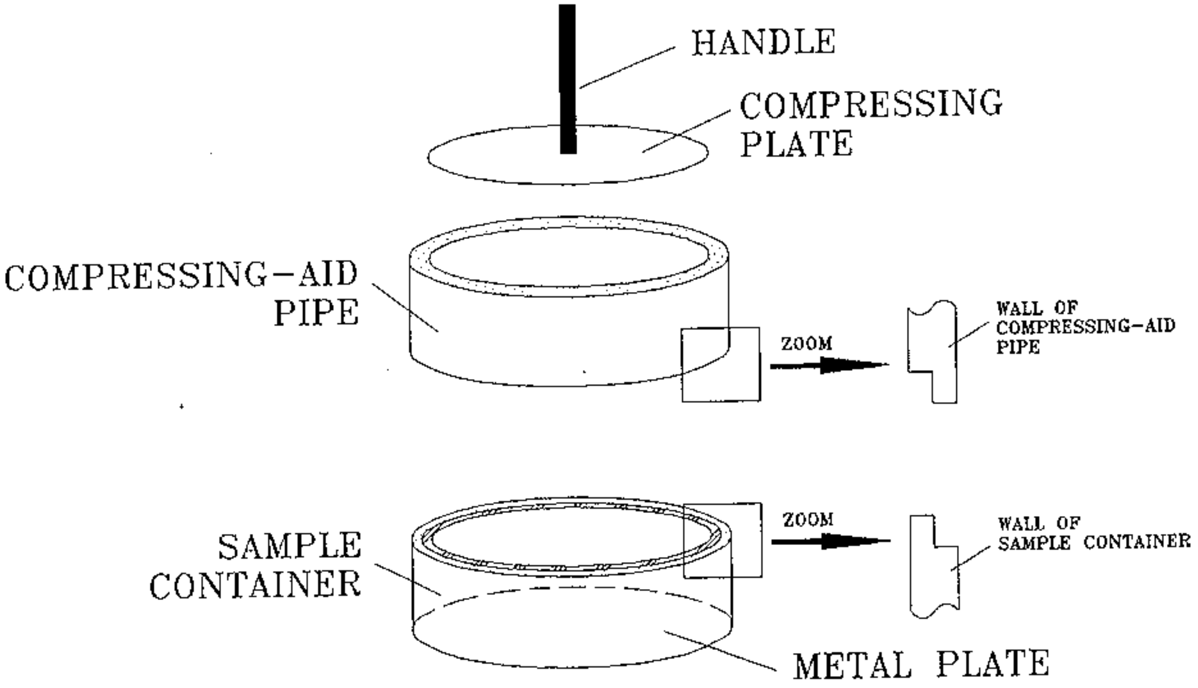
The following data were collected regarding sample size and shape variation:

1. For rubber buffings, measurements were made at two moisture contents and two compaction densities for frozen and thawed materials.
2. For granulated rubber, measurements were made at two moisture contents and three compaction densities for frozen and thawed materials.
3. For rubber chips, measurements were made at two moisture contents and two compaction densities for frozen and thawed materials.
4. For combinations of materials at three different gradations, measurements were made for frozen and thawed materials.

The percent by weight of the combinations of materials are listed in Table 4.

3.3.1 Test Procedure for Frozen Samples

Two identical test samples are required for tests using Model TCFGM. Equal weights of these samples were obtained by using a digital scale. The samples were then placed into sample container assembly. The samples were compressed, using the compressing plate. Next, each sample container was covered by a circular metal plate and then placed in the Model TCFGM instrument.



igure 5. Configuration of Sample Container and Accessories

Table 4. Particle Mixes by Percent Weight for Combined Materials Test

	Frozen Samples			Thawed Samples		
	#1	#2	#3	#1	#2	#3
Granulated Rubber	50%	50%		50%	50%	
Rubber Buffings	50%		50%	50%		50%
Rubber Chips		50%	50%		50%	50%

A cylindrical shroud was placed around the test stack. Before the test, this enclosure was filled with loose-fill insulation. Finally, a bell jar was placed over the whole assembly. The guard main heaters were set by adjusting the input voltage (which could be read from the digital display) to about 0.8 volts. The voltage varied slightly with the sample size, compaction density and moisture content.

For each test, the temperature of the cold plates was set to 21°F. The main heater input voltage was adjusted so that the plate temperature was approximately 24°F. This resulted in the temperature difference between the hot and cold plates being about 3°F.

Time to establish a steady-state condition for one test was about two to three days. The data collected -- hot plate thermocouple millivolt readings, cold plate thermocouple millivolt readings, main heater input voltage and current -- were input into a computer spreadsheet. Type K thermocouple tables were used to convert the thermocouple millivolt readings to temperatures in degrees Fahrenheit. Thermal conductivity values were then calculated (Datasheets for frozen sample tests are attached in Appendix B.).

3.3.2 Test Procedure for Thawed Samples.

The Anacon Model 88 instrument was used to measure thermal conductivity values for thawed materials. The sample was weighed and then placed into the sample container assembly. The sample was compressed with the compressing plate, and, next, placed into a "Ziploc" plastic bag to prevent moisture loss. The bagged sample container assembly was then inserted into the Anacon Model 88 instrument.

The Anacon Model 88 was designed with fixed 100°F hot plate and 50°F cold plate temperatures. Therefore, the sample was tested using a 30 F°/inch temperature gradient. The Anacon Model 88 instrument was precalibrated using a rigid foam plastic insulation of known thermal conductivity.

The sample thickness value was checked in the digital display by pushing the selector switch to "TH" position. The torque knob was adjusted to ensure that the thickness reading was 1.77 inches, the actual thickness of the sample.

The stabilization time was about 12 hours. The value of thermal conductivity in Btu-in/hr-ft^2-F° was read from the digital display. The thermal conductivity value, along with temperatures of the cold and hot plates and sample thickness, was recorded.

3.3.3 Determination of Moisture Content

For an unwetted sample, bulk weight was obtained using a digital scale before the test. After the test, the sample was placed in a drying oven. The drying process took about 24 hours. The sample was weighed again after the drying process to obtain its dry weight. The following equation was used to calculate moisture content of the sample:

$$Moisture\ Content=\frac{Bulk\ Weight-Dry\ Weight}{Dry\ Weight}\times 100\%$$

For a wetted sample, the dry weight of the sample was obtained using the same method described above. Then it was wet by the following procedure. First, the sample was put into a Ziploc plastic bag. Then water was added to the sample. The bag was sealed and shaken to mix the sample and water. Finally, the sample was removed from the bag, allowed to drain, and weighed in the sample container. The reason for not weighing the sample in the plastic bag was to eliminate the effect of the water drops on the plastic bag's surface. For consistency, a fixed amount of water was added to the sample so that the frozen and thawed samples of each kind of material had similar moisture contents.

3.4 Data Analysis

Thirty four thermal conductivity values were collected for different samples (different compaction densities, different moisture contents and different materials). The trend, which appeared reasonable, was that higher compaction densities and higher moisture contents resulted in higher thermal conductivities.

The thermal conductivity values in units of Btu/hr-ft-F° are summarized in Tables 5, 6, 7 and 8. The results of data analysis are plotted in Figures 6, 7, 8 and 9. The data show that larger grained samples have higher thermal conductivities. The frozen samples also have higher thermal conductivity values than thawed samples.

4. RESILIENT MODULI OF RUBBER SAMPLES

The moduli of resilience of the granulated rubber and rubber buffings were measured using a MTS cyclic testing machine at UAF's School of Engineering. Samples, described in Table 10, were placed in the triaxial testing cell, and confining pressures of three psi and five psi were applied to them. Results of the moduli of resilience tests are also presented in Table 10. Tests could not be conducted on the rubber chips due to the triaxial test cell diameter (4

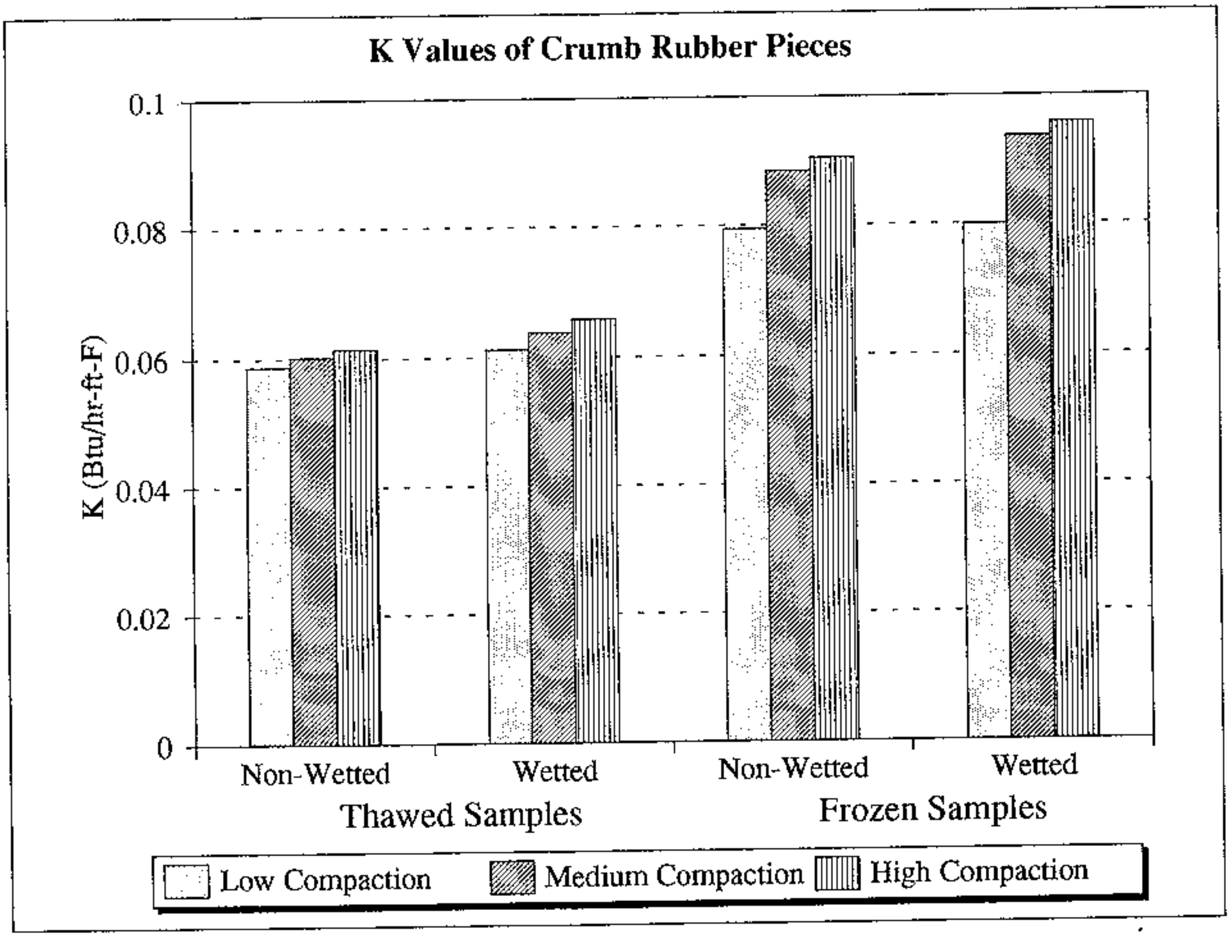


Figure 6. Thermal Conductivity of Granulated Rubber

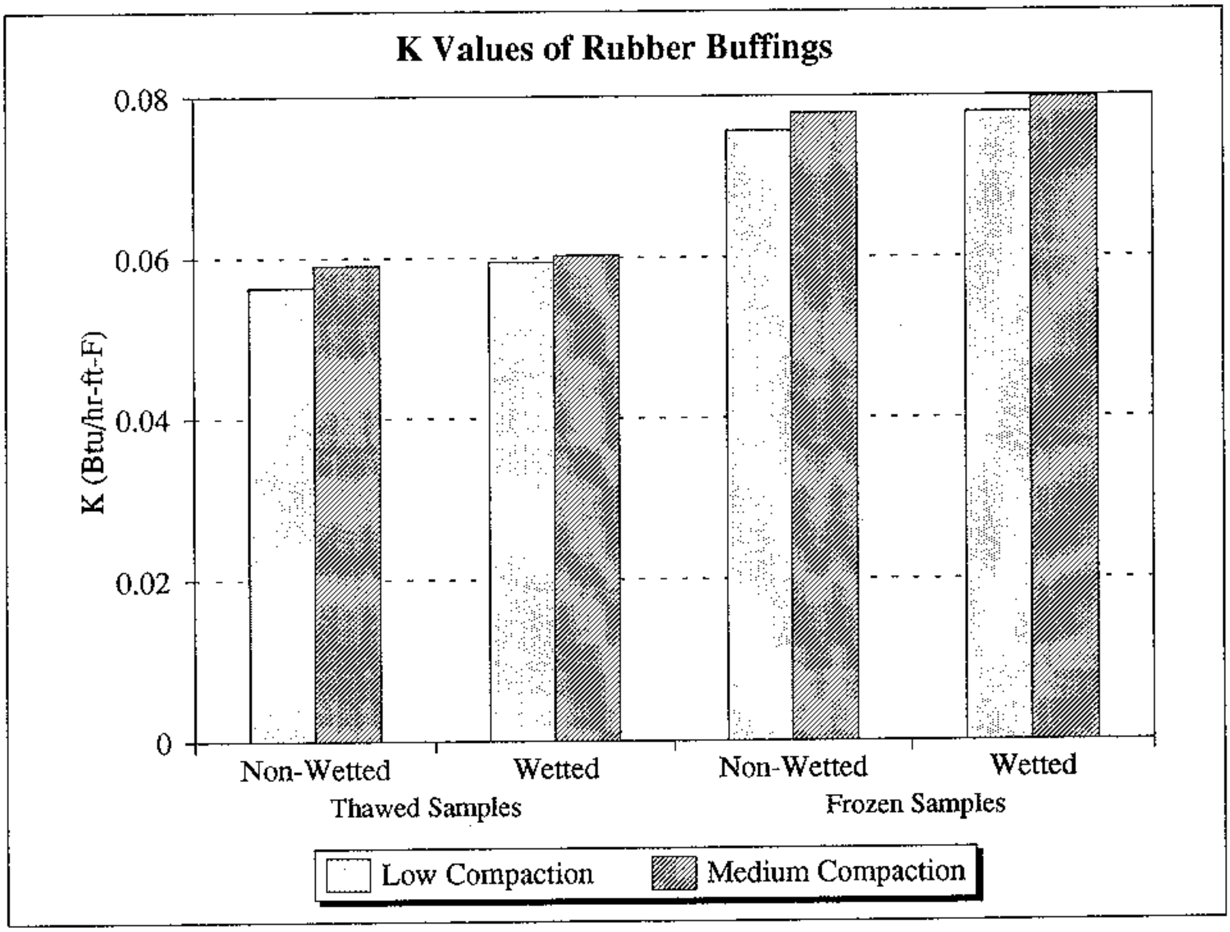


Figure 7. Thermal Conductivity of Rubber Buffings

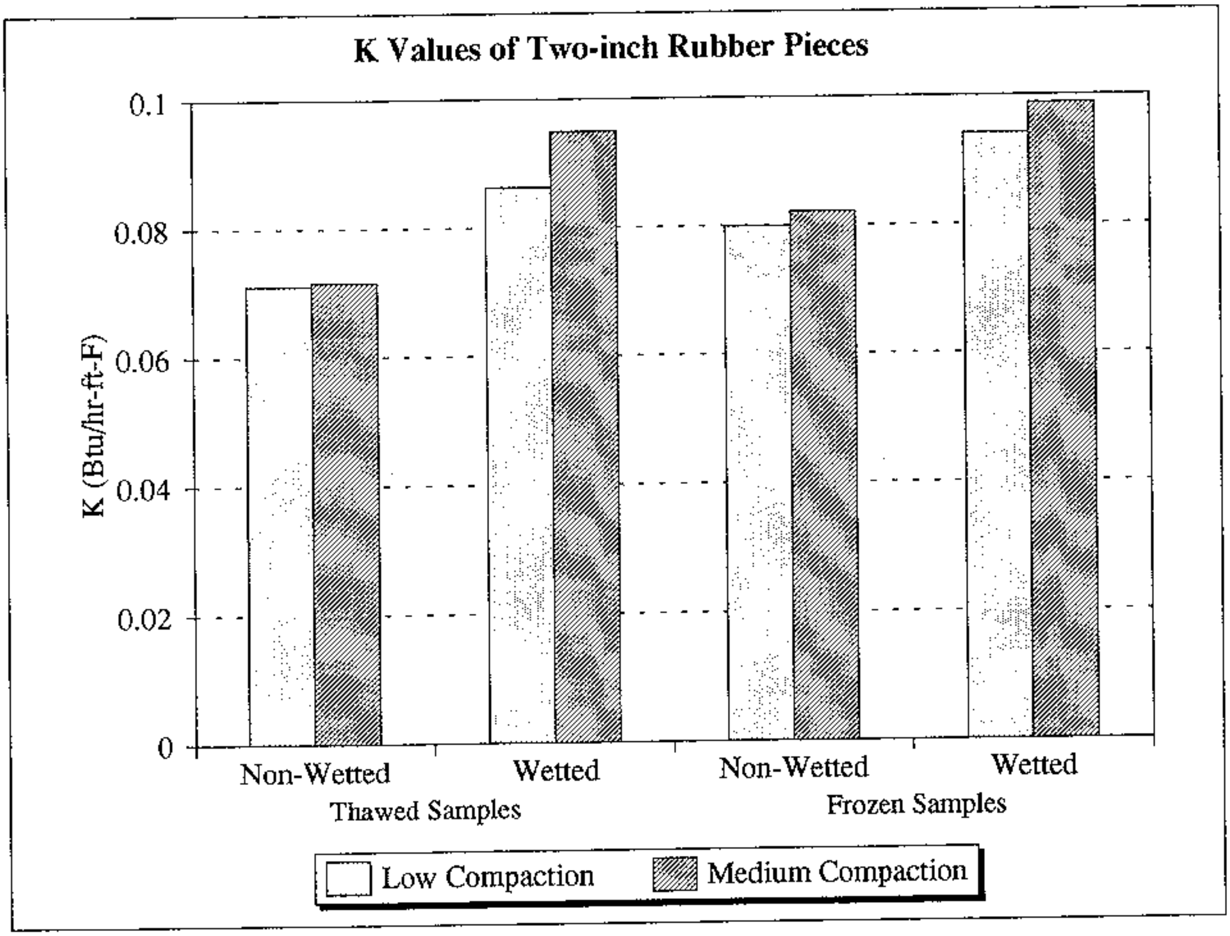


Figure 8. Thermal Conductivity of Rubber Chips

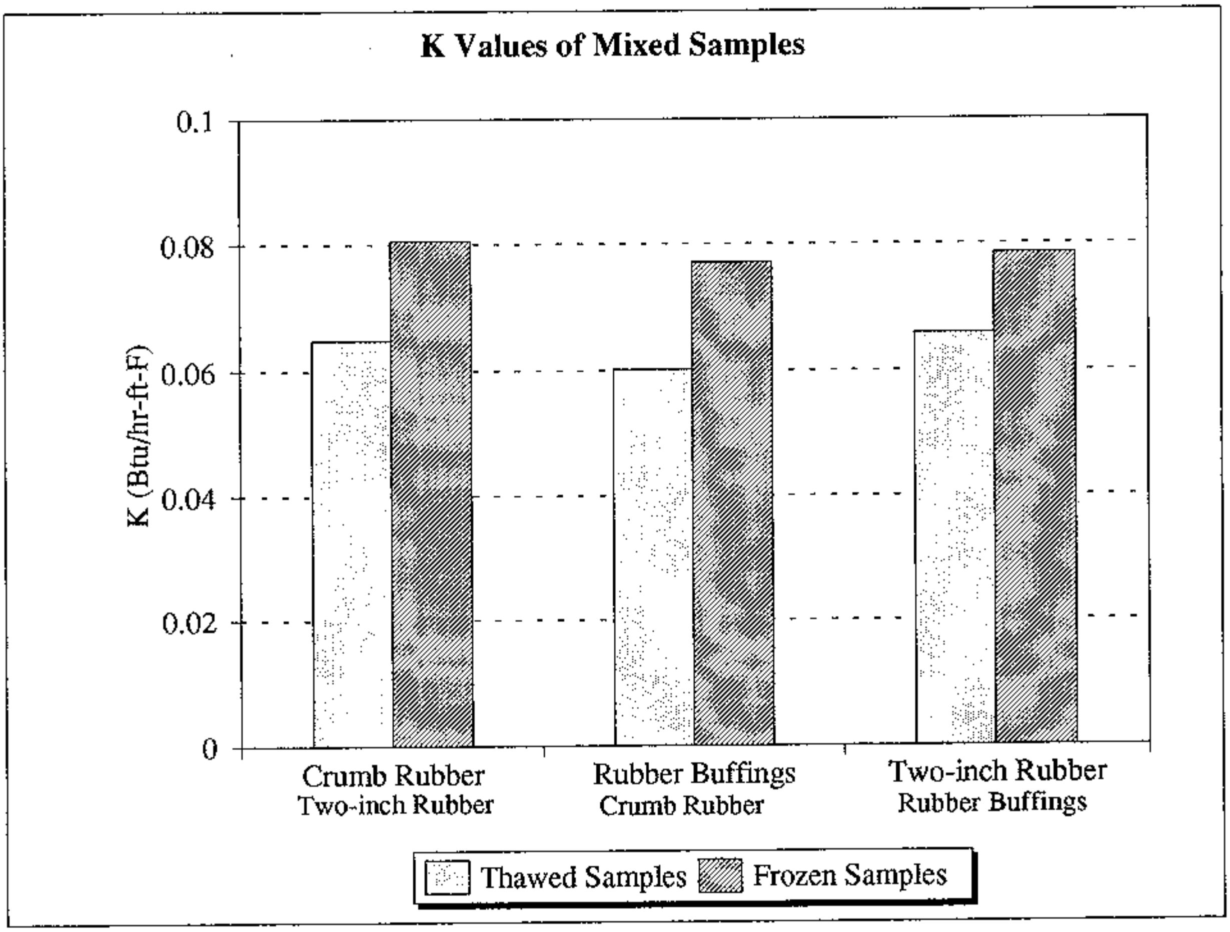


Figure 9. Thermal Conductivity of Mixed Samples

inches), which is not sufficiently large to achieve a true test on the composite material, and due to the wires projecting from the rubber chips which would puncture the triaxial membranes.

5. CONCLUSIONS AND RECOMMENDATIONS

Based upon laboratory results, thermal conductivity values of the tire rubber samples vary between 0.0563 ~ 0.0988 Btu/hr-ft-F°. The most common insulating materials for road construction are extruded polystyrene and expanded polystyrene. The thermal conductivities of extruded polystyrene are 0.016 - 0.018 Btu/hr-ft-F°, of expanded polystyrene, 0.019 ~ 0.021 Btu/hr-ft-F° (*ASHRAE Handbook*, 1993). Even though tire rubber has a higher thermal conductivity than extruded or expanded polystyrene, it can still be classified as an insulating material.

Table 5. Summary of Thermal Conductivity Values (Btu/hr-ft-F°) for Granulated Rubber

Crumb Rubber Pieces		Moisture Content	Low Compaction	Medium Compaction	High Compaction
Thawed Samples	Non-Wetted	<1%	0.0587	0.0602	0.0613
	Wetted	3%	0.0612	0.0637	0.0658
Frozen Samples	Non-Wetted	<1%	0.0794	0.0883	0.0903
	Wetted	3%	0.0799	0.0935	0.0957

Table 6. Summary of Thermal Conductivity Values (Btu/hr-ft-F°) for Rubber Buffings

Rubber Buffings		Moisture Content	Low Compaction	High Compaction
Thawed Samples	Non-Wetted	<1%	0.0563	0.0590
	Wetted	4-5%	0.0594	0.0602
Frozen Samples	Non-Wetted	<1%	0.0757	0.0778
	Wetted	4-5%	0.0779	0.0798

Table 7. Summary of Thermal Conductivity Values for (Btu/hr-ft-F°) Rubber Chips

Rubber Chips		Moisture Content	Low Compaction	High Compaction
Thawed Samples	Non-Wetted	2%	0.0710	0.0716
	Wetted	5%	0.0863	0.0950
Frozen Samples	Non-Wetted	2%	0.0799	0.0821
	Wetted	5%	0.0942	0.0988

Table 8. Summary of Thermal Conductivity Values (Btu/hr-ft-F°) for Mixed Materials

Mixture Materials	Granulated Rubber (50%) Rubber Chips (50%)	Granulated Rubber (50%) Rubber Buffings (50%)	Rubber Chips (50%) Rubber Buffings (50%)
Thawed Samples	0.0648	0.0602	0.0658
Frozen Samples	0.0806	0.0771	0.0785

The use of tire rubber as an insulating material in road construction is an attractive possibility, based on the results of this study. The cost analysis of using different granulated or shredded tire rubber types versus common insulating materials for constructing a one-mile long, 60 feet wide insulating layer beneath the road surface is presented in Table 9. Because the thermal conductivities of tire rubber are about triple the thermal conductivities of rigid foam plastic insulating materials (extruded and expanded polystyrene), different thicknesses of insulating layers are employed in the cost analysis to arrive at identical thermal resistance. The relationship between thermal resistance and thickness of insulating layer is:

$$R=\frac{x}{k}$$

where R = thermal resistance, hr-ft^2-F°/Btu

x = thickness of layer

k = thermal conductivity of material

Assuming a thermal resistance of 20 hr-ft^2-F°/Btu, the thickness of an insulating layer composed of extruded polystyrene is 4 inches, expanded polystyrene, 4.1 inches; granulated rubber, 1.2 feet; rubber buffings, 1.16 feet; and rubber chips, 1.4 feet.

Costs of extruded and expanded polystyrene were obtained from Fairbanks Sand & Gravel, Inc.. Cost for nominal two-inch rubber chips from Waste Recovery, Ltd., Portland, Oregon, including shipping to Fairbanks, is about \$4.36/ft^2. Rubber buffings are available free from Mobat Tires or Bandag, Inc., Fairbanks, Alaska, but not in large quantity. Price of granulated rubber from Rubber Granulators does not include shipping, otherwise it will be about \$6.48/ft^2.

Table 9. Cost Analysis for Using Tire Rubber as an Insulating Material

Material	Granulated Rubber	Rubber Buffings	Rubber chips	Extruded Polystyrene	Expanded Polystyrene
Thickness of Insulation Layer for R20	1.2 ft	1.16 ft	1.4 ft	4.0 in	4.1 in
Density (lb/ft^3)	36	30	28	1.8~3.5	1.0
Material Cost \$/ft^2 FOB FAI	\$6.48	NA	\$4.36	\$1.60	\$1.46
Total Cost	\$2,161,000	NA	\$1,454,000	\$507,000	\$487,000

In addition to the material cost, there is a labor cost difference between using tire rubber and conventional polystyrene as an insulating layer. Detailed studies are recommended to define these labor costs. Landfill relief cost should also be included in a future cost-benefit analysis. The economics of using rubber chips would improve if an Alaskan chipper was available because the transportation costs would be reduced.

From an environmental point of view, using granulated or shredded tire rubber as an insulating material is attractive. Current federal laws favor recycling used tire rubber. Full-scale field test sections are recommended to determine the thermal behavior of tire rubber under actual conditions. Test sections with different thicknesses of insulating layers and differing tire rubber grain sizes are recommended. Instrumentation should be installed to monitor temperatures at different depths in the ground.

Table 10. Resilient Moduli of Rubber Samples

Crumb Rubber			
Sample Weight:	2.47 lb		
Sample Initial Height:	8.07 in.		
Sample diameter:	3.76 in.		
Density:	47.4 lb/ft^3		
Resilient Modulus (psi)			
σ_d (psi)			
$\sigma 3$ (psi)	5	10	15
3	144	166	193
5	230	243	215
Rubber Buffings			
Sample Weight:	2.15 lb		
Sample Initial Height:	7.78 in		
Sample Diameter:	3.82 in		
Density:	41.81 lb/ft^3		
Resilient Modulus (psi)			
σd (psi)			
$\sigma 3$ (psi)	5	10	15
3	94	106	145
5	151	162	185

6. REFERENCES

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APPENDICES

APPENDIX A

A. Apparatus

1. Ro-Tap Sieve Shaker (Model 8, C.E, Tyler) -- a mechanically operated sieve shaker as described in ASTM D1511 and described in "Testing Sieves and Their Uses" Handbook

2. Sieves -- U.S. Standard Sieves conforming to ASTM Specification E11.

3. Bottom Receiver Pan and Top Sieve Cover

4. Scale with a sensitivity of 0.1 gram

5. Soft Brush

6. Jar, capacity of one pint with large opening

7. Rubber balls with 1.5 inch diameter, enough for two balls per screen

B. Procedure

1. Select test screens appropriate to the particle size distribution of the individual sample being tested.

2. Clean screens with brush, making sure all particles are removed.

3. Stack test screens in order of increasing mesh size with smallest number (coarsest sieve on top, and largest number (finest sieve) on bottom.

4. Add bottom receiver pan to stack.

5. Prepare 100.0 grams of sample as follows:

   5.1. Weigh 100.0 grams of ground rubber sample.

5.2 Weigh 5 grams of talc for products designated coarser than 50 mesh, and 25 grams of talc for products designated 50 mesh or finer (this will yield a total final sample weight of 105.5 or 125.0 grams).

5.3 Add the talc to sample, and mix thoroughly by placing talc and sample in a pint size jar and shake by hand until particle agglomerates are broken, and talc is uniformly mixed (for a minimum of 1 minute).

6. Introduce the above prepared sample into the top sieve pan and place the sieve cover on the stack.

7. Place the stack in the Ro-Tap Sieve Shaker.

8. Activate the Ro-Tap Sieve Shaker for 10 minutes for products designated coarser than 50 mesh, and for 45 minutes for products designated 50 mesh or finer.

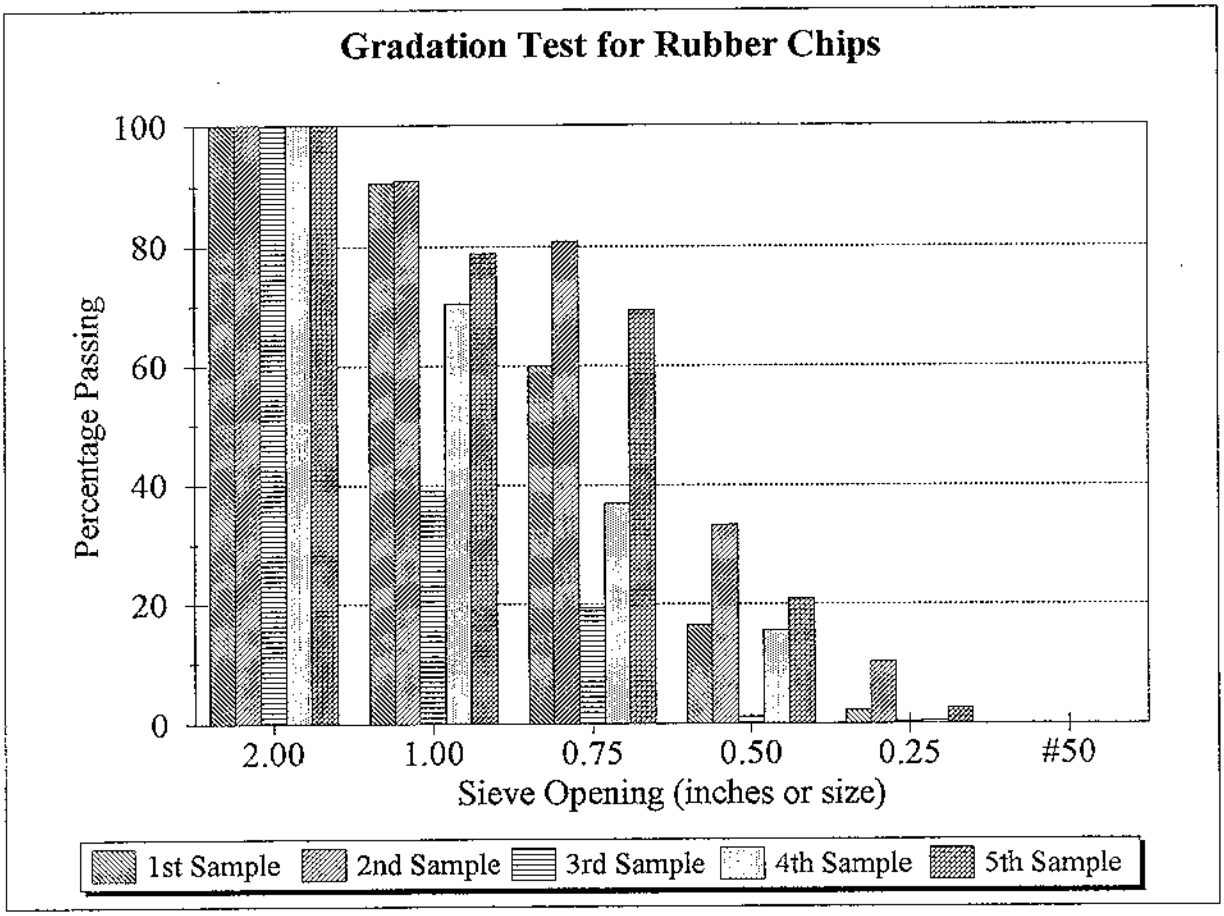
9. After Ro-Top Sieve Shaker completes the appropriate cycle, remove stack.

10. Starting with the top sieve and taring the weighing dish to account for its weight, remove the screened fraction by gently tapping its contents to one side, pouring the contents on the scale, and recording its weight to the nearest 0.1 gram. Repeat this procedure for each pan.

11. Any material adhering to the bottom of the screen shall be brushed into the next finer screen.

12. As a Quality Assurance measure, the sum of the weights of each fraction shall not be less than the original weight of the rubber sample plus 70.0 percent of the talc added, or greater than the original weight of the rubber sample plus 100.0 percent of the talc added. Repeat the test if either of these conditions occur.

13. To calculate the weight of the contents of the bottom pan, empty its contents on the scale and record. Sum total weight of the contents of each sieve tray including the bottom pan and subtract 100. The remainder is to be subtracted from the bottom pan contents. This is the adjusted bottom pan contents weight, accounting for the talc used.


Gradation Test for Rubber Chips
100
80
60
40
20
0
Percentage Passing
2.00
1.00
0.75
0.50
0.25
#50
Sieve Opening (inches or size)
1st Sample
2nd Sample
3rd Sample
4th Sample
5th Sample

Granulated Rubber (Sample 1)

Weight of Sample : 100.6 g
Weight of Talc added : 25 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.0	0.0	0.0	100.6	100.00
#10	467.0	526.0	59.0	59.0	41.6	41.35
#30	480.8	506.6	25.8	25.8	15.8	15.71
#50	378.1	391.2	13.1	13.1	2.7	2.68
#80	357.8	364.7	6.9	2.7	0.0	0.00
#200	511.4	517.3	5.9	0.0	0.0	0.00
Bottom Pan	371.4	386.3	14.9	0.0	0.0	0.00
Total Weight =			125.6	100.6		

Granulated Rubber (Sample 2)

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.0	0.0	0.0	100.0	100.00
#10	467.0	531.7	64.7	64.7	35.3	35.30
#30	480.8	504.0	23.2	23.2	12.1	12.10
#50	378.1	388.7	10.6	10.6	1.5	1.50
#80	357.8	363.4	5.6	1.5	0.0	0.00
#200	511.4	524.4	13.0	0.0	0.0	0.00
Bottom Pan	371.4	379.1	7.7	0.0	0.0	0.00
Total Weight =			124.8	100		

Granulated Rubber (Sample 3)

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.5	0.5	0.5	99.5	99.50
#10	467.0	527.7	60.7	60.7	38.8	38.80
#30	480.8	505.8	25.0	25.0	13.8	13.80
#50	378.1	390.1	12.0	12.0	1.8	1.80
#80	357.8	364.8	7.0	1.8	0.0	0.00
#200	511.4	521.1	9.7	0.0	0.0	0.00
Bottom Pan	371.4	381.5	10.1	0.0	0.0	0.00
Total Weight =			125	100		

Rubber Buffings

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	535.3	4.3	4.3	95.7	89.77
#10	467.0	471.3	4.3	4.3	91.4	85.74
#30	480.8	552.4	71.6	71.6	19.8	18.57
#50	378.1	400.1	22.0	19.8	0.0	0.00
#80	357.8	361.3	3.5	0.0	0.0	0.00
#200	511.4	514.4	3.0	0.0	0.0	0.00
Bottom Pan	371.4	387.6	16.2	0.0	0.0	0.00
Total Weight =			124.9	100		

Rubber Chips (Sample 1)

Weight of Sample : 106.6 g
Weight of Talc added : 5 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	106.6	100.00
1.0000	623.6	633.7	10.1	10.1	96.5	90.53
0.7500	567.1	599.7	32.6	32.6	63.9	59.94
0.5000	635.4	681.8	46.4	46.4	17.5	16.42
0.2500	531.0	546.2	15.2	15.2	2.3	2.16
#50	378.1	380.4	2.3	2.3	0.0	0.00
Bottom Pan	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			111.6			

Rubber Chips (Sample 2)

Weight of Sample : 117 g
Weight of Talc added : 5 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	116.9	100.00
1.0000	623.6	634.3	10.7	10.7	106.2	90.85
0.7500	567.1	578.9	11.8	11.8	94.4	80.75
0.5000	635.4	690.9	55.5	55.5	38.9	33.28
0.2500	531.0	557.9	26.9	26.9	12.0	10.27
#50	378.1	389.9	11.8	11.8	0.2	0.17
Bottom Pan	371.4	376.6	5.2	0.2	0.0	0.00
Total Weight =			121.9			

Rubber Chips (Sample 3)

Weight of Sample : 100.3 g
Weight of Talc added : 5 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	100.6	100.00
1.0000	623.6	685.0	61.4	61.4	39.2	38.97
0.7500	567.1	586.9	19.8	19.8	19.4	19.28
0.5000	635.4	653.7	18.3	18.3	1.1	1.09
0.2500	531.0	531.7	0.7	0.7	0.4	0.40
#50	378.1	378.5	0.4	0.4	0.0	0.00
Bottom Pan	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			105.6	100.6		

Rubber Chips (Sample 4)

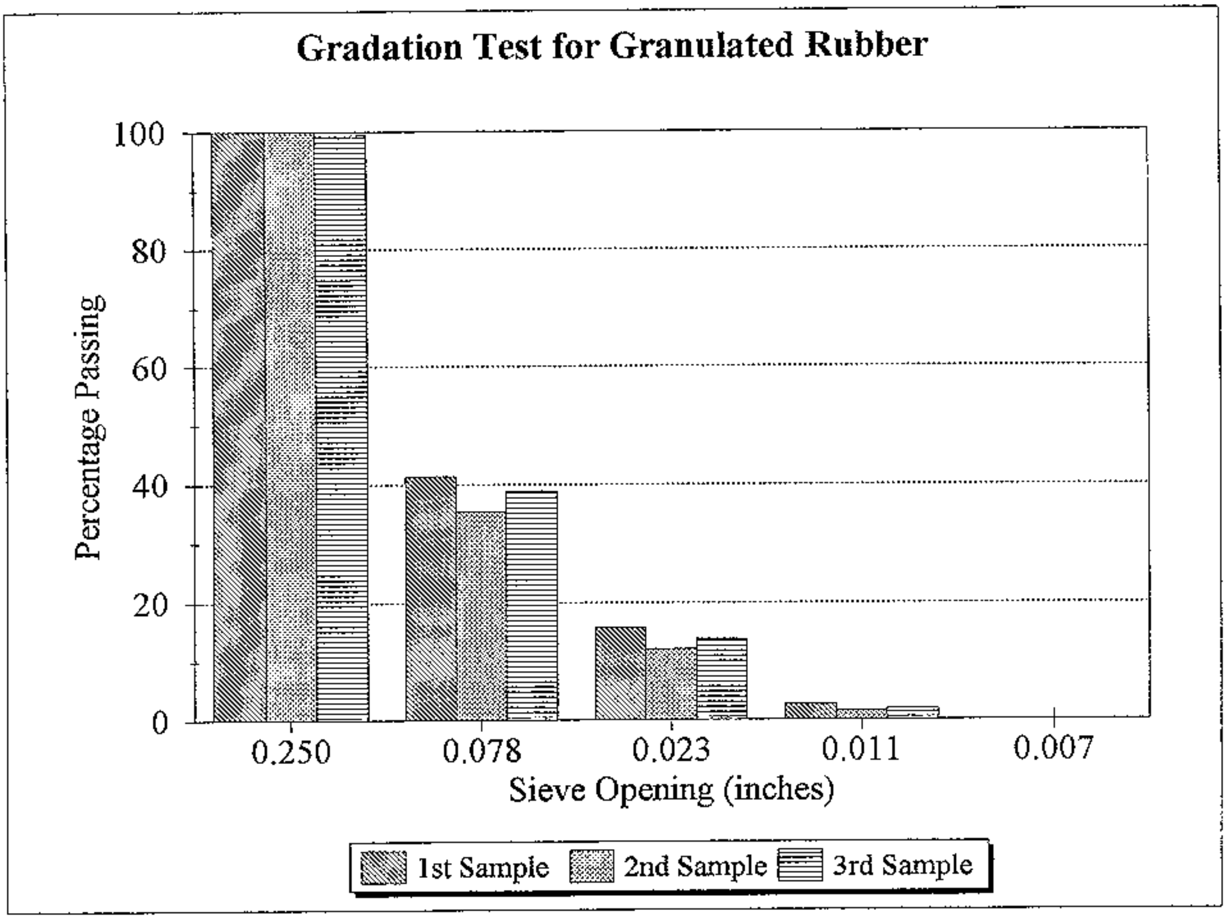
Weight of Sample : 100.5 g
Weight of Talc added : 5 g

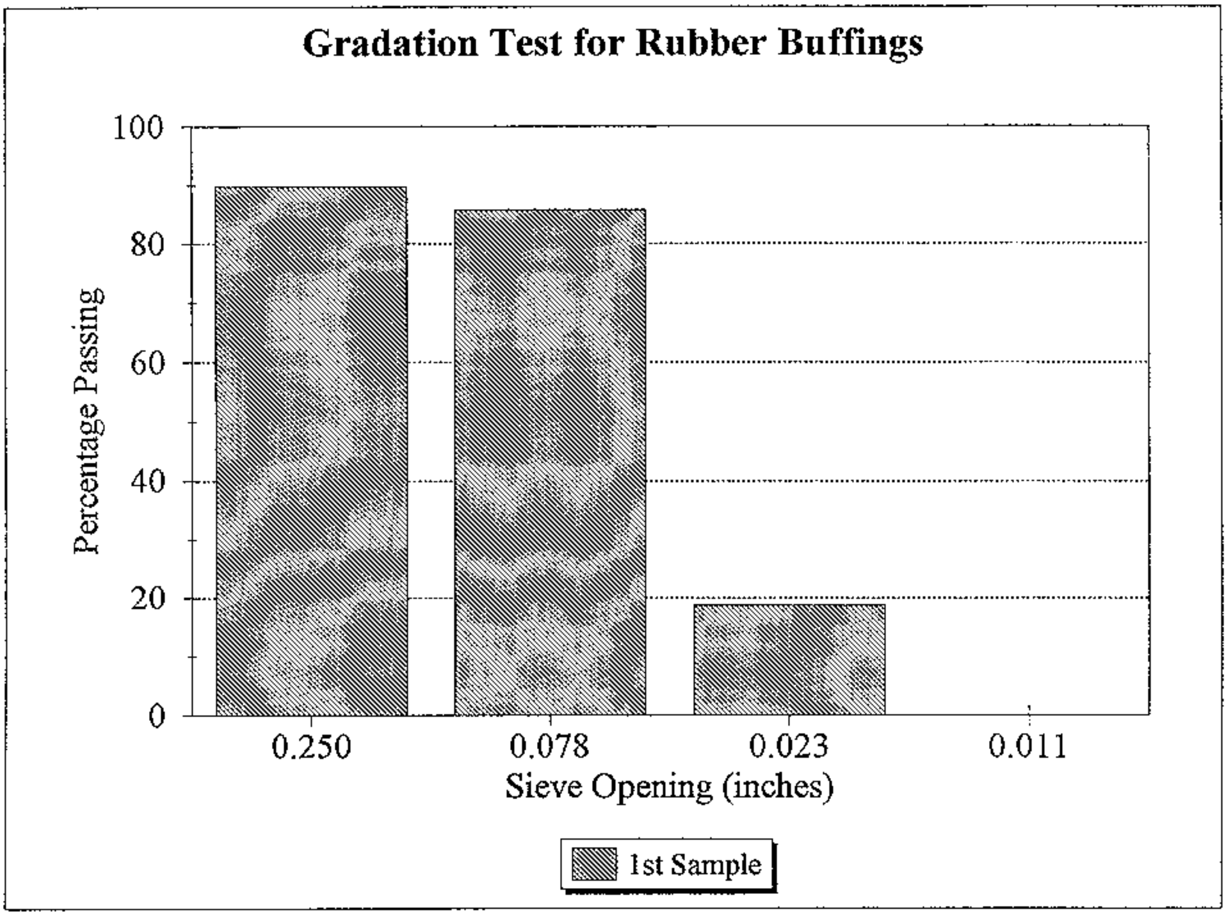
Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	100.6	100.00
1.0000	623.6	653.3	29.7	29.7	70.9	70.48
0.7500	567.1	600.9	33.8	33.8	37.1	36.88
0.5000	635.4	656.9	21.5	21.5	15.6	15.51
0.2500	531.0	546.1	15.1	15.1	0.5	0.50
#50	378.1	378.6	0.5	0.5	0.0	0.00
Bottom Pan	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			105.6	100.6		

Rubber Chips (Sample 5)

Weight of Sample : 100.2 g
Weight of Talc added : 5 g

Sieve Opening (in. or size)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	99.2	100.00
1.0000	623.6	644.6	21.0	21.0	78.2	78.83
0.7500	567.1	576.5	9.4	9.4	68.8	69.35
0.5000	635.4	683.5	48.1	48.1	20.7	20.87
0.2500	531.0	549.2	18.2	18.2	2.5	2.52
#50	378.1	380.6	2.5	2.5	0.0	0.00
Bottom Pan	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			104.2	99.2		

Gradation Test for Granulated Rubber
100
80
60
40
20
0
Percentage Passing
0.250
0.078
0.023
0.011
0.007
Sieve Opening (inches)
1st Sample
2nd Sample
3rd Sample


Gradation Test for Rubber Buffings
100
80
60
40
20
0
Percentage Passing
0.250
0.078
0.023
0.011
Sieve Opening (inches)
▨ 1st Sample

Granulated Rubber (Sample 1)

Weight of Sample : 100.6 g
Weight of Talc added : 25 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.0	0.0	0.0	100.6	100.00
0.0787	467.0	526.0	59.0	59.0	41.6	41.35
0.0234	480.8	506.6	25.8	25.8	15.8	15.71
0.0117	378.1	391.2	13.1	13.1	2.7	2.68
0.0070	357.8	364.7	6.9	2.7	0.0	0.00
0.0029	511.4	517.3	5.9	0.0	0.0	0.00
0.0000	371.4	386.3	14.9	0.0	0.0	0.00
Total Weight =			125.6	100.6		

Granulated Rubber (Sample 2)

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.0	0.0	0.0	100.0	100.00
0.0787	467.0	531.7	64.7	64.7	35.3	35.30
0.0234	480.8	504.0	23.2	23.2	12.1	12.10
0.0117	378.1	388.7	10.6	10.6	1.5	1.50
0.0070	357.8	363.4	5.6	1.5	0.0	0.00
0.0029	511.4	524.4	13.0	0.0	0.0	0.00
0.0000	371.4	379.1	7.7	0.0	0.0	0.00
Total Weight =			124.8	100		

Granulated Rubber (Sample 3)

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	531.5	0.5	0.5	99.5	99.50
0.0787	467.0	527.7	60.7	60.7	38.8	38.80
0.0234	480.8	505.8	25.0	25.0	13.8	13.80
0.0117	378.1	390.1	12.0	12.0	1.8	1.80
0.0070	357.8	364.8	7.0	1.8	0.0	0.00
0.0029	511.4	521.1	9.7	0.0	0.0	0.00
0.0000	371.4	381.5	10.1	0.0	0.0	0.00
Total Weight =			125	100		

Rubber Buffings

Weight of Sample : 100 g
Weight of Talc added : 25 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
0.2500	531.0	535.3	4.3	4.3	95.7	89.77
0.0787	467.0	471.3	4.3	4.3	91.4	85.74
0.0234	480.8	552.4	71.6	71.6	19.8	18.57
0.0117	378.1	400.1	22.0	19.8	0.0	0.00
0.0070	357.8	361.3	3.5	0.0	0.0	0.00
0.0029	511.4	514.4	3.0	0.0	0.0	0.00
0.0000	371.4	387.6	16.2	0.0	0.0	0.00
Total Weight =			124.9	100		

Rubber Chips (Sample 1)

Weight of Sample : 106.6 g
Weight of Talc added : 5 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	106.6	100.00
1.0000	623.6	633.7	10.1	10.1	96.5	90.53
0.7500	567.1	599.7	32.6	32.6	63.9	59.94
0.5000	635.4	681.8	46.4	46.4	17.5	16.42
0.2500	531.0	546.2	15.2	15.2	2.3	2.16
0.0117	378.1	380.4	2.3	2.3	0.0	0.00
0.0000	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			111.6			

Rubber Chips (Sample 2)

Weight of Sample : 117 g
Weight of Talc added : 5 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	116.9	100.00
1.0000	623.6	634.3	10.7	10.7	106.2	90.85
0.7500	567.1	578.9	11.8	11.8	94.4	80.75
0.5000	635.4	690.9	55.5	55.5	38.9	33.28
0.2500	531.0	557.9	26.9	26.9	12.0	10.27
0.0117	378.1	389.9	11.8	11.8	0.2	0.17
0.0000	371.4	376.6	5.2	0.2	0.0	0.00
Total Weight =			121.9			

Rubber Chips (Sample 3)

Weight of Sample : 100.3 g
Weight of Talc added : 5 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	100.6	100.00
1.0000	623.6	685.0	61.4	61.4	39.2	38.97
0.7500	567.1	586.9	19.8	19.8	19.4	19.28
0.5000	635.4	653.7	18.3	18.3	1.1	1.09
0.2500	531.0	531.7	0.7	0.7	0.4	0.40
0.0117	378.1	378.5	0.4	0.4	0.0	0.00
0.0000	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			105.6	100.6		

Rubber Chips (Sample 4)

Weight of Sample : 100.5 g
Weight of Talc added : 5 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	100.6	100.00
1.0000	623.6	653.3	29.7	29.7	70.9	70.48
0.7500	567.1	600.9	33.8	33.8	37.1	36.88
0.5000	635.4	656.9	21.5	21.5	15.6	15.51
0.2500	531.0	546.1	15.1	15.1	0.5	0.50
0.0117	378.1	378.6	0.5	0.5	0.0	0.00
0.0000	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			105.6	100.6		

Rubber Chips (Sample 5)

Weight of Sample : 100.2 g
Weight of Talc added : 5 g

Sieve Opening (inches)	Empty Sieve Wt. (g)	Sieve Wt. w/ rubber (g)	Weight Retained (g)	Weight adjusted (g)	Weight Passing (g)	% Passing
2.0000	775.7	775.7	0.0	0.0	99.2	100.00
1.0000	623.6	644.6	21.0	21.0	78.2	78.83
0.7500	567.1	576.5	9.4	9.4	68.8	69.35
0.5000	635.4	683.5	48.1	48.1	20.7	20.87
0.2500	531.0	549.2	18.2	18.2	2.5	2.52
0.0117	378.1	380.6	2.5	2.5	0.0	0.00
0.0000	371.4	376.4	5.0	0.0	0.0	0.00
Total Weight =			104.2	99.2		

APPENDIX B

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 8, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Rubber buffings, relatively dry, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.675
K (Btu/hr-ft-F)	0.0563

Bulk Weight (kg)	0.517
Dry Weight (kg)	0.513
Bulk Density (kg/m^3)	517
Dry Density (kg/m^3)	513
Moisture Content (%)	0.78

Thermal Conductivity Testing of Tire Rubber Samples

Test Date: Jan. 8,1994 Test Instrument: Dynatech Model TCFGM

Discription of Sample: Crumb rubber pieces, relatively dry, relatively low compaction, frozen

Bulk Density (kg/m^3)	Bulk Density (lbm/ft^3)	Dry Density (kg/m^3)	Dry Density (lbm/ft^3)	Moisture Content (%)	K (Btu/hr-ft-F)	K (W/m-K)
557.36	34.79	554.29	34.60	0.55	0.0805	0.1393

TC1 Reading	TH1 Reading	TC2 Reading	TH2 Reading	E (Volts)	I (Amps)
-0.243	-0.162	-0.248	-0.162	0.887	0.1176

TC1 (F)	TH1 (F)	TC2 (F)	TH2 (F)	Q (Btu/sec.)	S (ft^2)
21	24.5	21	24.5	0.3469	0.09
d1 (ft)	d2 (ft)	DT1 (F)	DT(2) (F)	DT1/d1 (F/ft)	DT2/d2 (F/ft)
0.1467	0.1458	3.5	3.5	23.86	24.00

TC1 (K)	TH1 (K)	TC2 (K)	TH2 (K)	Q (W)	S (m^2)
267.04	268.98	267.04	268.98	0.1016	0.0084
d1 (m)	d2 (m)	DT1 (K)	DT2 (K)	DT1/d1 (K/m)	DT2/d2 (K/m)
0.0447	0.0445	1.94	1.94	43.50	43.74

Bulk Weight (kg)	Dry Weight (kg)	Volume (m^3)
1.561	1.552	0.0028

<u>Check Result: 1 Btu/hr-ft-F=1.7295771 W/m-K</u>

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 10, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Rubber buffings, relatively dry, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft ^ 2-F)	0.708
K (Btu/hr-ft-F)	0.0590

Bulk Weight (kg)	0.556
Dry Weight (kg)	0.551
Bulk Density (kg/m ^ 3)	556
Dry Density (kg/m ^ 3)	551
Moisture Content (%)	0.91

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 11, 1994

Test Instrument: Anacon Model 88

Discription of Sample: 1 inch rubber pieces, relatively dry, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.852
K (Btu/hr-ft-F)	0.0710

Bulk Weight (kg)	0.451
Dry Weight (kg)	0.441
Bulk Density (kg/m^3)	451
Dry Density (kg/m^3)	441
Moisture Content (%)	2.27

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 11, 1994

Test Instrument: Anacon Model 88

Discription of Sample: 1 inch rubber pieces, relatively wet, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	1.036
K (Btu/hr-ft-F)	0.0863

Bulk Weight (kg)	0.464
Dry Weight (kg)	0.441
Bulk Density (kg/m^3)	464
Dry Density (kg/m^3)	441
Moisture Content (%)	5.22

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 11, 1994

Test Instrument: Anacon Model 88

Discription of Sample: 1 inch rubber pieces, relatively dry, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft ^ 2-F)	0.859
K (Btu/hr-ft-F)	0.0716

Bulk Weight (kg)	0.497
Dry Weight (kg)	0.489
Bulk Density (kg/m ^ 3)	497
Dry Density (kg/m ^ 3)	489
Moisture Content (%)	1.64

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 12, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively dry, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft ^ 2-F)	0.704
K (Btu/hr-ft-F)	0.0587

Bulk Weight (kg)	0.523
Dry Weight (kg)	0.52
Bulk Density (kg/m ^ 3)	523
Dry Density (kg/m ^ 3)	520
Moisture Content (%)	0.58

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 12, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively dry, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft ^ 2-F)	0.735
K (Btu/hr-ft-F)	0.0613

Bulk Weight (kg)	0.582
Dry Weight (kg)	0.578
Bulk Density (kg/m ^ 3)	582
Dry Density (kg/m ^ 3)	578
Moisture Content (%)	0.69

Thermal Conductivity Testing of Tire Rubber Samples

Test Date: Jan. 12, 1994 Test Instrument: Dynatech Model TCFGM

Discription of Sample: Crumb rubber pieces, relatively dry, relatively high compaction, frozen

Bulk Density (kg/m^3)	Bulk Density (lbm/ft^3)	Dry Density (kg/m^3)	Dry Density (lbm/ft^3)	Moisture Content (%)	K (Btu/hr-ft-F)	K (W/m-K)
592.03	36.96	588.41	36.73	0.62	0.0903	0.1562

TC1 Reading	TH1 Reading	TC2 Reading	TH2 Reading	E (Volts)	I (Amps)
-0.244	-0.175	-0.25	-0.176	0.876	0.1161

TC1 (F)	TH1 (F)	TC2 (F)	TH2 (F)	Q (Btu/sec.)	S (ft^2)
21	24	21	24	0.3382	0.09
d1 (ft)	d2 (ft)	DT1 (F)	DT(2) (F)	DT1/d1 (F/ft)	DT2/d2 (F/ft)
0.1442	0.1442	3	3	20.81	20.81

TC1 (K)	TH1 (K)	TC2 (K)	TH2 (K)	Q (W)	S (m^2)
267.04	268.71	267.04	268.71	0.0991	0.00836
d1 (m)	d2 (m)	DT1 (K)	DT2 (K)	DT1/d1 (K/m)	DT2/d2 (K/m)
0.0439	0.0439	1.67	1.67	37.93	37.93

Bulk Weight (kg)	Dry Weight (kg)	Volume (m^3)
1.634	1.624	0.00276

Check Result: 1 Btu/hr-ft-F=1.7295771 W/m-K

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 14, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively dry, relatively medium compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.722
K (Btu/hr-ft-F)	0.0602

Bulk Weight (kg)	0.554
Dry Weight (kg)	0.55
Bulk Density (kg/m^3)	554
Dry Density (kg/m^3)	550
Moisture Content (%)	0.73

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 14, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively wet, relatively medium compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.764
K (Btu/hr-ft-F)	0.0637

Bulk Weight (kg)	0.564
Dry Weight (kg)	0.55
Bulk Density (kg/m^3)	564
Dry Density (kg/m^3)	550
Moisture Content (%)	2.55

Thermal Conductivity Testing of Tire Rubber Samples

Test Date: Jan. 14, 1994 Test Instrument: Dynatech Model TCFGM

Discription of Sample: Crumb rubber pieces, relatively dry, relatively medium compaction, frozen

Bulk Density (kg/m^3)	Bulk Density (lbm/ft^3)	Dry Density (kg/m^3)	Dry Density (lbm/ft^3)	Moisture Content (%)	K (Btu/hr-ft-F)	K (W/m-K)
580.71	36.25	577.50	36.05	0.56	0.0895	0.1549

TC1 Reading	TH1 Reading	TC2 Reading	TH2 Reading	E (Volts)	I (Amps)
-0.245	-0.175	-0.24	-0.176	0.866	0.1148

TC1 (F)	TH1 (F)	TC2 (F)	TH2 (F)	Q (Btu/sec.)	S (ft^2)
21	24	21	24	0.3306	0.09
d1 (ft)	d2 (ft)	DT1 (F)	DT(2) (F)	DT1/d1 (F/ft)	DT2/d2 (F/ft)
0.1467	0.1458	3	3	20.45	20.57

TC1 (K)	TH1 (K)	TC2 (K)	TH2 (K)	Q (W)	S (m^2)
267.04	268.71	267.04	268.71	0.0968	0.0084
d1 (m)	d2 (m)	DT1 (K)	DT2 (K)	DT1/d1 (K/m)	DT2/d2 (K/m)
0.0447	0.0445	1.67	1.67	37.28	37.50

Bulk Weight (kg)	Dry Weight (kg)	Volume (m^3)
1.626	1.617	0.0028

Check Result: 1 Btu/hr-ft-F=1.7295771 W/m-K

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 15, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Rubber buffings, relatively wet, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft ^ 2-F)	0.713
K (Btu/hr-ft-F)	0.0594

Bulk Weight (kg)	0.537
Dry Weight (kg)	0.513
Bulk Density (kg/m ^ 3)	537
Dry Density (kg/m ^ 3)	513
Moisture Content (%)	4.68

Thermal Conductivity Testing of Tire Rubber Samples

Test Date: Jan. 16,1994 Test Instrument: Dynatech Model TCFGM

Discription of Sample: Rubber buffings, relatively dry, relatively low compaction, frozen

Bulk Density (kg/m^3)	Bulk Density (lbm/ft^3)	Dry Density (kg/m^3)	Dry Density (lbm/ft^3)	Moisture Content (%)	K (Btu/hr-ft-F)	K (W/m-K)
488.57	30.50	486.07	30.34	0.51	0.0768	0.1328

TC1 Reading	TH1 Reading	TC2 Reading	TH2 Reading	E (Volts)	I (Amps)
-0.243	-0.162	-0.243	-0.162	0.866	0.1148

TC1 (F)	TH1 (F)	TC2 (F)	TH2 (F)	Q (Btu/sec.)	S (ft^2)
21	24.5	21	24.5	0.3306	0.09
d1 (ft)	d2 (ft)	DT1 (F)	DT(2) (F)	DT1/d1 (F/ft)	DT2/d2 (F/ft)
0.1467	0.1458	3.5	3.5	23.86	24.00

TC1 (K)	TH1 (K)	TC2 (K)	TH2 (K)	Q (W)	S (m^2)
267.04	268.98	267.04	268.98	0.0968	0.0084
d1 (m)	d2 (m)	DT1 (K)	DT2 (K)	DT1/d1 (K/m)	DT2/d2 (K/m)
0.0447	0.0445	1.94	1.94	43.50	43.74

Bulk Weight (kg)	Dry Weight (kg)	Volume (m^3)
1.368	1.361	0.0028

Check Result: 1 Btu/hr-ft-F=1.7295771 W/m-K

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 17, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Rubber buffings, relatively wet, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.722
K (Btu/hr-ft-F)	0.0602

Bulk Weight (kg)	0.571
Dry Weight (kg)	0.551
Bulk Density (kg/m^3)	571
Dry Density (kg/m^3)	551
Moisture Content (%)	3.63

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 19, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively wet, relatively low compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.734
K (Btu/hr-ft-F)	0.0612

Bulk Weight (kg)	0.534
Dry Weight (kg)	0.52
Bulk Density (kg/m^3)	534
Dry Density (kg/m^3)	520
Moisture Content (%)	2.69

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 19, 1994

Test Instrument: Anacon Model 88

Discription of Sample: Crumb rubber, relatively wet, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	0.789
K (Btu/hr-ft-F)	0.0658

Bulk Weight (kg)	0.593
Dry Weight (kg)	0.578
Bulk Density (kg/m^3)	593
Dry Density (kg/m^3)	578
Moisture Content (%)	2.60

Thermal Conductivity Testing of Tire Rubber Samples

Test Date: Jan. 19,1994 Test Instrument: Dynatech Model TCFGM

Discription of Sample: Rubber buffings, relatively dry, relatively high compaction, frozen

Bulk Density (kg/m^3)	Bulk Density (lbm/ft^3)	Dry Density (kg/m^3)	Dry Density (lbm/ft^3)	Moisture Content (%)	K (Btu/hr-ft-F)	K (W/m-K)
527.14	32.91	524.64	32.75	0.48	0.0789	0.1365

TC1 Reading	TH1 Reading	TC2 Reading	TH2 Reading	E (Volts)	I (Amps)
-0.243	-0.162	-0.243	-0.162	0.878	0.1164

TC1 (F)	TH1 (F)	TC2 (F)	TH2 (F)	Q (Btu/sec.)	S (ft^2)
21	24.5	21	24.5	0.3399	0.09
d1 (ft)	d2 (ft)	DT1 (F)	DT(2) (F)	DT1/d1 (F/ft)	DT2/d2 (F/ft)
0.1467	0.1458	3.5	3.5	23.86	24.00

TC1 (K)	TH1 (K)	TC2 (K)	TH2 (K)	Q (W)	S (m^2)
267.04	268.98	267.04	268.98	0.0995	0.0084
d1 (m)	d2 (m)	DT1 (K)	DT2 (K)	DT1/d1 (K/m)	DT2/d2 (K/m)
0.0447	0.0445	1.94	1.94	43.50	43.74

Bulk Weight (kg)	Dry Weight (kg)	Volume (m^3)
1.476	1.469	0.0028

Check Result: 1 Btu/hr-ft-F=1.7295771 W/m-K

Thermal Conductivity of Tire Rubber Sample

Test Date: Jan. 20, 1994

Test Instrument: Anacon Model 88

Discription of Sample: 1 inch rubber pieces, relatively wet, relatively high compaction

THK (inch)	1.77
TH (F)	101
TC (F)	50
K (Btu-in/hr-ft^2-F)	1.14
K (Btu/hr-ft-F)	0.0950

Bulk Weight (kg)	0.513
Dry Weight (kg)	0.489
Bulk Density (kg/m^3)	513
Dry Density (kg/m^3)	489
Moisture Content (%)	4.91