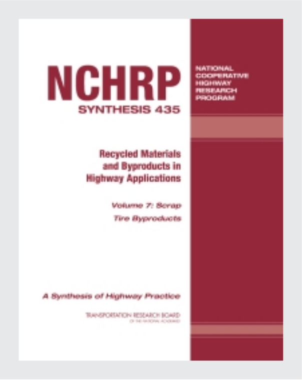
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Recycled Materials and Byproducts in Highway Applications

Volume 7: Scrap Tire Byproducts

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD

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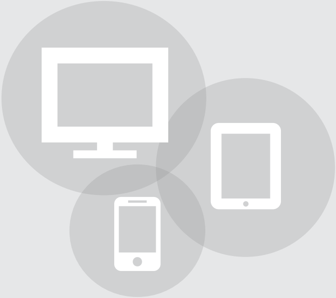

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A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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Project 20-05, Topic 40-01

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
Research Board

Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be found at: http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1	*Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2	*Coal Combustion Byproducts*
Volume 3	*Non-Coal Combustion Byproducts*
Volume 4	*Mineral and Quarry Byproducts*
Volume 5	*Slag Byproducts*
Volume 6	*Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7	*Scrap Tire Byproducts*
Volume 8	*Manufacturing and Construction Byproducts*

CONTENTS

CHAPTER ONE

SCRAP TIRE BYPRODUCTS

BACKGROUND

Approximately one scrap tire is generated per person in the United States every year (Zicari 2009; RMRC 2008). Approximately 30 million of these tires can be used for retreading, which leaves about 250 million scrap tires in need of alternative uses or disposal. For disposal purposes, about 75 tires take up a volume of one cubic yard of landfill space (Choi et al. 2007).

The types of scrap tires generated in the United States are shown in Table 1. Truck tires differ in composition compared with passenger and light truck tires. Truck tires contain a higher percentage of natural rubber, whereas passenger tires have higher percentages of synthetic rubbers. Natural rubber is more tolerant of heat generated from tire–pavement interactions; hence, its preferred use in commercial tires.

A brief overview of uses for scrap tires, provided by Zicari (2009), show the three main current uses as (1) a fuel source (main current use), (2) ground rubber byproducts, and (3) civil engineering applications (Table 2). Byproduct used in highway applications will vary substantially between states.

Types of scrap tire byproducts not used as a fuel source include:

- *Whole tires:* used as-is with no post-processing.
- *Slit tires:* cut in half or sidewalls separated from the tread.
  - *Shredded or chipped tires:* 4 by 4 in. (100 by 100 mm) to as large as 9 by 18 in. (229 by 457 mm) (Note: there are no equivalent sieve sizes for these measurements; sizing is done by manual measurements or visual observations).
- *Ground rubber:* ranging in sieve size from ¾ in. to the No. 100 sieve (19 mm to 0.15 mm) and regular in shape.
- *Crumb rubber:* ranging in sieve size from No. 4 to the No. 200 sieves (4.75 mm to less than 0.075 mm).

Ground rubber is produced using granulators, hammer mills, or fine grinding machines. Crumb rubber can be produced by one of three methods: cracker mill, granulator, or micro-milling. There are two methods of grinding: mechanical and cryogenic processing. The mechanical process reduces tires to chips and granulates the chips while at the same time removing the loose steel and fibers. Once contaminates have been removed, the granules are further ground to produce fine crumbs of rubber. The cryogenic process freezes the tire chips in liquid nitrogen (approximately minus 80°F), which makes the scrap tire brittle and easier to grind. Once cooled and crushed, the steel and fibers are removed. This process produces rubber particles with a range of sizes between 4.75 and 0.6 mm.

The ASTM D6270 (2008) Standard Practice for Use of Scrap Tires in Civil Engineering defines tire-derived aggregate (TDA) as ". . . pieces of scrap tires that have a basic geometrical shape and are generally between 12 mm and 305 mm (0.5 to 12 inch) in size and are intended for use in civil engineering applications."

This definition covers a portion of both the shredded, chipped, or ground rubber definitions cited in the RMRC (2008) reference. Further definitions for ground tire rubber byproducts are provided by the Rubber Manufacturers Association (RMA 2009). This reference notes ground tire byproducts are generated by tire buffings and processed whole tires that are sorted into four size-based categories:

- *Tire buffings:* byproduct of the retreading industry
- *Coarse rubber:* No. 4 to 1 in. sieve sizes (4.75 to 25 mm)
- *Ground rubber:* No. 80 to No. 10 sieve sizes (0.177 to 2.0 mm)
- *Fine ground rubber:* No. 40 to No. 80 sieve sizes (0.037 to 0.177 mm).

Information found in the literature uses all of these definitions, sometimes interchangeably. The lack of consistency in the use of terms and definitions makes it difficult to compare results from various studies. Additional information can be found at the following websites:

- Rubber Manufacturer's Association: www.rma.org
- Rubber Pavement Association: www.rubberpavements.org
- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center: http://www.fhwa.dot.gov/research/tfhrc/
- U.S. EPA Resource Conservation Challenge: http://www.epa.gov/epawaste/conserve/materials/tires/civil_eng.htm.

TABLE 1
TIRE GENERATION IN THE UNITED STATES

Tire Type	Millions of Tires	Market, %	Average Weight of Tires in Group, lb
Light Duty Tires	264.2	88.2	22.5
Passenger tire replacements	202.3	67.53	
Light truck tire replacements	36.0	12.02	
Tires from scrapped tires	25.9	8.65	110
Commercial Tires	35.3	11.80	
Medium, wide base, heavy truck replacement tires	17.8	5.94	
Tires from scrapped trucks and buses	17.6	5.86	
Total Scrapped Tires	299.6	100	32.8

After RMA (2006).

PHYSICAL AND CHEMICAL PROPERTIES

Scrap tires vary in chemical composition based on the type of tire. Table 3 shows the differences between passenger and truck tire scrap rubber. Truck tires are higher in natural rubber content than passenger tires and significantly lower in synthetic rubber. Carbon black, fabric filler, accelerators, etc., are similar in content for both types. The percentage of natural and synthetic rubber is a significant factor in how the scrap tire rubber interacts when used with asphalt cements. In some cases, there is sufficient incompatibility so that the rubber and asphalt cannot be blended. This is a function of crude source chemistry differences that define the ability of the asphalt cement to interact with or partially dissolve the scrap tire rubber byproducts.

The University of Maine website (2010) provided a summary of specific gravities and water absorption values for tire byproducts (Table 4). The water absorption capacity varies between 2.0% and 9.5%. Specific gravity of TDA materials depends on the amount of nonrubber components still in the particles. Specific gravities range from 1.02 to a high of 1.27 when steel wire is still in the TDA (Barker-Lemar 2005). Ranges of unit weights (Table 5) were also reported in a number of previous research documents. Unit weights increase with increasing compaction effort (energy). The loose densities of TDA are on the average about 28 lb/ft^3 and the compacted densities are generally about 40 lb/ft^3. Although limited data were provided, the use of a surcharge can be expected to further increase the density of the TDA layer.

TABLE 2
PERCENT OF CURRENT USES FOR SCRAP TIRES

Use	Percent of Use	
	New York*	United States**
Tire-Derived Fuel	39	52
Ground Rubber	27	17
Civil Engineering	19	12
Use Not Identified	15	19

After Zicari (2009).
*New York data from Empire State Development draft 2006 report.
**United States data from Rubber Manufacturers Association draft 2007 report.

TABLE 3
TYPICAL COMPOSITION AND WEIGHT OF PASSENGER AND TRUCK TIRES

Property	Passenger Tires	Truck Tires
Composition, % by weight		
Natural rubber	14	27
Synthetic rubber	27	14
Carbon black	28	28
Steel	14–15	14–15
Fabric, fillers, accelerators, and antioxidants, etc.	16–17	16–17
New Tires, lb	25	120
Scrap Tires, lb	22.5	110

After RMA (2009).

TABLE 4
SUMMARY OF PREVIOUSLY REPORTED SPECIFIC GRAVITIES AND ABSORPTION CAPACITIES

Tire Type and Source	Properties				Reference (reported in Barker-Lemar 2005)
	Specific gravity			Water absorption, %	
	Bulk	Saturated surface dry	Apparent		
Glass Belted	—	—	1.14	3.8	Humphrey et al. (1992)
	0.98	1.02	1.02	4.0	Manion and Humphrey (1992)
Steel Belted	1.06	1.01	1.10	4.0	Manion and Humphrey (1992)
Mixture	1.06	1.16	1.18	9.5	Bressette (1984)
	—	—	1.24	2.0	Humphrey et al. (1992)
Pine State Facility Mixture	—	—	1.27	2.0	Humphrey et al. (1992)
Palmer Facility Mixture	—	—	1.23	4.3	Humphrey et al. (1992)
Sawyer Facility Mixture	1.01	1.05	1.05	4.0	Manion and Humphrey (1992)
	—	0.88 to 1.13	—	—	Ahmed (1993)

After University of Maine website (2010); Barker-Lemar (2005).
— = not applicable.

TABLE 5
SUMMARY OF PREVIOUSLY REPORTED VALUES FOR UNIT WEIGHTS

Compaction Method	Particle Size, in.	Tire Type	TDA Recycler	Dry Unit Weight, pcf
Loose	0.5 to 5.5	—	—	26.0
Loose	3	Mixed	Palmer Shredding	21.3
Loose	2	Mixed	Pine State Recycling	30.1
Loose	1	Glass	F & B Enterprises	30.9
Loose	2	Mixed	Sawyer Environmental	25.5
Loose	2	Mixed	—	29.1
Loose	2	—	—	24 to 33
Loose	1	Mixed	—	30.5
Vibration	1	Mixed	—	31.0
Vibration	0.5	Mixed	—	29.5
50% Standard	1	Mixed	—	38.3
50% Standard	0.5	Mixed	—	40.0
60% Standard	3	Mixed	Palmer Shredding	38.7
60% Standard	2	Mixed	Pine State Recycling	40.1
60% Standard	1	Glass	F & B Enterprises	38.6
60% Standard	2	Mixed	Sawyer Environmental	39.0
Standard	2	Mixed	Sawyer Environmental	39.9
Standard	2	Mixed	—	39.6
Standard	1.5	Mixed	—	40.2
Standard	1	Mixed	—	40.7
Standard	0.5	Mixed	—	39.5
Standard[b]	0.75 to 3	—	—	37.0
Standard[c]	0.7 to 3	—	—	35.0
Standard[b]	3	—	Rodefeld	37.1[b]
Standard[c]	3	—	Rodefeld	34.9[c]
Modified	2	Mixed	Sawyer Environmental	41.2
Modified	2	Mixed	—	41.7
Modified	1	Mixed	—	42.7
—	2	Mixed	—	26 to 36
Surcharged with 3 ft Soil, Pavement, and Highway Traffic	2	—	—	52 to 53
Full-Scale Field Tests	1.5	—	—	44.3
Full-Scale Field Tests	3	—	—	43.1

After University of Maine (2010); Barker-Lemar (2005).

Compaction methods:

Loose = no compaction; tire shreds loosely dumped into compaction mold.
Vibration = Method D4253.
50% Standard = Impact compaction with compaction energy of 6,188 ft-lb/ft^3.
60% Standard = Impact compaction with compaction energy of 7,425 ft-lb/ft^3.
Standard = Impact compaction with compaction energy of 12,375 ft-lb/ft^3.
Modified = Impact compaction with compaction energy of 56,250 ft-lb/ft^3.

[b] 6-in. diameter mold compacted by 10-lb rammer falling 12 in.

[c] 12-in. diameter mold compacted by 60-lb rammer falling 18 in.

TABLE 6
TYPICAL COMPOSITION OF SCRAP TIRES

Material Components in Tires	Percent of Average Tire	
	% of tire	lb/average tire
30 different kinds of synthetic rubber	24	4.85
Eight types of natural rubber	20	3.97
Eight types of carbon black	24	4.85
Steel cords for belts	5	1.1
Polyester and nylon	5	1.1
Steel bead wire	5	1.1
Different kinds of chemicals, waxes, oils, pigments, etc.	15	3.09

After Bojenko et al. (2008).

ASTM D6270 defines two gradations for TDA depending on use. The Type A gradation is used for drainage, insulation, and vibration damping. This gradation has 100% passing the 4 in. sieve, with a minimum of 90% passing the 3 in. sieve and a maximum of 5% passing the 4.75 mm sieve. Type B is used for lightweight fill. The Type B gradation has 100% smaller than 18 in. and 90% smaller than 12 in. in the maximum dimension with a maximum of 50% passing the 3 in., 25% passing the 1.5 in., and 1% passing the 4.75 mm sieve.

The composition of scrap tires varies widely. Typical scrap tire components were reported by Bojenko et al. (2008) (Table 6). Scrap tires are not sorted by type, other than some recycling facilities separating truck tires from passenger car tires; therefore, the composition of any scrap tire byproducts will reflect all makes and models of tires. Bojenko et al. (2008) also reported information on the trace metal concentrations for scrap tires (Table 7).

TABLE 7
TRACE METAL CONCENTRATIONS IN RUBBER TIRES METAL

Trace Metal	Concentration, mg/kg
Al	280
Ba	<20
Be	<0.5
Bo	<500
Cd	3.6
Cr	107
Cu	3.3
Fe	4,480
Hg	0.1
Mg	<500
Mn	28
Mo	1
Ni	3.3
Se	<5
Sr	<100
Ti	48
Zn	15,500

After Bojenko et al. (2008).

ENGINEERING PROPERTIES

A range of physical properties for TDA byproducts has been reported in the literature. The available information includes ranges of values for:

- Thermal conductivity
- Compressibility
- Hydraulic conductivity (permeability)
- Cohesion and angle of internal friction
- Combustibility.

Thermal conductivity describes the ability of a material to conduct heat (Barker-Lemar 2005). The thermal conductivity of TDA is from 0.1 to 0.2 Btu/hr-ft, which is significantly lower than for granular soils (Table 8). These values indicate that TDA layers can provide good insulation for protection against frost heave.

TDA is highly compressible because of the large void spaces between the particles. The larger the void space between the particles the more vertical movement will be seen when a load is applied. Surcharges are typically used to remove the majority of the vertical movement before using the TDA layer in the application (Table 9).

Compressibility results in vertical settlement when loads are applied (Table 10). This information is necessary for guidance for the designer who must determine the amount of surcharge needed to reduce long-term settlement. Most volume change occurs immediately upon loading and begins to decrease with increasing loads (Wartman et al. 2007). Volume change occurs from both a reduction in voids and deformation of the tire particles. Compressibility is inversely proportional to the soil content when TDA is mixed with soils. The soil increasingly fills the voids spaces and supports the tire particles.

Hydraulic conductivity is a measure of the rate of water flow through a porous material and is an important property for evaluating the ability of water to drain through a TDA layer (Table 11). A wide range of hydraulic conductivity has been reported and varies with TDA particle size, compaction energy, and other test-specific variables. The range of reported values is between a low of 0.0005 cm/s to a high of 59.3 cm/s. This corresponds to a drainage rate of 1.42 ft per day to 168,094 feet per day, respectively. Smaller sizes of TDA compacted to a maximum density provided the lowest values of conductivity. Hydraulic conductivity can also be reduced by mixing TDA with soil, which will fill the void space and reduce flow.

Triaxial testing was used to determine cohesion, *C*, and the angle of internal friction, ϕ, have been reported by a number of researchers (Barker-Lemar 2005) (Table 12). Wartman et al. (2007) summarized research that showed that the shear strength was TDA particle size-independent. In other words,

TABLE 8
SUMMARY OF THERMAL PROPERTIES FOR TDA

Sample (location designation)	Density (pcf)	Void Ratio	Apparent Thermal Conductivity (Btu/hr-ft-°F)	Surcharge
Gravel	117.6	0.41	0.295	none
	121.6	0.36	0.326	half
	123.0	0.34	0.345	full
TDA (F&B-g)	38.5	0.85	0.120	none
	43.3	0.64	0.113	half
	45.4	0.56	0.114	full
TDA (F&B-s)	39.1	0.85	0.145	none
	42.8	0.69	0.130	half
	45.3	0.6	0.134	full
TDA (Palmer)	39.7	1.00	0.159	none
	45.1	0.76	0.119	half
	48.5	0.63	0.125	full
TDA (Pine State)	39.2	0.97	0.158	none
	45.4	0.70	0.139	half
	49.6	0.56	0.114	full
TDA (Sawyer)	36.0	1.13	0.184	none
	41.0	0.87	0.148	half
	43.7	0.76	0.156	full

After Barker-Lemar (2005).

research using tire chips produce similar results to experiments using larger shredded tire particles.

The TDA has a low modulus as a result of the large strain. The deformation is primarily a function of the void space between tire particles. Volume change (compressibility) and constrained modulus have a moderate degree of TDA particle size dependence, with more compressibility resulting from using larger TDA sizes.

Combustibility is the ability of a material to react vigorously with oxygen to produce heat and flames. The components in tires can be flammable and in-use conditions that may generate self-combustion of the TDA are a concern (Barker-Lemar 2005; Tandon et al. 2007; Cheng 2010). Self-starting fires have been documented when the layer thickness was at least 20 ft (compacted). Possible sources of internal heating include the oxidation of the exposed steel in belted tires, oxidation of rubber, and microbial action. Possible conditions of contributing to heat generation include access to air, access to water, retention of heat (function of high insulation value), smaller TDA sizes and granulated rubber particles, the presence of organic nutrients, and layer thickness. TDA is reported to have a flash point of 580°F (University of Maine 2010).

TABLE 9
COMPRESSIBILITY OF DIFFERENT SIZE TIRE SHREDS

Tire Shred Size (in.)	Compressibility (%)	Stress (lb/ft^2)
0.75 to 1.5	30	1,440
0.08 to 2	33–37	4,176 (loose before load)
	52	4,176 (compacted before load)
0.08 to 1	33–35	4,176 (loose before load)
	45	4,176 (loose)
0.08 to 3	38–41	4,176 (compacted before load)
0.08 to 2	29–37	4,176 (compacted before load)
0.5 to 1.5	27	—
1.18	25	104
	40	8,532
2 to 3	37	14,400
8 to 16	55	793
3	18–28	522
0.5 to 5.5	31	665
	50	3,400
	65	21,000

After Barker-Lemar (2005).
— = data not provided.

TABLE 10
VERTICAL STRAIN THAT CAN BE ANTICIPATED WITH TDA SETTLEMENT

Average Vertical Stress, psi	Anticipated Range of Vertical Strain, %
10	19 to 33
20	25 to 37
30	29 to 42
40	33 to 44
50	36 to 46
60	39 to 48
70	40 to 50

After Barker-Lemar (2005).

ENVIRONMENTAL PROPERTIES

Air Quality

Emissions are a concern when using crumb rubber as an asphalt modifier because of the higher hot mix asphalt (HMA) plant and compaction temperatures needed to obtain a workable viscosity and in-place density. General guidelines for best HMA management of emissions provided by the Rubber Pavements Association (RPA) include (2009):

- Produce crumb rubber-modified (CRM) mixes at the lowest possible temperatures, preferably lower than 325°F.
- Keep flights in drum dryers in good shape to promote the best drying of the aggregate and reduce the extent to which the flames reach the CRM binder.
- Maintain material temperatures so that scorching of the binder is prevented.
- Lower rates of production to reduce visible emissions.
- Tarp trucks, shorten windrows for belly dump operations, and use material transfer devices to minimize cooling of the mix.
- Only pave when the weather will not speed cooling of the mix. Avoid cool and windy conditions.
- Odor reduction additives may be helpful in the mixes.

TABLE 11
RANGE OF HYDRAULIC CONDUCTIVITY FOR TDA LAYERS WITH VARIOUS TEST CONDITIONS

Tire Size, in.	Hydraulic Conductivity, cm/s	Test Condition Information
0.18	0.002	3,132 psf
	5×10^{-4}	7,308 psf
0.75	0.79 to 2.74	Simulated overburden of 0 to 25 ft of MSW
1.5	1.43 to 2.64	Simulated overburden of 0 to 35 ft of MSW
2	0.7	2,500 psf (40 ft MSW)
	0.53	5,000 psf (80 ft MSW)
	0.25	10,000 psf (160 ft MSW)
	0.12	15,000 psf (240 ft MSW)
	1.2	—
0.04 to 1.5	6.9	Void ratio = 0.833
	1.5	Void ratio = 0.414
0.2 to 0.6	0.03	ASTM D2434
0.2 to 2.0	3.8 to 59.3	—
0.25 to 0.5	0.16	—
0.4 to2	7.7	Void ratio = 0.925
	2.1	Void ratio = 0.488
0.5 to 1.0	0.18	—
0.5 to1.5	0.58	—
	7.6	Void ratio = 0.693
	1.5	Void ratio = 0.328
0.5 to 3	16.3	Void ratio = 0.857
	5.6	Void ratio = 0.546
0.5 to 5.5	0.65	3,400 psf, Compression—50%
	0.01	2,1000 psf, Compression—65%
0.75 to 3	15.4	Void ratio = 1.114
	4.8	Void ratio = 0.583
1.0 to 1.5	0.18	—
1 to 2	1	—
1 to 2.5	2.9 to 23.5	—
2.4 to 4.0	55	1,879 psf
	20	3,132 psf
	10	7,308 psf
	6	11,484 psf
2 to 3	0.6	Stress (psf): 0
	0.45	1,440 psf
	0.4	2,881 psf
8 to 16	9	Void ratio = 2.77
	3.2	Void ratio = 1.53
	1.8	Void ratio = 0.78

After Barker-Lemar (2005).
— = data not provided; MSW = municipal solid waste; psf = pounds per square foot.

TABLE 12
SUMMARY OF COHESION AND ANGLE OF INTERNAL FRICTION

TDA Size, in.	C, lb/ft^2	Friction Angle, ^{o}	Specific Test Conditions
<0.04	100	30	Tested at dry unit weight of 33 pcf
0.04 to 0.16	70	31	—
<0.08	0	45	Tire shreds without steel–triaxial tests under confining pressure of 720 to 1,148 psf
0.16 to 0.27	130	27	—
0.18	1,462	6	10% strain
0.2 to 0.6	147	27	ASTM D3080
<0.37	0	47 to 60	—
0.5	747	20.5	Standard compaction and 20% strain as failure
<0.74	0	54	—
1	818	24.6	Modified compaction energy and 20% strain as failure
	694	25.3	Standard compaction energy and 20% strain as failure
	779	22.6	50% standard compaction energy and 20% strain as failure
1.5	69	38	Saturated
1.5 to 55.1	65	38	115 to 585 psf peak failure criterion
	0	38	115 to 585 psf 10% failure criterion
<1.5	180	25	Normal stress range: 400–1,500 psf
	0	57	—
1 to 2	80	27.5	—
	1,482	11	15% strain
	1,712	15	20% strain
<2, 2–4, and 4–6	0 to 62.6	30	146–1,460 psf
<2.0	90 to 160	21 to 26	—
<3.0	240	19	—
2	150	27	—
	0	17 to 35	17 degrees at 5% strain, 35 degrees at 20% strain
2 to 3	—	37 to 43	0
2-in. shredded	660	14	—
2-in. square	540	21	—
3	90	32	—

After Barker-Lemar (2005).
— = data not provided.

Four studies have been conducted over the last 15 years that evaluated emissions from the production of conventional HMA to that of CRM HMA. The first study that reported measured emissions was from the Michigan Department of Transportation (DOT) in 1994. The second study was conducted by the Texas Transportation Institute in 1995 and evaluated the recyclability of the CRM HMA by analyzing previously reported data. The Institute data mining research concluded that the CRM HMA is likely recyclable and air quality should not be compromised. Construction issues were not addressed in this study. The third reported research project was conducted by the Northern California Rubberized Asphalt Technology Center in 2001. This study evaluated if additional permitting would be required for CRM HMA by comparison to the standards set out the 2000 EPA AP-42 guide "Hot mix asphalt plant emission assessment report." The RPA reported results for emission testing at a drum mix plant and the fourth study (Roschen 2002) provided similar testing for batch plants. The data in the Roschen report appear to repeat (or be the original source of) the RPA drum mix plant data.

Emissions are compared based on the pounds per ton of HMA produced, which is a parameter that reflects the production rate of the mixes at the plant. For the Roschen study, the production rates were reported as 206 and 336 tons per hour for conventional mixes at the batch and drum plants, respectively. The production rates for the CRM HMA at the same two plants were lower at 185 and 307 tons per hour, respectively. These production rates represent the maximum capacity of each plant for each mix. The operating temperatures of each plant were 318°F and 311°F for the conventional HMA mixes at drum and batch plants, respectively. The temperatures were increased when producing the CRM HMA to 335°F and 318°F, respectively. Results showed that the particulate emissions were similar for both mixes, but somewhat different between batch and drum mix plants (Table 13).

TABLE 13
COMPARISON WITH EPA AP-42 FOR SACRAMENTO COUNTY, CALIFORNIA STUDY

Source of Data	Particulate Emissions (pounds per ton)	
	Conventional asphalt concrete	CRM HMA
Dutra (batch plant)	0.0013	0.0015
MVR (drum plant)	0.0025	0.0030

After Roschen (2002).

The toxic potency index was evaluated using Bay Area Air Quality Management District Regulation 2-1-316 for each plant (Table 14). The emissions produced at the drum plant were similar for both conventional and CRM HMA. The emissions at the batch plant showed significant differences between the productions of conventional compared with CRM HMA. In this case, the emissions increased approximately twenty-fold when producing the CRM HMA. The presence of benzene was attributed to the tailpipe exhaust in the truck load-out shed since neither the CRM nor the extender oil used in this mix contained benzene.

Operational data, material conditions, and stack measurements are included in Table 15. The operational characteristics, continuous emissions measurements, and polyaromatic compounds (PAH) contents were consistent between the drum and batch plants.

The National Institute for Occupational Health and Safety (NIOSH) (2001) reported on testing from personal breathing zone air samples from CRM and conventional HMA paving operations. Testing included measurements of total particulates (TPs), benzene soluble particulate (BSP), polycyclic aromatic compounds, organic sulfur-containing compounds, and benzothiazole (Table 16). Only the TP and BSP have occupational limits. Sampling was also completed to identify emissions from any solvents used to clean equipment in the field, diesel exhaust, and carbon monoxide. NIOSH checked if the asphalt fume was mutagenic by testing on bacteria, collecting questionnaires completed by paving workers, and testing breathing capacity of workers during the day.

Findings from this research showed:

- Personal breathing zone exposures were high during CRM paving.
- Eye, nose, and throat irritation were the most commonly reported worker complaints and were associated with the TPs during CRM HMA paving.
- Solvent levels were generally very low; however, benzene was detected at several sites.
- High carbon monoxide exposures were measured near some workers, but exposure to diesel fumes was low. This was eventually traced back to sampling near a poorly tuned engine.
- Benzothiazole was found at all sites, but it is not known if these levels would have a health effect.
- None of the asphalt fume samples tested was mutagenic.

The conclusion by NIOSH was that CRM exposures are potentially more hazardous than conventional HMA and that fumes should be reduced whenever possible.

Discussion and review (possibly still unpublished) of the NIOSH (2001) report included information that reflected poorly on the precision/accuracy of the tests leading to the TP and BSP values. Exxon Environmental, Inc., in East Millstone, New Jersey, asked the question, “Why do BSPs sometimes exceed TPs as BSPs are only part of TPs?” After extensive testing and study, they concluded that filters used in the BSP testing could have significant quantities of BSPs invalidating the testing, and the large amounts of solvent used, even the purest grades available as recommended in the EPA/NIOSH test procedures, could have significant quantities of BSPs, likewise

TABLE 14
COMPARISON WITH EPA AP-42 FOR SACRAMENTO COUNTY, CALIFORNIA STUDY

Compound	Reg 2-1-316 Threshold (lb/yr)	Toxic Potency Index for Two Locations			
		Dutra (batch plant)		MVR (drum plant)	
		Conventional asphalt concrete	Asphalt rubber concrete	Conventional asphalt concrete	Asphalt rubber concrete
Benzene	6.7	1.90E-07	5.12E-06	6.32E-06	5.40E-06
Toluene	39,000	5.77E-11	1.99E-09	5.20E-10	4.64E-10
Xylene	58,000	0	1.42E-08	3.40E-10	8.93E-10
1,3-Butadiene	1.1	0	0	5.00E-06	6.20E-06
Naphthalene	270	4.89E-08	5.35E-08	1.16E-08	2.17E-08
Benz(a)anthracene	0.044	2.73E-08	0	0	0
Total Toxic Potency Index		2.66E-07	5.19E-06	1.13E-05	1.16E-05

After Roschen (2002).
Toxic Potency Index for each contaminant is calculated by dividing the measured emission factor (lb/ton) by the annual emission threshold (lb/yr).

TABLE 15
EMISSION RESEARCH REPORTED FOR MICHIGAN DOT 1994 STUDY

Operating Data/Conditions/Measurements	Control 2	RBR 1
HMA Production Rate (tons per hour)	351	357
Dry Aggregate Rate (tons per hour)	330	333
Asphalt Cement Added (%)	5.75%	6.84%
Materials Moisture Content	4.17%	5.21%
Fuel Consumption (gal/hr)	655	690
Exhaust Gas Temperature (°F)	311	324
Mix Temperature (°F)	296	316
Sample Volume (SCF)	46.501	42.823
Sample Volume (cu. m)	1.317	1.213
Exhaust Gas Moisture (%)	27.00%	29.30%
Stack Temperature (°F)	260	271
Actual Exhaust Gas Flow (ACFM)	89,540	95,450
Dry Exhaust Gas Flow (DSCFM)	47,076	47,836
Dry Exhaust Gas Flow (DSCMM)	1,333	1,355
Continuous Emissions Measurements and Method 18 Results		
CO_2, %, Orsat Result	5.79%	6.02%
O_2, %, Orsat Result	12.75%	12.10%
N_2, %, Orsat Result	81.46%	81.88%
Carbon Dioxide (CO_2)	6.00%	6.48%
Oxygen (O_2)	12.87%	12.18%
Carbon Monoxide (CO) PPM	430.5	259.5
Nitrogen Oxides (NO_x) PPM	139.3	124.4
Sulfur Dioxide (SO_2) PPM	74.4	76.7
Non Methane Total Hydrocarbons (NMTHC) as Carbon PPM	225.5	183.0
Methane (CH_4) as Measured PPM	27.7	10.6
Methane as Carbon PPM	20.7	7.9
Total Hydrocarbons (THC) as Carbon PPM	245.1	191.3
NMTHC as Carbon PPM	225.5	183.0
PAH Emissions Measurements (lb/hr)		
Acenaphthene	0.0018	0.0021
Acenaphthylene	0.0022	0.0026
Anthracene	0.0003	ND
Benz(a) anthracene	0.0002	ND
Chrysene	0.0003	ND
Fluoranthene	0.0030	0.0024
Fluorene	0.0051	0.0055
Naphthalene	0.0502	0.0622
Naphthalene, 2-Methyl-	0.0578	0.0788
Phenanthrene	0.0120	0.0141
Pyrene	0.0030	0.0022
Cunene	0.0056	0.0069
o-Cresol (2-Methylphenol)	0.0029	0.0011
m-/p-Cresol (3-/4-Methylphenol)	0.0052	0.0058

After RMA (2009).
ND = not detectable.

invalidating the testing. It is important that this possibility be considered when conducting environmental testing.

Water Quality

Liu et al. (1998) provided a summary of earlier leachate testing studies which are summarized in Table 17. There is a general agreement that lower pH conditions result in higher concentrations of metals being leached out of the TDA in unbound application, but the concentrations are usually below the primary drinking water standards. The most common metal that exceeds the secondary drinking water standards is iron. High concentrations of carbon black were leached out of the TDA at high pH levels. Only one study evaluated the occurrence of PAH in the leachate; however, both TDA and HMA leachate were found to generate PAH compounds. Further studies were recommended for these compounds.

TDA Above the Ground Water Table

Humphrey and Swett (2006) evaluated water quality index tests for TDA in unbound applications that were placed above the ground-water table. The investigation monitored five projects for total dissolved solids (TDS), total solids, biological oxygen demand, and contamination oxygen demand (Table 18). The measured pH was near neutral. The North Yarmouth project showed that both the control and the TDS exceeded secondary drinking water standards, but the initial preconstruction data showed that these levels of TDS

TABLE 16
EMISSION RESULTS FROM ENVIRONMENTAL STUDIES

Compound	Emission Factor (pounds per ton)					
	RPA (2001) (drum plant)			Roschen (2002) (batch plant)		
	Conventional asphalt concrete	Asphalt rubber concrete	EPA AP-42	Conventional asphalt concrete	Asphalt rubber concrete	EPA AP-42
Benzene	4.23E-05	3.62E-05	3.90E-04	1.27E-06	3.43E-05	2.80E-04
Toluene	2.03E-05	1.81E-05	1.50E-04	2.25E-06	7.75E-05	1.00E-03
Ethyl Benzene	0	3.20E-06	2.40E-04	0	7.37E-06	2.20E-03
Xylene	1.97E-05	5.18E-05	2.00E-04	0	8.26E-04	2.70E-03
1,3-Butadiene	5.50E-06	6.82E-06	NA	0	0	NA
Naphthalene	3.12E-06	5.87E-06	9.00E-05	1.32E-05	1.45E-05	3.60E-05
2-Methylnaphthalene	7.78E-07	1.60E-06	7.40E-05	1.12E-05	2.15E-05	7.10E-05
Acenaphthylene	1.71E-07	1.01E-07	8.60E-06	3.43E-07	3.99E-07	5.80E-07
Acenaphthene	1.66E-08	1.86E-09	1.40E-06	1.05E-06	1.63E-06	9.00E-07
Fluroene	5.27E-08	3.68E-08	3.80E-06	6.61E-07	1.37E-06	1.60E-06
Phenanthrene	1.09E-07	8.02E-08	7.60E-06	1.28E-06	1.83E-06	2.60E-06
Anthracene	1.19E-07	4.79E-09	2.20E-07	4.09E-07	5.04E-07	2.10E-07
Fluoranthene	8.28E-09	4.04E-09	6.10E-07	6.15E-08	4.00E-08	1.60E-07
Pyrene	1.16E-09	3.52E-09	NA	2.78E-07	1.64E-07	NA
Benz(a)anthracene	0	0	2.10E-07	1.20E-09	0	4.60E-09
Chrysene	0	0	1.80E-07	7.55E-09	2.55E-09	3.80E-09
Benzo(b)fluoranthene	0	0	1.00E-07	0	0	9.40E-09
Benzo(k)fluoranthene	0	0	4.10E-08	0	0	1.30E-08
Benzo(e)pyrene	0	0	1.10E-07	5.56E-09	2.82E-09	NA
Benzo(a)pyrene	0	0	9.80E-09	0	0	3.10E-10
Perylene	0	0	8.80E-09	1.51E-09	0	NA
Indeno(1,2,3-c,d)pyrene	0	0	7.00E-09	0	0	3.00E-10
Dibenz(a,h)anthracene	0	0	NA	0	0	9.50E-11
Benzo(g,h,l)perylene	0	0	4.00E-08	0	0	NA

After RMA (2009) and Roschen (2002).
NA = not available.

were not related to TDA. Secondary drinking water standard inorganic chemical compounds are "non-enforceable guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water" (EPA 2006).

Thirteen inorganic chemicals for primary drinking water standards were measured on filtered samples, except for mercury (Table 19). All of the projects showed concentrations below the regulatory allowed limits with one exception. The C&E (climate and energy) project showed concentrations for antimony, arsenic, lead, selenium, and titanium, but no control was taken; therefore, it was unclear where the contamination was coming from. These results appeared reasonable because none of these chemicals are commonly used in the manufacture of tires.

Nine inorganic compounds related to secondary drinking water standards were directly monitored on filtered samples (Table 20). The C&E project compounds were higher than the limit for aluminum; however, there was no control sample available for the preconstruction condition. The TDA was source of elevated levels of iron (Fe) and manganese (Mn). There was an elevated chloride content in two projects that was attributed to the use of road salts. The zinc was lower in TDA areas for two projects when compared with the control sections (statistically significant). Sulfate was lower than control on one project.

Organic compounds were measured for two field studies where the water passing through the TDA was used for the analysis. Volatile organic compounds (VOCs) per EPA Method 8260 are shown in Table 21. The semi-volatile organic compounds (SVOCs) were measured per capillary column EPA Method 8270. No difference between control and TDA projects were observed.

Aquatic toxicity was evaluated for one project with the U.S. EPA (EPA 2006) freshwater short-term toxicity tests. The results showed no effect from TDA. Projects with adjacent wells (three) showed no statistical differences found between the control wells and those adjacent to the TDA projects. A summary for TDA used above the water tables were:

- Drinking water standards are not exceeded when TDA is used above the ground-water table.
- Would be unlikely to increase levels of metals above naturally occurring levels.
- Secondary drinking water standards may be exceeded for concentrations of iron and manganese.
- VOCs and SVOCs were generally below reporting limits.
- Aquatic toxicity tests showed no effect from TDA.

TABLE 17
SUMMARY OF RESULTS FROM PREVIOUS STUDIES

Source of Information	pH Range	Metals	Other Information	Comments
Minnesota Pollution Control Agency (1990)	3.5 to 8.0	• As, Ca, Cr, Se, and Zn were over the Mn drinking water standards in some cases. • Fe exceeded secondary drinking water standards. • Leach more in lower pH water	• PAHs were exceeded for all conditions for both TDA and HMA.	• Use TDA above the water table • Limit infiltration of water through scrap tires • Drain surface water away from TDA base
Wisconsin (1992)	Neutral	• If any compounds leached, the concentrations decreased with time except for Ba, Fe, Mn, and Zn. • Fe and Mn were at or above the drinking water standards.	• NA	• Not a hazardous waste • Little or no influence on ground-water quality
Scrap Tire Management Council Study (1991)	Neutral	No regulatory limits were exceeded.	• NA	• No differences in results from TCLP and EP Tox test results
Virginia DOT	TCLP	• 1-yr study showed no concentrations exceeded limits. • Metals leached most readily at lower pH. • Fe concentrations were highest.	• Significant amounts of carbon black leached at higher pH. • Some gas generation observed after two weeks at very low pH.	
Illinois DOT (1990)	EP Tox	• Metals were usually below or close to detection limits.	• Organics were below or close to detection limits.	
Kent State University, Ohio	Field study	• No regulation limits were exceeded.		
Wageningen Agricultural University, Denmark	Field study	• NA	• Measured the release of CO_2 from TDA–soil mixtures, which was attributed to the degradation of TDA particle components such as steric acid.	

Liu et al. (1998).
NA = not available; TCLP = Toxicity Characteristic Leaching Procedure.
As = arsenic; Ba = barium; Ca = calcium; Cr = chromium; Fe = iron; Mn = manganese; Se = selenium; Zn = zinc.

TABLE 18
MEAN VALUES OF WATER QUALITY INDEX TESTS FROM FIELD STUDIES WITH DIRECT COLLECTION OF SAMPLES

Analyte	Secondary Standard	Wisconsin		North Yarmouth			Winter Farm Road**	Ohio Monofills		Binghamton, NY	
		West 4-in. TDA	East 2-in. TDA	Control	TDA Section C	TDA Section D		C&E	American	Control TF2	TDA TF1
pH	6.5–8.5	7.5	7.5	7.21	7.11	7.05	NA	7.29	7.51	7.06	6.79
Total Dissolved Solids, mg/L	500	1,883	230	1,096	1,049	902	320	NA	NA	NA	NA
Total Solids, mg/L	NA	NA	NA	1,117	1,062	925	610	NA	NA	NA	NA
BOD, mg/L	NA	16.3	38.7	1.79	1.34	2.04	NA	NA	NA	NA	NA
COD, mg/L	NA	163	279	56.6	58	61.1	NA	NA	NA	NA	NA

After Humphrey and Swett (2006).
NA = not available.
*Results for unfiltered sample reported.
**Results from a single sample reported.
References: Wisconsin (Edil and Bosscher 1992; Eldin and Senouci 1992; Bosscher et al. 1993); North Yarmouth (Humphrey and Katz 2000); Witter Farm Road (Humphrey 1999); Ohio Monofills (Chyi 2000); Binghamton (Brophy and Graney 2004); Secondary standard (EPA 2006).

TABLE 19
MEAN CONCENTRATIONS OF INORGANIC ANALYTES WITH PRIMARY DRINKING WATER STANDARDS FROM FIELD STUDIES WITH DIRECT COLLECTION OF SAMPLES

Constituents	RAL	Wisconsin		North Yarmouth			Witter Farm Road**	Ohio Monofills		Binghamton, NY	
		West 4-in. TDA	East 2-in. TDA	Control	TDA Section C	TDA Section D		C&E	American	Control TF2	TDA TF1
Sb	0.006	NA	NA	100% <0.05	100% <0.05	NA	0.129	100% <0.005	NA	NA	
As	0.01	NA	NA	NA	NA	NA	NA	0.31	67% <0.001	NA	NA
Ba	2	0.346	0.281	0.0688	0.0339	0.0395	0.017	0.218	0.0603	0.796	0.392
Be	0.004	NA	NA	100% <0.005	100% <0.005	NA	100% <0.1	100% <0.001	NA	NA	
Ca	0.005	NA	NA	95% <0.0005	100% <0.0005	96% <0.0005	<0.0005	80% <0.1	67% <0.001	0.0325	0.008
Cl	0.1	NA	NA	0.0118	0.0126	0.0119	<0.006	NA	NA	NA	NA
Cu	1.3	NA	NA	91% <0.009	91% <0.009	96% <0.009	<0.009	80% <0.02	67% <0.01	NA	NA
F	4	NA	NA	NA	NA	NA	NA	0.8018	0.7356	NA	NA
Pb	0.015	90% <0.003	0.008	88% <0.002	88% <0.002	94% <0.002	<0.002	0.19	67% <0.001	NA	NA
Hg	0.002	NA	NA	100% <0.0005	100% <0.0005	NA	NA	NA	NA	NA	
NO_3	10	NA	NA	NA	NA	NA	NA	0.9217	0.8933	NA	NA
Se	0.05	NA	NA	NA	NA	NA	NA	0.231	100% <0.001	NA	NA
Ti	0.002	NA	NA	NA	NA	NA	NA	80% <0.002	100% <0.002	NA	NA

After Wartmen et al. (2007).
**Results from a single sample reported.
NA = not available; RAL = regulatory allowed limits.

TABLE 20
MEAN CONCENTRATIONS OF INORGANIC ANALYTES WITH SECONDARY DRINKING WATER STANDARDS FROM FIELD STUDIES WITH DIRECT

Analyte	Secondary Standard	Wisconsin		North Yarmouth			Winter Farm Road**	Ohio Monofills		Binghamton, NY	
		West 4-in. TDA	East 2-in. TDA	Control	TDA Section C	TDA Section D		C&E	American	Control TF2	TDA TF1
Al	0.2	NA	NA	81% <0.07	100% <0.07	100% <0.07	<0.07	7.97	67% < 0.1	NA	NA
Cl	250	477	600	345.8	331.9	338.	111	44.2	34.6	NA	NA
Cu	1	NA	NA	91% <0.009	91% <0.009	96% <0.009	<0.009	80% <0.02	67% <0.01	NA	NA
F	2	NA	NA	NA	NA	NA	NA	0.8	0.736	NA	NA
Fe	0.3	0.71	1.13	0.0198	0.0795	0.555	0.158	0.19	0.103	0.255	15
Mn	0.05	1.129	1.522	0.0421	4.38	2.56	2.53	2.72	1.93	0.26	6.21
Ag	0.1	NA	NA	NA	NA	NA	NA	80% <0.005	100% <0.001	NA	NA
SO_4^2	250	115	213	25.3	18.9	11.4	3.51	468.5	600.7	NA	NA
Zn	5	0.093	0.23	1.1	0.0111	0.0111	0.082	0.492	100% <0.005	0.3	0.0343

After Humphrey and Swett (2006).
Units = mg/l. NA = not available.
When possible, the calculated mean is reported; if the mean could not be calculated because of limited number of samples with concentrations above the detection limit, then the percent of the results below the detection limit is reported.
*Results for unfiltered sample reported.
**Results from a single sample reported.
References: Wisconsin (Eldin and Senouci 1992; Bosscher et al. 1993); North Yarmouth (Humphrey and Katz 2000); Witter Farm Road (Humphrey 1999); Ohio Monofills (Chyi 2000); Binghamton (Brophy and Graney 2004); Secondary standard (EPA 2006).

TABLE 21
CONCENTRATIONS ON ORGANIC ANALYTES FROM THREE PROJECTS

Compound		RAL	Sampling Date (mg/L)				
			12/28/1995	4/5/1996	6/22/1999	11/8/2000	1/1/2002
North Yarmouth Project							
1,1-dichloroethane	VOC	0.005	ND*	ND*	ND*	ND#	ND#
cis-1,2-dichloroethene[1]	VOC	0.07	ND*	ND*	ND*	ND#	ND#
Toluene	VOC	1	ND*	ND*	0.07	ND#	ND#
4-methyl-2-pentanone	VOC	—	ND*	ND*	ND*	ND**	ND**
Acetone	VOC	—	ND**	ND**	ND**	ND**	ND**
Aniline	SVOC	—	ND**	ND**	ND**	ND*	ND*
bis(2-ethylhexyl)phthalate	SVOC	—	ND**	ND**	ND**	ND*	0.006
3&4-methylphenol	SVOC	—	ND**	ND**	0.1	ND*	ND*
Benzoic acid	SVOC	—	ND**	ND**	0.025	ND*	ND*
Phenol	SVOC	—	ND**	ND**	0.074	ND*	ND*
North Yarmouth—TDA Section C							
1,1-dichloroethane	VOC	0.005	ND*	ND*	ND*	0.0013	ND#
cis-1,2-dichloroethene[1]	VOC	0.07	ND*	ND*	ND*	0.0015	ND#
Toluene	VOC	1	ND*	ND*	ND*	ND#	ND#
4-methyl-2-pentanone	VOC	—	ND*	ND*	ND*	ND**	ND**
Acetone	VOC	—	ND**	ND**	ND**	0.014	0.024
Aniline	SVOC	—	ND**	ND**	ND**	0.005	ND*
bis(2-ethylhexyl)phthalate	SVOC	—	ND**	ND**	ND**	ND*	ND*
3&4-methylphenol	SVOC	—	ND**	ND**	ND**	ND*	ND*
Benzoic acid	SVOC	—	ND**	ND**	ND**	ND*	ND*
Phenol	SVOC	—	ND**	ND**	ND**	ND*	ND*
North Yarmouth—TDA Section D							
1,1-dichloroethane	VOC	0.005	ND*	ND*	<0.005	On 11/8/2000 and 1/1/2002 the sample was a composite from Sections C and D—see above for results	
cis-1,2-dichloroethene[1]	VOC	0.07	ND*	ND*	ND*		
Toluene	VOC	1	ND*	ND*	ND*		
4-methyl-2-pentanone	VOC	—	ND*	ND*	<0.005		
Acetone	VOC	—	ND**	ND**	ND**		
Aniline	SVOC	—	ND**	ND**	ND**		
bis(2-ethylhexyl)phthalate	SVOC	—	ND**	ND**	ND**		
3&4-methylphenol	SVOC	—	ND**	ND**	ND**		
Benzoic acid	SVOC	—	ND**	ND**	ND**		
Phenol	SVOC	—	ND**	ND**	ND**		

After Humphrey and Swett (2006).
RAL = regulatory allowable limits; ND = not detectable; MRL = 0.0005.
*MRL = 0.005.
**MRL = 0.010.
= not included in analysis on that date.
— = not available.
[1] Cis-1,2-dichloroethene also known as cis-1,2-dichloroethylene.

TDA Below the Ground-Water Table

Humphrey and Katz (2001) studied the use of TDA below the ground-water table in three types of soil studied (peat, marine clay, and glacial till). The TDA was placed in a trench 2 to 6 ft wide at a depth below the water table and oriented perpendicular to the ground-water flow. Monitoring wells were set up so that one well was placed upgrade for control measurement, one directly in the TDA, between one and three wells were placed 2 ft down grade of the TDA, and one 10 ft down grade.

An analysis for the primary drinking water standards showed that the TDA had a limited potential for raising the barium concentration slightly, but not above the standard limits. The secondary drinking water standards analysis showed that water in direct contact with the TDA (trench) showed an increase in the levels of Fe, Mn, and zinc (Zn). The concentrations of Mn and Zn decreased with time and were seen in both the trenches and down grade.

The VOC analysis showed cis-1,2-dichloroethene and benzene were found at most sampling dates, but at concentrations below standard limits. The TDA slowly released these compounds, but increases were only detectable close to the TDA location. Other compounds found in the water included 1,1-dichloroethane, 4-methyl-2-pentanone, and acetone that were also released at low levels in the trenches, but did not migrate down grade.

SVOC measurements showed that the concentrations of aniline increased but remained at low levels. The m,p-cresol was above the detection limits about half of the time in the trenches, but was not found in the down-grade wells except in the clay soils. This compound may be released but tends not to migrate. Benzoic acid was found in about half of the trenches and N-nitrosodiphenyl-amine was found in about one-third of the trenches, but did not migrate to the down-grade wells.

Aquatic toxicity showed only a limited effect on the survival rate of Ceriodaphnia Dubai (species of water flea) in water in direct contact with the TDA. Concentration should not influence survival rate after some dilution.

The summary for using TDA below the water table was:

- The concentrations of iron, manganese, and zinc increased when TDA was in direct contact with water; however, the increase did not extend to more than 3 m down-gradient from the trench.
- The concentrations decreased to background levels a short distance away from the submerged TDA.
- Only low levels of VOCs and SVOCs were found in water in direct contact with the TDA and would be below the detectable limits a short distance away.

CHAPTER TWO

APPLICATIONS

TDA has been used in a number of highway applications. The information in this section is organized into three major categories: Bound Applications—Portland Cement and Concrete, Bound Applications—Asphalt Cement and Concrete, and Unbound Applications—Bases, Embankments, and Fills. Each category has a number of specific applications.

BOUND APPLICATIONS—PORTLAND CEMENT AND CONCRETE

Research was found for the uses of TDA and crumb rubber in a number of portland cement and/or concrete applications including:

- Precast portland cement concrete (PCC) applications
- Scrap tire fibers in PCC
- Crumb rubber in mortars
- TDA and crumb rubber in PCC
- PCC pavements.

Precast Portland Cement and Concrete Applications

Allen (2004) noted that crumb rubber concrete in precast panels was useful because it was lightweight, helped control noise, and improved insulation properties. The major disadvantage to using crumb rubber concrete was the loss of strength.

“Concrete Pavement’s New Road Map” (Kuennen 2006) listed those benefits achieved with using crumb rubber in precast panels for PCC pavements:

- Improved thermal cycling resistance that provides a concrete that is less likely to crack and shatter under repeated freeze-thaw cycles.
- Easier transportation of lightweight precast panels.
- Lower overall cost.
- Promotion of recycling.

In Thailand, Sukontasukkul (2009) evaluated the thermal and acoustical properties of crumb rubber concrete mixes for potential use in sound barrier panels. Materials used in the study included a Type I portland cement, 9.5 mm coarse aggregate, river sand, super plasticizer Type F, and various concentrations and sizes of crumb rubber. Crumb rubber and aggregate properties are shown in Table 22. The gradations used in the study were mostly one-sized. Mixes with the individual crumb rubber sizes and a combination of the two sizes were used at varying percentages of 10%, 20%, and 30%.

Testing used ASTM C642 for density and voids, ASTM C177 for steady state heat flux and thermal transmission measurements, and ISO 10534-1 for sound absorption coefficient and impedance measurements using an impedance tube. Density and porosity decreased with increasing amounts of crumb rubber (Table 23). Thermal conductivity is a measure of the heat transmitted through a unit thickness in a direction normal to the surface under steady state conditions. The use of crumb rubber in PCC significantly lowered the thermal conductivity (Table 24). The No. 6 crumb rubber provided the most reduction at 30%, whereas the No. 25 crumb rubber PCC at 10% was almost as low. The rate of heat transfer per unit time (W/h) and the heat resistivity (m^2/KW) were calculated using the thermal conductivity and an assumed temperature difference of about 55°F. Sound absorption was measured at low to mid frequency (125, 250, and 500 Hz) and high frequency (1000, 2000, and 4000 Hz) ranges (Table 25). Mixes with crumb rubber absorbed sound better than the control PCC at the higher frequencies.

Overall, the crumb rubber mixes improved sound resistivity by about 36%. Conclusions were that crumb rubber PCC reduced the unit weight of the mix from 14% to 28%, reduced thermal conductivity, and provided some improved sound absorption.

Tire Derived Aggregate Fibers in Portland Cement Concrete

Hernandez-Olivares et al. (2002, 2006) reported on research conducted in Spain that evaluated the use of scrap tire fibers in PCC. The materials used in the study included cement, coarse aggregate (12 to 19 mm), sand (3 to 6 mm), fine aggregate (<3 mm), superplasticizer, retarder, polypropylene fibers (0.1% by volume), and crumb rubber (3.5% and 5.0% by volume). The polypropylene fiber was added to minimize the drying shrinkage cracking, but was sufficiently low in concentration to expect a noticeable impact on the hardened PCC mechanical properties.

Scrap tire byproduct was obtained using strip processing to produce rubber fibers with lengths ranging between 0.33 and 0.9 in. This type of cutting process produced about 4% rubber powder.

TABLE 22
PHYSICAL PROPERTIES OF FINELY GROUND CRUMB RUBBER

Properties	Crumb Rubber			Aggregates	
	No. 6 (3.36 mm)	No. 25 (0.707 mm)	No. 6 + No. 25	Coarse	Fine
Bulk Specific Gravity	0.96	0.62	0.77	2.68	2.43
Bulk Specific Gravity, SSD	0.97	0.62	0.78	2.69	2.47
Apparent Specific Gravity	0.97	0.62	0.78	2.7	2.55
Water Absorption, %	0.92	1.05	0.95	0.25	2.04
Fineness Modulus	4.93	2.83	3.77	—	2.9

After Sukontasukkul (2009).
— = data not provided.

TABLE 23
POROSITY OF PCC MIXES WITH CRUMB RUBBER

Type	Crumb Rubber, %	Density, lb/ft^3	Porosity, %
Control	0	157.9	9.35
No. 6 (3.36 mm)	10	135.5	8.48
	20	131.7	6.50
	30	126.7	6.38
No. 25 (0.707 mm)	10	130.5	6.79
	20	123.0	5.90
	30	113.6	5.81
No. 6 and No. 25 (combination)	10	131.1	7.91
	20	120.5	7.02
	30	118.6	6.09

After Sukontasukkul (2009).

Testing included a scanning electron microscopy study that was used to evaluate the cement–rubber interface after hydration. A high concentration of calcium oxide crystals was found on the rubber surface. Silicon and aluminum oxides were also observed.

Dynamic testing of samples was used to calculate the complex modulus of the mixes as well as the ability of the mixes to dissipate elastic energy at low frequency dynamic loads. Typical results of decreasing mechanical properties with increasing rubber content were found. The rubber fibers resulted in more energy being absorbed, which tended to disrupt crack propagation.

Li et al. (2004) used scrap tire fibers (i.e., small strips of tire rubber) in place of crumb rubber to evaluate the possibility of improving the mechanical properties of scrap tire rubber PCC. The hypothesis was based on the proven improvement of concrete mechanical properties with the use of fibers. The objective of the research was to determine if tire fibers would provide a similar improvement.

Materials used in the study were Type I portland cement, gravel, natural sand, water, and air entrainment admixture. Two geometries of scrap tire byproducts were used. The first was a tire chip with a size of 1 in. by 1 in. by 0.2 in. thick. The second geometry was a long thin rectangle with different lengths (tire fibers). All were 1 in. width by 0.2 in. thick and the lengths varied (2, 3, and 5 in.) (Figure 1). Two types of tires (passenger tires, combination of truck and passenger car tires) with and without steel belts were used. The steel belts were left in the TDS to improve the stiffness of the tire fibers and reduce the cutting cost of the scrap tire byproduct.

Fresh concrete properties showed that the workability of the mixes was acceptable with or without the tire byproducts.

TABLE 24
THERMAL PROPERTIES OF PCC MIXES WITH CRUMB RUBBER

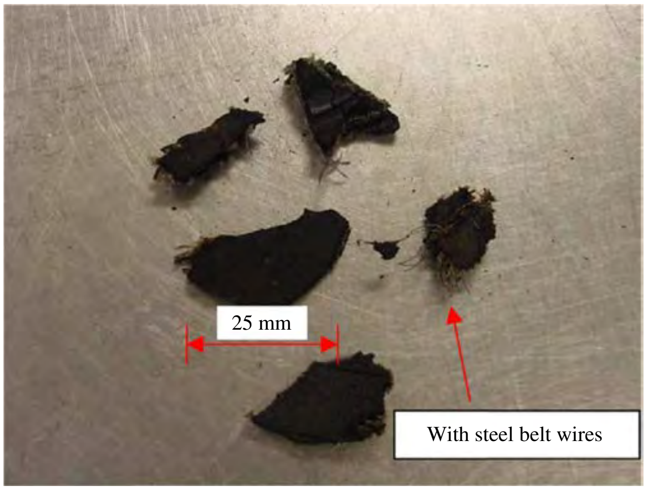
Type	Crumb Rubber, %	Thermal Conductivity, W/m.K	Heat Transfer, W/h	Heat Resistivity, m^2/KW
Control	0	0.531	1514	0.19
No. 6 (3.36 mm)	10	0.443	1263	0.23
	20	0.295	841	0.34
	30	0.241	687	0.41
No. 25 (0.707 mm)	10	0.290	827	0.34
	20	0.275	784	0.36
	30	0.267	761	0.37
No. 6 + No. 25	10	0.313	893	0.32
	20	0.304	867	0.33
	30	0.296	844	0.34

After Sukontasukkul (2009).
W/m.K – 6.9335 BTU/hour-foot-˚F.

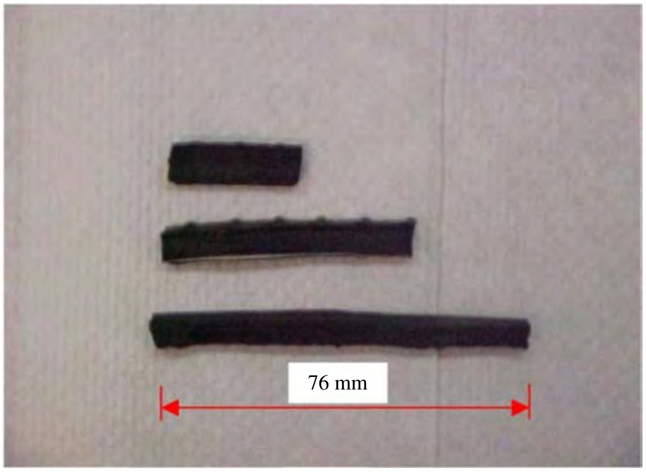
TABLE 25
ACOUSTICAL PROPERTIES OF PCC MIXES WITH CRUMB RUBBER

Material	Crumb Rubber, %	Frequency, Hz					
		125	250	500	1000	2000	4000
Control	0	23.0	11.5	6.8	24.5	9.1	20.1
No. 6 (3.36 mm)	10	23.0	12.0	12.1	31.5	17.0	25.0
	20	23.5	11.3	9.5	37.0	15.1	24.0
No. 25 (0.707 mm)	10	24.5	11.0	10.0	26.5	16.0	27.5
	20	24.5	11.3	9.3	29.0	23.5	27.1
No. 6 + No. 25	10	25.1	11.5	9.5	29.0	15.1	24.8
	20	25.5	12.2	13.5	30.1	20.3	30.0

After Sukontasukkul (2009).
Measurement was carried out in the following condition: temperature: 23.0 ± 2.0°C; pressure: 1013 ± 15 hPa; relative humidity: 50.0 ± 15.0%. Uncertainty of measurement: the uncertainty stated in the table is the expanded uncertainty obtained by multiplying the standard uncertainty by the coverage factor, $k = 2$. It has been determined in accordance with EA publication EA-4/02 ‘‘Expression of the Uncertainty of Measurement in Calibration” and ‘‘Guide to the Expression of Uncertainty in Measurement”. The obtained values lie within the assigned range of value with a probability of 95%.



(a) Waste tire chips



(b) Waste tire fibers

FIGURE 1 TDA chips and fibers used in Li et al. study (2004).

Air voids were slightly higher when the mixes included the tire byproducts.

Testing of the hardened concrete included measurements of compressive strengths, tensile strengths, and modulus of elasticity. Compressive strength was reduced between 35% and 47%, depending on the size and source of the tire fibers (Table 26). The strength decreased with the increasing length of tire fiber. This is contrary to the typical results seen for conventional fiber-reinforced concrete. It was noted that the longer tire fibers tended to agglomerate and be nonuniformly dispersed in the mix during vibration and compaction of the fresh PCC. There was a corresponding decrease in modulus. The range of the decrease was between 10% and 22%.

The load and displacement of the samples during the splitting tension testing showed that the concrete with the tire fibers had a somewhat lower peak load, but a significant increase in the area under the load-displacement curve. This was an indication of an improvement in the toughness of the mix. That is, the tire fibers had the capability of absorbing dynamic loads and resisting crack propagation.

Finite element modeling was used to show that the tensile stress concentrations were significantly smaller in the tire fiber mixes than either the control or the tire chip. Retaining the steel in the tire fibers increased the stiffness of the tire byproduct used and was considered a desirable property. A restriction on the length (i.e., aspect ratio) to the 2 in. length to maximize benefits and minimize the agglomeration of the tire fibers was recommended.

Crumb Rubber and Tire Derived Aggregate in Mortars

Yilmaz and Degirmenci (2009) conducted research in Turkey to evaluate the combined use of portland cement (10%),

TABLE 26
FRESH AND HARDENED TDA FIBER PCC RESULTS

Waste Tire Type	TDA Fiber Dimensions, in.	PCC Properties				
		Slump, in.	Air content, %	Compressive strength, psi	Modulus of elasticity, psi	Tensile strength, psi
Control PCC	NA	5.0	4.5	5,656	5,076	464
Mixed Truck and Car Tire Chips *With* Steel Belt Wires	1 x 1 x 0.2	4.9	4.1	3,336	4,206	348
	2 x 0.2 x 0.2	6.0	5.0	3,626	4,496	377
Car Tire Fibers *With* Steel Belt Wires	2 x 0. 2 x 0.2	5.8	5.0	3,336	4,351	363
Car Tire Fibers *Without* Steel Belt Wires	1 x 0.2 x 0.2	5.8	5.0	3,336	3,916	334
	3 x 0.2 x 0.2	5.5	5.0	3,046	4,148	305
	5 x 0.2 x 0.2	6.0	5.0	2,901	4,134	334

After Li et al. (2004).
NA = not available.

Class C fly ash (60% and 70%), and crumb rubber (20% and 30%) for use as an acceptable mortar. The unit weight decreased and water absorption increased with increasing crumb rubber percent. The crumb rubber increased the water to cementitious material ratio.

Hardened property results showed that the compressive strength of the mixes decreased with increasing crumb rubber content. Compressive strengths were only slightly influenced by the TDA size (Table 27). The combined use of the fly ash and the crumb rubber resulted in less of a decrease in strength. The optimum content of 20% crumb rubber, 10% fly ash, and 70% cement provided the best properties for mortars. The flexural strength of the mix was improved with the use of crumb rubber at 20%, but was decreased at 30% crumb rubber. Figure 2 shows the distribution of the particles in the PCC.

Tire Derived Aggregate in Portland Cement Concrete

A California Integrated Waste Management Board (Cheng 2006) conducted a study on the use of shredded tires in a demonstration slurry cutoff wall (i.e., moisture barrier) in Gridley, California. The function of the cutoff wall was to form a seepage barrier to stop the migration of water through an impervious barrier. The mix design for the slurry evaluated the use of TDA from 2 in. by 2 in., to 8 in. by 8 in. in sizes. Laboratory mixes were prepared in a drum mixer.

A medium scale test was conducted by constructing two slurry walls: one without TDA and one with TDA. Initial testing showed that the larger size particles would not produce an acceptable mix because the slump was difficult to measure and samples for compression testing could not be

TABLE 27
MIX VARIABLES AND HARDENED CRUMB RUBBER PCC PROPERTIES

Mix	Crumb Rubber Range of Sizes, mm	Crumb Rubber, %	Cement, %	Fly Ash, %	W/(PC+FA)	Dry Unit Weight, kg/m^3	Water Absorption, %	Compressive Strength 28 days, MPa	Flexural Strength 28 days, MPa
Group I	0 to 0.25	20	10	70	0.55	1,078	30	4.63	0.94
	0.25 to 0.50				0.50	1,192	26	4.81	1.17
	0.50 to 1.0				0.46	1,200	24	4.84	1.40
Group II	0 to 0.25	30	10	60	0.63	1,011	29	3.94	0.93
	0.25 to 0.50				0.57	1,096	27	4.37	1.05
	0.50 to 1.0				0.52	1,144	25	4.83	1.11

After Yilmaz and Degirmenci (2009).
1 MPa = 145.0377 psi.

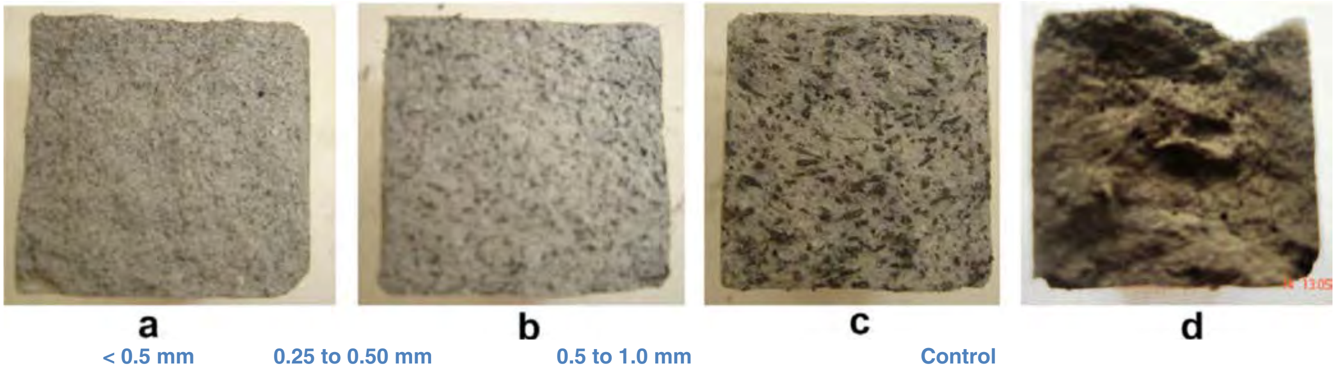


FIGURE 2 Distribution of crumb rubber in PCC mixes evaluated by Yilmas and Degirmenci (2009).

fabricated. The minus 2 in. square particle size was selected for use in the project. Both mixes were tested for permeability and compressive strength. The results showed that the TDA slurry had acceptable properties. The final mix design provided to the contractor was 67% soil, 3% bentonite clay, 5% cement, and 25% tire chips.

Field testing of the slurry used a Kelly ball to measure workability because the tire chips tended to stack in the slump cone, which limited the usefulness of this test. The permeability testing was conducted on oversized cylindrical specimens (12 in. diameter) using ASTM D5084 to determine that the requirements of the permeability did not to exceed 5×10^{-7} cm/s.

The full-scale placement was done with standard equipment. The contractor did not notice a significant difference in placing the TDA slurry compared with conventional slurries. Lessons learned included:

- On-site truck dumps of to-be-mixed TDA resulted in TDA particles being spread around the construction site, which then had to be cleaned up.
    - Suggested that the TDA be pre-measured and bagged for use on site.
- Limit the backfill of the trench to 1 ft below the surface.
    - Tire particles tended to protrude from the mix and may be a problem with the cover materials.
- Clay can be used to finish filling the last 1 ft of the trench.

Zheng et al. (2008) evaluated the damping characteristics of rubberized PCC, which is important for dynamic calculations made during the design phase of a project. The damping characteristics were determined for a simply supported beam subjected to a flexural free vibration. Materials used for the PCC beams tested in this study were Type I portland cement, river sand, and a ground rubber with 80% of the particles with a size of 2.36 mm. The coarse ground rubber (tire chips) evaluated had sizes ranging from 15 to 40 mm with exposed steel belt strands and rubber contents of 15%, 30%, and 45% by volume.

Fresh PCC properties showed that the slump decreased with increasing ground rubber content. The PCC mixtures with the finer ground rubber were more workable than those with the large size ground rubber. The unit weights, as expected, decreased with increasing TDA content.

Hardened properties were determined for modulus of elasticity (ASTM C469) using the chord modulus approach. The modulus decreased with increasing rubber content (Table 28). The mix with 15% of the fine ground rubber had the least

TABLE 28
DIFFERENCE OF MODULUS BETWEEN SCRAP TIRE FIBER CONCRETE AND CONTROL CONCRETE

Item	Control PCC (1)	PCC with Fine Ground Rubber (2)			PCC with Coarse Ground Rubber (3)		
		15%	30%	45%	15%	30%	45%
Dynamic Modulus of Elasticity, GPa	43.7	41.2	35.2	31.2	35.4	36.5	32.8
Ratio of Dynamic Modulus Change[a], %	—	5.72	19.45	28.60	18.99	16.48	24.94
Static Modulus of Elasticity, GPa	31.8	27.1	24.10	22.3	23.10	24.30	22.1
Ratio of Static Modulus Change[b], %	—	14.78	24.21	29.87	27.36	23.58	30.50

After Zheng et al. (2008).

[a] Ratio of dynamic modulus change = [(2) – (1)]/(1) x 100% for fine TDA or [(3) – (1)]/(1) x 100% for coarse TDA.

[b] Ratio of static modulus change = [(2) – (1)]/(1) x 100% for fine TDA or [(3) – (1)]/(1) x 100% for coarse TDA.

TABLE 29
COMPARISON OF DYNAMIC MODULUS BY DIFFERENT METHODS USING GROUND RUBBER CONCRETE

PCC Mix	Elastic Wave Method, GPa	Beam Element Method, GPa	Difference, %
Control	43.7	41.7	4.54
Fine TDA, 15%	41.2	38.2	7.21
Fine TDA, 30%	35.2	32.6	7.30
Fine TDA, 45%	31.2	28.1	9.89
Coarse TDA, 15%	35.4	32.6	7.89
Coarse TDA, 30%	36.5	33.5	8.12
Coarse TDA, 45%	32.8	29.7	9.32

After Zheng et al. (2008).

reduction in modulus of any of the ground rubber PCC mixes. The elastic wave modulus was also determined for the beams. Both testing configurations produced similar values for the modulus (Table 29). Ground rubber mixes had lower moduli values than the control PCC.

The beams were also used to determine the percent damping (Table 30). Higher percentages of TDA increasingly improved the damping potential. Damping increased with increasing amplitude (acceleration) and also increased with the concentration of the ground rubber in the mixes. The magnitude of the damping was dependent on the size of the crumb rubber.

Results showed a difference of about 37.4% between dynamic and static modulus for the control PCC mixes (dynamic > static). When ground rubber was used, the difference increased to about 50%. Use of the ground rubber significantly improved the damping ratios with the coarse ground rubber at 40% providing the most damping. The relationship between damping characteristics and ground rubber percent is nonlinear. The optimal percent would be less than 30% to optimize both the static and dynamic properties. Damping properties of the ground rubber mixes were more sensitive to vibrations response amplitude than the control mix.

Ganjian et al. (2009) conducted research using Iranian standard materials. Materials used in the study were crushed siliceous aggregates, portland cement, super plasticizers, and coarse TDA and crumb rubber powder. The scrap tire materials were used as a cement replacement. At 5% replacement, the compressive and tensile strengths were only slightly reduced compared with the control. For this use of scrap tires, both the permeability and water absorption of the mixes increased with time and increasing percent of rubber.

Oikonomou and Mavridou (2009) conducted research in Greece that evaluated the ability of a fine, primary two-sized crumb rubber (median diameter of 0.3 mm) to enhance PCC resistance to chloride ion penetration. Materials in the study were portland cement, siliceous sand, and crumb rubber with a gradation close to the sand, and a range of admixtures, superplasticizer, SBR latex, and 60% anionic bitumen emulsion. Water to cement ratios were a constant except for two of the mixes.

TABLE 30
DAMPING RATIO FOR PCC MIXES WITH TDA

Test no.	Control		Fine Ground Rubber, 15%		Fine Ground Rubber, 30%		Coarse Ground Rubber, 45%	
	Amplitude acceleration, mg	Damping, %	Amplitude acceleration, mg	Damping, %	Amplitude acceleration, mg	Damping, %	Amplitude acceleration, mg	Damping, %
Fine TDA								
1	8.9	0.45	8.3	0.62	12.1	0.75	10	0.7
2	14.3	0.54	15.7	0.73	18	0.88	21.2	0.98
3	19.4	0.61	25.1	0.85	27.3	1.05	23.7	1.01
4	31.2	0.74	30.5	0.95	34.8	1.17	33.2	1.14
5	40.2	0.74	40	1.12	42.3	1.42	42.1	1.42
Coarse TDA								
1	8.9	0.45	12	0.68	9.1	0.89	9.8	0.85
2	14.3	0.54	17.6	0.78	17.3	1.41	20.8	1.39
3	19.4	0.61	32.6	0.93	33.2	1.45	22.3	1.49
4	31.2	0.74	40.2	1.16	38.1	1.61	31.3	1.55
5	40.2	0.74	45	1.38	40.5	1.74	41.5	1.67

After Zheng et al. (2008).
1 g = 32.17405 ft/s^2.

TABLE 31
PROPERTIES FOR PCC WITH ONLY CRUMB RUBBER AT VARIOUS CONCENTRATIONS

Properties	Mixture Properties						
Crumb Rubber, %	0.0	2.5	5.0	7.5	10.0	12.5	15.0
Specific Density, gm/cm^3	2.23	2.11	2.03	1.94	1.84	1.76	1.68
Compressive Strength, MPa	40.75	30.92	21.33	16.15	11.12	9.70	8.60
Flexural Strength, MPa	9.00	7.50	5.70	5.25	4.30	3.50	2.90
Absorption of Water by Immersion Under Vacuum, %	8.81	8.25	7.37	7.25	7.03	6.87	6.79
Charge Passed, Coulombs	6,103	5,265	5,080	4,551	4,257	3,956	3,915

After Oikonomou and Mavridou (2009).
1 MPa = 145.0377 psi.

All laboratory tests were conducted for mortar samples. All samples were moist cured for 28 days at 68°F at greater than 95% humidity. Workability (flow) of the mortar decreased with the increasing percent of rubber. Compressive strength, flexural strength, and modulus decreased with increasing crumb rubber content (Tables 31 and 32). Water absorption decreased with increasing crumb rubber percents and at the same resistance as chloride ion penetration increased. The mix with 12.5% crumb rubber had the least reduction in compressive strength, although the reduction was still significant. The next best combination of admixture and crumb rubber was with the bituminous emulsion. Conclusions were that crumb rubber concrete would be a good product in applications needing a high resistance to chloride penetration but with a minimal strength requirement.

Kaloush et al. (2005) conducted a study where the objectives of the Arizona research were to evaluate the properties of crumb rubber concrete and work towards the eventual development of a specification for nonstructural and low loading conditions. Materials included testing compression and three-point bending flexural testing. The crack mouth opening deformation was measured using the three-point beam with an initial notch of 0.5 in. Coefficient of thermal expansion was determined using AASHTO TP60-00. Indirect tensile stress was determined using disc specimens with the thickness of about 1 in. with a 4 in. diameter. The ability of the mixes to deform (strain) improved by 39% to 116% when rubber was included in the mix. Findings were that the crumb rubber in the concrete improved the ductility and toughness compared with the control mixes. Although the tensile strength decreased with increasing rubber content, so did the ability of the mix to deform before failure. Rubber concrete was more resistant to length changes owing to temperature changes.

Portland Cement Concrete Pavements

Hernandez-Olivares et al. (2007) conducted research in Spain that evaluated the use of the Westergaard equations to calculate the minimum thickness for tire rubber-reinforced concrete pavements. Theoretical results indicated that the dynamic loading of a concrete beam can be used to estimate the flexural stiffness and fatigue life. The analyses indicated that tire byproducts in PCC slabs on an elastic base result in a slight increase in the design thickness (about 3.5%).

TABLE 32
PROPERTIES FOR PCC WITH A RANGE OF ADDITIVES

Properties	Mixture					
Crumb Rubber, %	0.0	12.5	0.0	12.5	0.0	12.5
Super Plasticizer, %	1	1	0	0	0	0
Latex, %	0	0	5	5	0	0
Bituminous Emulsion, %	0	0	0	0	5	5
Specific Density, gm/cm^3	2.26	1.79	2.18	1.70	2.21	1.75
Dynamic Modulus of Elasticity, GPa	42.48	15.37	35.20	11.38	39.53	13.47
Compressive Strength, MPa	43.70	13.68	35.83	8.95	42.89	12.79
Flexural Strength, MPa	10.26	4.50	8.36	3.20	10.11	4.10
Absorption of Water by Immersion Under Vacuum, %	7.91	6.25	6.79	4.92	6.96	5.01
Charge Passed, Coulombs	5,910	3,640	5,334	2,824	5,208	2,692

After Oikonomou and Mavridou (2009).
1 MPa = 145.0377 psi.

BOUND APPLICATIONS—ASPHALT CEMENT AND CONCRETE

Four main categories for using TDA or crumb rubber in asphalt binders and concrete were found in the literature:

- CRM asphalt binders
- Crumb rubber and TDA fiber-modified HMA for noise reduction
- Crumb rubber and TDA-modified HMA
- CRM asphalts in surface treatment applications.

It is important that the reader note that there was no standard use of terms for scrap tire use in asphalt applications. For example, VSS (2010a) uses the term "asphalt rubber" to mean styrene-butadiene-styrene latex polymer BASF NX1118. For this section, CRM will be used to mean scrap tire rubber with steel or fabric removed and in small aggregate shapes typically less than 0.5 in. TDA will be used for the larger size shape scrap tire byproducts.

CRM asphalt binders can be produced using one of two wet processes (Santucci 2010). The original definition of CRM binder, called asphalt rubber, is defined in ASTM 6114 as "A blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted with the asphalt sufficiently to cause swelling of the rubber particles." Typical ranges of CRM are 18% to 22%. Extender oils may or may not be used to reduce the viscosity and promote workability.

The original *wet process* requires that the blending and reaction chamber equipment be added to the on-site HMA plant equipment. This type of configuration limits the production rate of CRM HMA to the production rate of the blending equipment producing the CRM binder. It can be noted that the crumb rubber can substantially dissolve in the asphalt with sufficient time. The extent of the asphalt–rubber interactions will be dependent on the asphalt cement chemistry, time allowed for interaction (blending), and temperature.

In the middle 1980s, terminal blending of the CRM and asphalt started to be produced by introducing the crumb rubber into the asphalt as it is loaded at the refinery or blending terminal and shipped to the HMA plant as a finished product (Paramount Asphalt 2008). Initially, the percentage of CRM was kept to about 10%; however, several projects have been placed recently using between 15% and 18% CRM. Terminal blending also allows CRM binder to be provided to multiple job sites because the production is not limited to equipment located at one HMA plant. Terminal blend CRM binders use a fine mesh crumb rubber to promote the asphalt–rubber interaction and shorten the required interaction time.

The *dry process* of using crumb rubber and larger TDA particles in HMA applications use the byproduct as an aggregate and consider there is only a limited interaction between the crumb rubber and/or TDA (FHWA 2010). The performance of highway applications using the dry process has been mixed.

Crumb Rubber and Tire Derived Aggregate-Modified Asphalt Binders

Lee et al. (2008) studied the influence of CRM reaction times on binder properties and molecular size changes using gel permeation chromatography. Seven reactions times (5, 30, 60, 90, 120, 240, and 480 minutes) at 177°C with 10% crumb rubber by weight of binder using a performance grade (PG) 64-22 virgin asphalt were blended with a high shear radial flow mixer. The 30-min reaction time was the reaction time used in field applications in South Carolina. The unmodified asphalt binder was also subjected to the same mixing times and temperatures so that the influence of heat hardening of the asphalt could be factored out of viscosity changes resulting from the crumb rubber.

Gel permeation chromatography analysis was used to quantify large molecular size changes with reaction times because these sizes have been shown to have a good relationship to the aging characteristics of the asphalt cement. Molecular sizes increased with increasing aging and reaction times for both the unmodified, but aged, and the CRM-modified asphalt. That is, the inclusion of the CRM did not influence the aging characteristics of the virgin binder. The rheology testing showed little change in the PG maximum acceptable summer pavement temperature grading. Viscosities increased substantially up to 60 min of reaction time after which the viscosity was not significantly different.

MacLeod et al. (2007) used three grades of virgin binders (150-200 pen, 200-300 pen, and 300-400 pen) modified with one CRM with an average particle size of approximately 0.85 mm to evaluate the impact of the virgin asphalt grades on binder properties. A range of CRM concentrations in each of the virgin binders was evaluated for their influence on the Superpave binder properties and grading. Modified binders were mixed using a low shear mixer for 3 or 6 h at 180°C. The ability to store the CRM binders at elevated temperatures without separation was also evaluated.

Results showed that the true Superpave grades had increasingly wider ranges of in-service temperatures with increasing CRM concentrations (Table 33, 3 h blending; Table 34, 6 h blending). The maximum summer temperature increased by about 1.2°C to 1.5°C for each 1% of CRM. The low winter temperature was decreased by about 0.2°C for each 1% of CRM. The maximum percentage of 10% CRM in the binder was recommended because of the maximum allowable viscosity for workability (pumpability). This level of CRM would generally result in an increase in the maximum allowable summer temperature about 15°C above that of the virgin binder.

TABLE 33
SUPERPAVE RESULTS OF 200/300 ASPHALTS MODIFIED WITH 0% TO 15% CRUMB RUBBER MATERIALS WITH 3.0 HOUR MIXING TIME AT 180°C

Testing	Sample No.					
	1441	2166	2165	2200	2150	2147
RM content in 200/300 pen asphalt, %	0	6	9	10.5	12	15
180°C mixing temp., mixing time, hours	0	3	3	3	3	3
Standard Tests						
Penetration at 25°C, 100 g/5 s, dmm	260	162	140	125	114	94
Softening point, °C	37.2	44	47	49.3	52.2	56.9
Flash point, °C	261	290	285	271	—	—
Superpave Tests						
Original binder properties						
Viscosity at 135°C, MPa·s	200	600	996	1,423	3,943	7,890
Dynamic shear (*G**/sin), kPa min. 1.0 kPa	1.02	1.05	1.02	1.09	1.01	1.09
Temperature, °C	53	63	67	69	74	82
Rolling Thin Film Oven Test (RTFOT)						
RTFOT mass loss, %	–0.844	–0.880	–0.760	–0.660	–0.750	–0.470
Dynamic shear (*G**/sin), kPa min. 2.20 kPa	2.2	2.46	2.25	2.35	2.21	2.34
Temperature, °C	54	60	65	65	69	73
Pressure Aging Vessel (PAV) Residue						
PAV aging temperature, °C	90	100	100	100	100	100
Dynamic shear (*G**/sin), kPa max. 5000 kPa	3,490	4,192	4,331	3,708	4,372	4,543
Temperature, °C	13	10	7	10	7	4
Creep stiffness, *S*, at 60 s max. 300 MPa	278	254	212	214	208	194
M value at 60 s min. 0.300	0.32	0.307	0.306	0.308	0.305	0.309
Temperature, °C	–26.0	–27.0	–27.0	–28.0	–28.0	–29.0
T critical °C	–38.0	–39.1	–39.2	–39.9	–39.2	–40.7
Superpave grading	PG52-34	PG58-34	PG64-34	PG64-34	PG64-34	PG70-34
True Superpave grading	PG53-36	PG60-37	PG65-37	PG65-38	PG69-38	PG73-39
High–low temperature spread using bending beam rheometer low-temperature parameter, °C	89	97	102	103	107	112
High–low temperature spread using critical cracking temperature, °C	91	99	104	105	108	113

After MacLead et al (2007).
High–low temperature spread is the range of temperature represented by the PG grade. PG53-36 has a high critical temperature of 56°C and a low critical temperature of –36°C; therefore, the range is 91°C.

VanTimmeren (2009) reported on the initial development of pelletized asphalt-lime-rubber to provide for the easy use of crumb rubber asphalt without having to blend on-site. The pellets can be added at the reclaimed asphalt pavement (RAP) feed in HMA plants. The lime used was at the same percentage typically used as an anti-strip in HMA.

Paramount Asphalt (2008) noted that terminal blend technology has been around since the mid-1980s. In this process, the crumb rubber was blended into the asphalt binder at the asphalt terminal or refinery and shipped to the HMA plant as a finished product. Percentages as high as 25% have been used, but a minimum of 10% was typically used. A laboratory study conducted in 1998 at the University of Nevada, Reno, compared terminal blend HMA with the conventional on-site CRM asphalt process. No statistical difference was seen between the two methods of producing the rubber-modified binders for mix fatigue and rutting. A field evaluation of the performance of the terminal blend mix showed very good resistance to thermal cracking, moisture damage, and rutting.

Xiao et al. (2009) evaluated binder property changes when using warm mix asphalt (WMA) products to reduce the mixing and compaction temperatures. WMA products allowed for lower production and placement temperature, which is important in reducing the emissions. A limited number of CRM HMA samples were prepared and used to verify the binder properties used to indicate fatigue life to that of the WMA CRM HMA mixes.

Materials used in the project were one virgin asphalt (PG64-22), one minus 40 mesh crumb rubber, and two sources of aggregates (granite, schist) meeting a 12.5 mm gradation. WMA products used were Asphamin (zeolite) and Sasobit (paraffin). The zeolite contained about 21% crystalline water by weight, which produces fine foamed asphalt when mixed with the hot asphalt. The paraffin was a long chain

TABLE 34
SUPERPAVE RESULTS OF 200/300 ASPHALTS MODIFIED WITH 0% TO 15% CRUMB RUBBER MATERIALS WITH 6.0 HOUR MIXING TIME AT 180°C

Testing	Sample No.					
	1441	2166	2165	2200	2150	2147
CRM content in 200/300 asphalt, %	0	6	9	12	15	0
180°C mixing temp., mixing time (h)	0	6	6	6	6	0
Standard Tests						
Penetration at 25°C, 100 g/5 s, dmm	260	178	145	118	94	260
Softening point, °C	37.2	42.7	46.2	49.9	58.8	37.2
Flash point, °C	261	283	287	283	283	261
Superpave Tests						
Original binder properties						
Viscosity at 135°C, MPa·s	200	593	814	3257	8533	200
Dynamic shear (G*/sin), kPa min. 1.0 kPa	1.02	1.05	1.03	1.01	1.04	1.02
Temperature, °C	53	61	67	73	82	53
Rolling Thin Film Oven Test (RTFOT)						
RTFOT mass loss, %	–0.844	–0.630	–0.710	–0.810	–0.460	–0.844
Dynamic shear (G*/sin), kPa min. 2.20 kPa	2.2	2.29	2.4	2.36	2.38	2.2
Temperature, °C	54	60	63	67	74	54
Pressure Aging Vessel (PAV) Residue						
PAV aging temperature, °C	90	100	100	100	100	90
Dynamic shear (G*sin), kPa max. 5000 kPa	3490	3727	4702	3486	2989	3490
Temperature, °C	13	10	7	7	7	13
Creep stiffness, *S*, at 60s max. 300 MPa	278	265	240	193	171	278
M value at 60 s min. 0.300	0.32	0.302	0.312	0.319	0.307	0.32
Temperature, °C	–26.0	–28.0	–28.0	–27.0	–28.0	–26.0
T critical, °C	–38.0	–39.2	–40.2	–39.5	–40.0	–38.0
Superpave grading	PG52-34	PG58-34	PG58-34	PG64-34	PG70-34	PG52-34
True Superpave grading	PG53-36	PG60-38	PG63-38	PG67-37	PG74-38	PG53-36
High–low temperature spread using bending beam rheometer low-temperature parameter, °C	89	98	101	104	112	89
High–low temperature spread using critical cracking temperature, °C	91	99	103	106	114	91

After MacLeod et al. (2007).
High–low temperature spread is the range of temperature represented by the PG grade. PG53-36 has a high critical temperature of 56°C and a low critical temperature of –36°C; therefore, the range is 91°C.

aliphatic hydrocarbon obtained from coal gasification using the Fischer-Tropsch (FT) process.

Superpave binder testing showed the viscosity at 135°C increased with the addition of the CRM, however, both WMA products reduced the viscosity when compared with the CRM without the WMA. The anticipated high summer pavement temperature (64°C) showed CRM significantly increased the stiffness of the binder. The binders with the WMA products showed an increase in the maximum high temperature of 27% (Asphamin) and 41% (Sasobit). Stiffness at the intermediate temperature (25°C) showed a lower stiffness for the CRM binders compared with the unmodified PG64-22. This indicated a more flexible binder at these temperatures than the unmodified binder, which can result in a reduction in fatigue cracking of the pavements. The stiffness at the cold temperature (–12°C) was significantly lower for the CRM mixes with either of the WMA products. The WMA CRM binders had stiffness values that were lower than the CRM-only binder by 36% (Asphamin) and 76% (Sasobit).

Beam fatigue testing was used to verify the impact of the WMA CRM and CRM-only binder results on the mix fatigue properties (20°C, 10 Hz sinusoidal loading frequency). In general, mixes using CRM showed improved fatigue resistance. The large variability in the results made it difficult to evaluate the influence of the WMA products.

Crumb Rubber and Tire Derived Aggregate-Modified Hot Mix Asphalt for Noise Reduction

Sacramento County (1999) reported on the six-year retention of noise reduction for Sacramento County projects on CRM HMA pavements placed on an expressway. The noise reduction was maintained over six years, primarily in the 500 to 4,000 Hz frequency bands (Table 35).

TABLE 35
SUMMARY OF SACRAMENTO COUNTY NOISE STUDY WITH TIME

Roadway	Pavement Type	Time After Paving Completed	Change in Noise Levels, dB L_{eq}
Alta Arden Expressway	Rubberized Asphalt	1 month	–6 dB
		16 months	–5 dB
		6 years	–5 dB
Antelope Road	Rubberized Asphalt	6 months	–4 dB
		5 years	–3 dB
Bond Road	Conventional Asphalt	1 month	–2 dB
		4 years	0 dB

After Sacramento County (1999).

WSDOT (2005) evaluated various pavement surfaces for their ability to mitigate tire–pavement noise. WSDOT noted that the sources of traffic noise help explain why noise can be reduced in some areas by surface type selection. Cars emit noise mostly from zero to 2 ft above the pavement surface from the vehicle–pavement interaction. Typical levels of noise are between 72 and 74 dB(A) at 55 mph at a distance of 50 ft. Medium sized trucks emit the most noise between 2 and 5 ft above the surface as a result of vehicle–pavement interactions and engine exhaust noise. Typical levels of noise are between 80 and 82 dB(A) at 55 mph and a distance of 50 ft. Heavy trucks emit the most noise between 6 and 8 ft above the surface from a combination of vehicle–pavement interactions, engine noise, and exhaust stack noise (about 12 to 15 ft above the surface). Typical noise levels are between 84 and 86 dB(A) at 55 mph and a distance of 50 ft. The influence of surface type selection will depend on the number and type of vehicles as well as the location of the noise receptor.

WSDOT started the documentation of noise reduction for various pavement surfaces for potential consideration of surface design as a source of noise mitigation. To have surface design considered, three objects needed to be met. The first was that the DOT needs to certify that initial noise reduction can be achieved; second, that the noise reductions had a certain life span; and third, that the DOT had to commit to replacing the pavement with one of similar noise quality in the future. All of these requirements require documented proof.

Phase one of the study was started in 2005. A summary of WSDOT pavements indicated that a range of benefits and disadvantages could be obtained with different surfaces (Table 36). Dense graded HMA tended to be quieter than average when first constructed and the sounds were at lower and less objectionable frequencies. These pavements generally maintained these characteristics throughout the life of the pavement. Open graded and rubber asphalts showed better initial reductions in noise but had difficulty in maintaining the reduction because of climate-related factors such as surface sanding and studded tire wear in winter conditions.

Freitas and Inacio (2009) evaluated the characteristics of various gap graded pavements with different asphalt using cores tested in a laboratory sound tube (Kundt's tube). In addition to testing the cores, two types of rubberized asphalt mixtures were prepared and tested in the laboratory. The tire-surface noise is one component of the noises produced by vehicles. At speeds between 40 km/h and 110 km/h the tire-surface noise was the most prominent. The characteristics of the pavement that influence noise were aggregate gradation, texture, porosity, age, stiffness, and distresses.

Porous surfaces were considered desirable for their ability to absorb noise. Porous surfaces can reduce sound by up to

TABLE 36
RESULTS REPORTED FOR WASHDOT NOISE STUDY (2005)

Pavement Option	Initial Noise—New Pavement			Long-Term Noise			Pavement Lifespan (life to removal)	Long-Term Pavement Cost
	Sound quantity (decibel change from average)	Dominant frequency or pitch	Rating	Sound quantity (decibel change from average)	Dominant frequency or pitch	Rating		
Open Graded Asphalt	−2 dB	Lower	Good	0 to −2 dB	Middle/ Higher	Fair/Poor	Short (4 to 10 years)	High
Dense Graded Asphalt	−1 dB	Lower	Good	0 to −1 dB	Lower	Fair	Medium (14 to 18 years)	Moderate
Concrete	0 to +2 dB	Depends on surface finish	Fair	Depends on studded tire damage	Higher	Poor	Long (40 to 50 years)	Moderate
Rubber Asphalt	(specific dB comparison unavailable)	Lower	Good	Unknown	Middle	Fair	Nighttime temperatures restrict material placement	High

Source: WSDOT (2005).

6 dB(A) compared with typical dense graded HMA. In porous pavements, sound waves entered the upper layer of the surface and were partially reflected and partially absorbed. The absorption of the sound energy was the result of the viscous losses as the pressure wave pumps air in and out of the voids and the thermal elastic damping. Characteristics that influence absorption, other than porosity, included thickness of the porous layer, flow resistivity that is a function of the aggregate gradation, and the angle of incidence of the sound waves on the surface.

Mixes in the study were gap graded mixes with medium air voids (18%) and low air voids (5%). The impedance tube method was used to measure noise absorption. In this test method standing waves were created within the tube using a loudspeaker fed with sound waves (pure tones, sine wave sweeps, etc.) that contains the HMA sample. The pure tone sounds measured the maximum and minimum sound pressure in the tube using a microphone that can be moved up and down the inside of the vertically positioned tube. A newer method used a two microphone arrangement that could measure the sound absorption characteristics obtained from the frequency response between the microphones.

Typical absorption curves (frequency vs. sound) were characterized by the dB value where the absorption curve reaches the first of two maximums and was related to the porosity and flow resistivity of the absorbing material. The frequency at which the measured absorption curve reached it first maximum and is a function of the layer thickness and tortuosity of the material also needs to be included in the characterization. The normal incidence sound absorption was evaluated for various combinations of aggregate gradation, air voids (porosity), and asphalt with and without CRM.

Results for six samples for each set of mix variables were used to obtain average results. All cores were taken from the same slab. The noise measurements were very sensitive to small changes in the mix variables. The average of multiple results showed clear differences between low and medium air void levels. The higher voids clearly absorbed more sound than the lower voids. Changing the asphalt binder had little influence on sound absorption compared with the air voids.

Paje et al. (2010) used four test sections, each about 200 m in length, constructed near Barcelona, Spain, to study the acoustical characteristics of gap graded mixes with different binders. Binders used in the study included polymer-modified bitumen, crumb rubber (wet process), crumb rubber binder with 1% TDA (dry process), and crumb rubber binder with 2% TDA. The crumb rubber binder used 9% by weight of binder. The TDA was used to replace fine aggregates in the gap graded HMA. The macrotexture measurements were taken with a laser texture meter for all four sections. Noise measurements were made using the close proximity testing method.

Results showed that replicate sound measurements over the length of the test sections had good agreement, but the variability of the acoustical properties of the pavement within a section varied substantially. The variability was attributed to the localized variations in the mix properties that occur with normal construction and HMA production. The standard deviation of replicate measurements was less than 1 dB(A). Significant differences were observed between the different mixtures between 600 Hz and 1 kHz range. The dB(A) in this range showed a tendency to decrease with increasing rubber content. All test sections showed that the frequency spectrum exhibited a peak of around 800 Hz. The portion of the frequency spectrum between 1,250 and 3,500 Hz represents sound associated with air pumping and other mechanisms related to air flow in and around the tire tread patterns. This is the range of frequencies that are most improved with the use of TDA in the concrete.

Data indicated a strong influence by the lack of homogeneity of the pavement surface on the sound measurements; however, there was evidence of a linear relationship between texture and noise generation. Increasing texture within the test section corresponded to increasing noise. The authors recommend that the variability in the surface texture be considered when measuring pavement noise.

Crumb Rubber and Tire Derived Aggregate in Hot Mix Asphalt

The Utah DOT (2003) bulletin summarized the pros and cons of CRM HMA applications in Utah. The bulletin noted that terminal blend CRM binder was a more recent approach and could provide better incorporation of the crumb rubber into the asphalt binder. Beneficial properties attributed to the CRM HMA were improved durability of the surface course, reduction in noise of between 6 and 10 dB(A) compared with transversely tined concrete pavements, and the reduction of landfilling used tires. Benefits could only be achieved by states with a tire recycling plant; however, Utah did not have one at the time the bulletin was developed.

Limitations to the use of CRM binders in Utah were listed as:

- Air temperatures at the time of construction. Utah set critical temperatures as a minimum (70°F) and a maximum (>100°F), which would limit the construction season.
- Dense graded CRM HMA mixes were not stable when placed in layers of less than 2.5 in.
- A solid paving surface underneath was needed for good compaction.
- Mixed results were reported with long-term durability in cold freeze-thaw environments.
- Potential for debonding and raveling of the CRM HMA surface layer.
- Similar in performance to a polymer-modified asphalt but costs from 30% to 50% more.
- Needed to compete in the modified asphalt market without a special requirement for use.

Xiao et al. (2007) studied the influence of combinations of CRM, RAP, and RAP-CRM on rutting resistance. Materials included in the study were one aggregate source, and two RAP sources at various concentrations (0%, 15%, 25%, and 30%) that were blended with virgin asphalt to produce a combined final PG64-22 asphalt. The crumb rubber was obtained from two methods of grinding (ambient, cryogenic) used at one of four concentrations (0%, 5%, 10%, and 15%), and at one of three particle sizes (minus 1.4 mm, 0.60 mm, and 0.425 mm). A mechanical mixer was used to prepare the binders at a temperature of 350°F for 30 min reaction time using 700 rpms.

Results showed an increase in optimum binder content, theoretical maximum gravity, and bulk specific gravity of the compacted sample, all of which increased with crumb rubber content. Increasing the percentage of RAP when using the CRM binder increased indirect tensile strength and rut resistance. Increasing the crumb rubber content decreased the indirect tensile strength and creep stiffness but still resulted in increased rut resistance. Little to no difference was seen between the methods of grinding the crumb rubber or the sizes of crumb rubber particles used in this study.

Swiss researchers Partl et al. (2010) evaluated the moisture sensitivity of open graded mixes with CRM binders. Materials used to prepare two different open graded mixtures with one of two different coarse aggregates (basalt and basalt-expanded clay combination) (Table 37), and one CRM binder (20% by weight) of bitumen. Expanded clay coarse aggregate was used to enhance the acoustical properties of the mix.

Testing included typical volumetric mix properties and basic CRM binder properties. The coaxial shear test (CAST; Figure 3), developed at the Swiss Federal Laboratories for Materials Testing and Research in 1987, evaluated the lateral deformations of a cored sample with a donut shape under cyclic mechanical loading. Compacted samples were cored out in the center then cut into 50 mm slices so that the outer and inner diameter of the samples are 150 and 58 mm, respectively. The samples were glued to an outer steel ring and an inner steel core after being sealed with an epoxy resin to prevent the glue from entering the mix voids. The rings were used to constrain the sample from deforming in the lateral direction. A load was applied to the upper surface of the sample and the vertical deformation was recorded by measuring the downward movement of the internal steel core. The temperature and moisture condition of the sample could be simultaneously adjusted during load applications. Data collected from the dynamic testing was used to calculate the water (moisture) sensitivity index and temperature sensitivity index (Table 38). An elastic-based damage model was used to assess the fatigue resistance of the mixes.

Conclusions were that open graded mixes showed better fatigue resistance and reduced moisture damage compared with conventional HMA mixes. Improvements were attributed to both the CRM binder and increased asphalt content. Expanded clay slightly reduced moisture sensitivity and fatigue life, but improved the resistance to temperature changes.

Liseane et al. (2010) evaluated the influence of CRM binders on rut resistance with repeated simple shear testing at constant height (RSST-CH) and a loaded wheel tester in Brazil. Materials included ambient and cryogenic ground rubber and two virgin asphalts (50/70 and 35/50 pen grades) to prepare both terminal blends and field blend asphalts with various CRM contents (Table 39). Both dense and gap graded mixes were prepared and tested. Results indicated that CRM

TABLE 37
MATERIAL PROPERTIES FOR PARTL et al. (2010) STUDY

Testing	Properties for CRM Mixes		
	Mineral aggregates	Expanded clay	Design curve
Sieves (mm)	Cumulative Percent Passing, %		
12	80.12	19.88	100.0
8	73.09	19.21	92.3
4	22.75	1.29	24.0
2	12.86	0.06	12.9
0.42	6.54	0.04	6.6
0.177	5.06	0.04	5.1
0.074	4.60	0.04	4.6
Mix Properties			
Expanded Clay, % by weight	10		
CRM Binder Content, % by weight	10.1		
Rubber Content	20% on bitumen		
Air Void Content, %	15		
VMA, %	31.3		
VFB, %	52		
Binder Properties			
Penetration, 77°F, 0.1 mm	48		
Softening Point, °C	59		
Fraass Breaking Point, °C	–14		
Dynam ic Viscosity, 175°C, MP.s	1,800		
Elastic Recovery, 77 °F, %	70		

FIGURE 3 Coaxial shear test (CAST) for fatigue test (Partl et al. 2010): (a) sample cored out in the center then cut into 50 mm slices; (b) sealed with an epoxy resin; (c) samples are glued to an outer steel ring and an inner steel core; and (d) vertical deformation is recorded.

binders used to prepare gap graded mixes provided the best rut resistance, regardless of test method. The study was too limited to draw conclusions about the influence of the type of grinding or method of blending on the results.

Crumb Rubber-Modified Asphalts in Surface Treatment Applications

A number of pavement surface treatments can be prepared with CRM binders:

- Chip or cape seals
- Rubber emulsion asphalt slurry (REAS)
- Crack sealing.

Chip or Cape Seals

Chip seals are a commonly used preservation and/or maintenance highway application that consist of the spray application of the binder on a clean, dry pavement surface followed closely by an application of small, relatively one or two sized

TABLE 38
RESULTS FROM CAST DYNAMIC TESTING

Mix	Air Voids, %	Water Sensitivity Index*	Temperature Sensitivity Index*	Calculated Numbers of Cycles to Fatigue Failure	
				Wet	Dry
Open Graded Basalt Aggregate with CRM Binder	15	0.05	0.24	1,052,004	1,043,738
Expanded Clay and Basalt Aggregate with CRM Binder	15	0.41	0.16	1,047,738	1,031,405
Control	13	0.79	—	1,016,567	944,244
Control	20	1.67	0.35	1,021,024	833,804

After Partl et al. (2010).
*Lower index numbers indicate better performance.

TABLE 39
SUMMARY OF BINDER PROPERTIES FOR TERMINAL AND CONTINUOUS BLEND CRM BINDERS

Mix Variables	Binder Designations				
	ARTB1	ARTB2	ARCB1	ARCB2	Control
Asphalt Cement Grade	50/70 pen	50/70 pen	35/50 pen	35/50 pen	50/70 pen
Type of Grinding Process	Ambient	Ambient	Cryogenic	Ambient	NA
Concentration of Crumb Rubber, %	20	15	21	21	NA
Method of Modifying Binder	Terminal blend	Terminal blend	Continuous	Continuous	NA
Binder Results after RTFOT					
Change of Mass, %	0.3	0.3	0.9	0.2	0.3
Softening Point Elevation, °C	1.0	2.9	17.2	11.2	4.3
Penetration 25°C,100 g, 5 s, dmm	28.8	25.3	15.5	19.5	22.3
Apparent Viscosity, cP, 175°C	5,350	1,962	3,025	8,813	96
Retained Penetration, %	72	60.2	92.2	99	43.3

After Liseane et al. (2010).
NA = not applicable; RTFOT = rolling thin film oven test.

aggregates (chips). The chips are rolled to seat the chips in the binder. The surface may be finished with a fog seal to improve chip retention and to improve the color contrast for striping and marking. When a CRM binder chip seal is placed as an interlayer between an old pavement and a new overlay to reduce reflective cracking, it has been called a stress absorbing membrane interface. When the same product is used as a chip seal, it has been referred to as a stress absorbing membrane. There has been a proliferation of names for the CRM chip seals.

International Surfacing Systems (ISS 2007a,b), a major long-time supplier of CRM binders, prepared a guide specification for polymer-modified asphalt rubber (PMAR) stress absorbing membrane and PMAR stress absorbing membrane interlayer. This product used a polymer as well as the crumb rubber in the binder modification.

The ISS suggested specification indicates that the selection of the virgin asphalt grade would be modified with the crumb rubber based on climate (Table 40). The recommended CRM gradation is shown in Table 41. The combined polymer and crumb rubber modifications should be able to produce a modified binder that meets the requirements in Table 42. Suggested limits for PMAR binder can be found in Table 43.

TABLE 40
ISS GUIDE FOR BINDER GRADES
FOR SAMS AND SAMIS

Climate	PG Grading
Cold	PG52-28
Moderate	PG58-22
Hot	PG64-16 or PG70-10

After ISS (2007a,b).
Sam = stress absorbing membrane; SAMI = stress absorbing membrane interface.

Paramount Asphalt (2008) documented a project in Kern County in Bakersfield, California, which used a PG76-22PM (polymer-modified) and a PG70-22TR (10% tire rubber). The asphalt distributor truck was required to heat up PG70-22TR to 315°F from the delivery temperature of 285°F because the binder had cooled over the long haul distance. The aggregate used for the chip seal was a 4.75 to 9.5 mm chip, which was precoated with 0.25% PG64-10 for the tire rubber section and 0.5 to 0.7% for the PM section. The application rates were 0.32 to 0.35 gal/yd^2 for the binder and 17 to 19 lb/yd^2. The ambient temperature the morning the chip seals were placed started at 68°F. The construction of both sections showed no difference in handling between the two binders. The chip seal was fogged with 0.07 gal/yds^2 Topein C

TABLE 41
SAM AND SAMI CRM AND SBS POLYMER REQUIREMENTS

Sieve Size	Reclaimed Tire CRM Percent Passing	SBS Polymer Percent Passing
#8 (2.36 mm)	100	Per PMAR binder manufacturer
#10 (2 mm)	95–100	Per PMAR binder manufacturer
#16 (1.18 mm)	45–75	Per PMAR binder manufacturer
#30 (0.600 mm)	2–20	Per PMAR binder manufacturer
#50 (0.300 mm)	0–10	Per PMAR binder manufacturer
#200 (0.075 mm)	—	—

After ISS (2007a,b)
Sam = stress absorbing membrane; SAMI = stress absorbing membrane interface; SBS = styrene-butadiene-styrene; PMAR = polymer-modified asphalt rubber.

TABLE 42
RECOMMENDED CHEMICAL COMPOSITION OF CRM

Test	Minimum	Maximum
Acetone Extract	6.00%	16.00%
Ash Content	—	8.00%
Carbon Black Content	28.00%	38.00%
Rubber Hydrocarbon	42.00%	65.00%
Natural Rubber Content	22.00%	39.00%

After ISS (2007a,b).

product, which was a standard practice in Kern County. Both products were performing well with no noticeable difference between the two binder products.

Updyke (2009) placed terminal blend test sections in Los Angeles County to evaluate the impact of the existing pavement condition on the performance of the chip seal. Before placing the terminal blend binder chip seal, one existing pavement section used a fully repaired pavement section, the second section only received minor rut filling and edge restoration, and a third section used a pavement fabric. The terminal blend binder was a PG76-22TR that contained 15% crumb rubber. Certificates of compliance were furnished for each truck load of CRM binder. Precoated 9 mm chips were used for all sections. The terminal blend binder over the fabric was the only section that had some construction concerns. The hot CRM binder temperatures resulted in some wrinkling of the fabric and the fabric tended to adhere to the pneumatic roller tires. The quality assurance testing evaluated the aggregate and binder content.

Rubber Emulsion Asphalt Slurry (REAS)

Phetcharat and Kongsuwan (2003) evaluated asphalt emulsion (CSS-1h emulsion with 60% residual asphalt) with varying concentrations of crumb rubber (100% passing the 0.6 mm sieve) blended for 10 min in the laboratory at 400 rpm. The general conclusions were that REAS binder helped the flexibility of the surface treatment, which can be expected to be seen in field applications as a higher resistance to reflective cracking.

For quality control purposes, VSS (2010b) noted that they test the crumb rubber at least once for every 250 tons; a minimum of once per project. REAS consisted of a combination of passenger and heavy vehicle (high natural rubber) crumb rubber. The steel and fibers, which were considered contaminates, were removed before grinding. Contaminates were limited to no more than 0.01% wire and no more than 0.05% fabric by weight of CRM. The crumb rubber particle length was not more than 3/16 in. The quality control testing recommended by VSS indicates that:

- Gradation tests for every truck of CRM delivered to a project are appropriate.
- Asphalt modifier, a resinous high flash point aromatic hydrocarbon compound, be tested at least once every 25 tons.

Test results should be provided with certificate of compliance. Up to 3% talc may be used to prevent CRM from sticking together and bagged for use. The CRM needed to be dry so as to not generate foaming when introduced into asphalt and conform to ASTM D297.

Updyke (2009) investigated the use of terminal blend binders to produce an asphalt emulsion slurry seal. This process is a relatively new use for crumb rubber and has limited performance information. Five-year warranties were used to place five projects in California during 2002 and 2004. Four of the projects used asphalt rubber and the fifth used a terminal blend. Currently, all projects are performing well and are expected to meet their 10-year design life.

TABLE 43
SUGGESTED LIMITS FOR POLYMER-MODIFIED ASPHALT RUBBER BINDER

Test	Range	Hot Climate	Moderate Climate	Cold Climate
Apparent viscosity, 347°F (175°C) Spindle 3 @ 12 RPM: cps (ASTM D2669)	Min. Max.	1,500 3,500	1,500 3,500	1,500 3,500
Cone Penetration, 77°F (25°C), 150 g, 5 s; 1/10 dm (ASTM D217)	Min. Max.	15 40	20 70	25 100
Softening Point, °F (°C) (ASTM D36)	Min.	150°F (66°C)	140°F (60°C)	130°F (54°C)
Resilience, 77°F (25°C), % (ASTM D3407)	Min.	40	30	20

After ISS (2007a,b).
Hot climate average July max. @ 110°F (43°C).
Average January low @ 30°F (−1°C) or above.
Moderate climate average July max. @ 100°F (38°C).
Average January low @ 15°F–30°F (–9°C to –1°C).
Cold climate average July max. @ 80°F (27°C).
Average January low @ 15°F (–9°C) or lower.
Note: Certain climates may overlap the above, defined areas. When in doubt of the type of asphalt cement to utilize, always look to the lower penetration materials in the hot temperature range and the higher penetration materials in the low temperature range.

The Los Angeles County (2010) article noted that a REAS surface treatment was higher in cost than conventional slurries but was expected to have a 50% longer life, with lasting color contrast for striping and marking, and high skid resistance. The estimated usage of scrap tires were more than 78 tires per lane-mile. This surface treatment was included in the 1998 *Green Book* REAS specifications.

Pacific Emulsions, Inc. (2010) described the use of a tire rubber-modified slurry seal (TRMSS) where the emulsion contains 10% crumb rubber. The CRM binder was a terminal blend used to formulate a cationic quick set emulsion that works well with negatively charged aggregates. This was produced with a 60% asphalt emulsion and a slurry seal Type II aggregate application rate of 13.5 lb/yd^2. The rubber asphalt emulsion was used to produce a slurry seal using a Type I aggregate gradation applied at 9 lb/yd^2. Advantages of TRMSS emulsion were that the cationic formulation works in cool weather as well as hot weather.

Matthews (2008) reported on the use of REAS over a scrub seal with RAP chips, which was placed in southern California in May 2007. The PASS™ scrub seal was covered with the RAP chips, which was covered with the REAS to produce a cape seal (i.e., chip seal topped with slurry). Some localized traffic damage resulted during the hot summer climate. The contractor's initial conclusion was that the virgin binder used in the REAS binder may need to be harder to provide better durability at high temperatures.

Crack Sealing

Symons (1999) summarized the findings from the long-term pavement performance (LTPP) study on crack sealants. The findings of this large-scale research program showed that the most cost-effective sealants were those with rubberized asphalt placed in standard or shallow-recessed "band-aid" configurations, with the recessed method showing the overall best longevity. The rubberized crack sealant life can be expected to perform for 5 to 8 years.

Chehovits and Galehouse (2010) evaluated the environmental impact of various pavement preservation choices with wide ranges in typical quantities used and with a range of anticipated life extensions. Crack sealants and fills commonly use CRM products. Although crack sealants and fill had a lower anticipated life extension, they had the least impact on energy usage and greenhouse gas production (Table 44).

UNBOUND APPLICATIONS—BASES, EMBANKMENTS, AND FILLS

Barker Lemar (2005) in an Iowa study noted that an ASTM D6270 Type A TDA was used to construct an embankment with maximum 3-ft-thick layers. Additional gradation requirements were that less than 50% was passing the 37.5 mm sieve and less than 5% was passing the 4.75 mm sieve. TDA for Class II fills were used for infill or as road base subgrade where deeper depths are required. Compaction and placement needed to be done with layer thicknesses limited to between 3 and 10 ft. The authors recommended the TDA have a maximum of 25% passing the 37.5 mm sieve and a maximum of 1% passing the 4.75 mm sieve for bases and infills.

Shalaby and Khan (2005) reported on Canadian research that evaluated the use of only large TDA (whole sidewalls) as a base for an unpaved roadway surface for access to a new gravel pit. The project site was northeast of Winnipeg, Manitoba, Canada, and had a subgrade of mostly a boggy area with incoming water flow from a nearby golf course.

The subgrade in the area was black organic topsoil (brown clay with fine sand, silt lenses) with a plastic clay subgrade. This material had a high plasticity and ranged from soft at the near surface to firm at a depth of about 12 ft. A total of five layers of tire sidewalls (6 in. per layer) were used and the top layer was covered with 18 in. of granular surface. The sides of the base were also covered with the granular material. Sensors were placed in the base to measure frost penetration and showed that the depth of penetration was about twice that typically seen for the soil.

TABLE 44
PAVEMENT PRESERVATION PROCESS ENERGY AND GREENHOUSE GAS EMISSIONS PER SQUARE YARD

Process	Anticipated Life Extension, years	Area Energy and GHG		Annualized Energy and GHG	
		BTU/yd^2	lb CO$_2$/yd^2	BTU/yd^2/yr	lb CO$_2$/ yd^2/yr
Hot Mix AC	5 to 10	46,300	9	4,660 to 9,320	0.9 to 1.8
HIR	5 to 10	38,700	7	3,870 to 7,740	0.7 to 1.4
Chip Seal	3 to 6	7,030	0.9	1,170 to 2,340	0.15 to 0.30
Slurry Seal	3 to 5	3,870	0.4	968 to 1,935	0.10 to 0.20
Crack Seal	1 to 3	870	0.14	290 to 870	0.05 to 0.14
Crack Fill	1 to 2	1,860	0.25	930 to 1,860	0.13 to 0.25
Fog Seal	1	500	0.07	500	0.07

After Chehovits and Galehouse (2010).
GHG = greenhouse gas; HIR = hot in-place recycling.

TABLE 45
SUMMARY OF ENGINEERING PROPERTIES

Engineering Property	Range of Values	Remarks
Size, mm	50 to 300	—
Specific Gravity	1.06 to 1.15	—
Water Absorption Capacity, %	3.9	Glass belted
	9.4	Steel belted
Uncompacted Unit Weight, lb/ft^3	18.7 to 31.2	For 25–75 mm shred size
Compacted Unit Weight, lb/ft^3	37.5 to 43.7	For 25–75 mm shred size
Compressibility, %	40	At 400 kPa surcharge
Poisson's Ratio	0.3	—
Elastic Modulus, psi	159.6	75 mm size tire shreds
Internal Friction Angle, °	19 to 25	—
Cohesion Intercept, psi	1.2 to 1.6	—
Shear Modulus, psi	391.6	75 mm size tire shreds
Thermal Conductivity (W/m◦C)	0.20 to 0.30	At a density range of 0.58–0.79 mg/m^3
Permeability (cm/sec)	0.1	Compacted

After Shalaby and Khan (2005).
1 kPa = 0.145038 psi.
1 kg/m^3 = 0.062428 lb/ft^3.

Results showed that the TDA sections had lower insulation values, which was not expected. The lack of insulation value of the tire layer was attributed to the lack of moisture content, which would be frozen throughout the winter in the soil.

Laboratory testing was conducted so that a shredded tire road design model could be developed. A one-dimensional constrained compression testing was used to evaluate the resilience of the tire layer at high stress levels during cyclic loading and unloading. Tables 45 and 46 show the information required for the tire layer for a mechanistic–empirical pavement design approach. A Poisson's ratio of 0.3 was assumed. The one-dimensional compressibility of the tire layers were predicted using three equations:

The first equation was used to determine compressibility of the TDA:

$$\delta = \lambda H \sigma_z$$

Where:

δ = compressibility of TDA,
λ = coefficient of TDA compressibility,
H = thickness of TDA layer, and
σ = stress at a depth of z in the TDA layer.

The relationship between stress and the coefficient used in the study was:

$$\lambda = 1/h_1\left(h_1 - h_2\right)/\left(\sigma_2 - \sigma_1\right)$$

Where:

h_1 = the TDA layer thickness at $\sigma_1 = 7.3$ psi, and
h_2 = the TDA layer thickness at $\sigma_2 = 29$ psi.

The stress at the middle of the TDA layer was obtained using the solution for axis-symmetric loading over an elastic half space:

$$\sigma_z = q\left[1 - \frac{z^3}{\left(a^2 + z^2\right)^{1.5}}\right]$$

Where:

q = uniform applied pressure, and
a = radius of the loaded area = 6 in.

TABLE 46
RESILIENT RESPONSE OF SHREDDED TIRES FROM CONSTRAINED COMPRESSION TESTS

Size of Tire Shreds, in.	Resilient Modulus at Normal Stress of: (psi)		
	7.3	14.5	29.0
2	50.6	63.2	84.4
6	24.4	34.5	52.1
12	20.0	29.6	46.7

After Shalaby and Khan (2005).

TABLE 47
PREDICTED DEFLECTIONS OF TIRE SHRED EMBANKMENT USING COMPRESSIBILITY PARAMETERS

Size of Tire Shreds (in.)	Coefficient of Tire Compressibility[a] (m^2/MN)	Thickness of Tire Shred Embankment (*h*)	Stress at Mid-layer Under 550 kPa Tire Pressure[b] Stress at *z* (kPa)	Deflection[c] (nm)
2	1.1	1.5	12	19.8
6	1.9	1.5	12	34.2
12	2.2	1.5	12	39.6

After Shalaby and Khan (2005).
[a] Stress vs. deflection response.
[b] Boussinesq's solution.
[c] From one-dimensional consolidation settlement testing.

Previous testing by the researchers indicated that the predicted values were a good representation of the actual deformations. Results showed that compression parameters of TDA can be reasonably determined from the one-dimensional constrained compression laboratory testing. These results can be used to estimate pavement layer responses (Table 47).

Initial research by Tatlisoz et al. (1997) used silty soils with TDA to provide improved soil properties (Table 48). The unit weight of the soil–TDA mixtures decreased with increasing TDA content. At the same time, the cohesion increased with increasing TDA content. Soil–TDA mixtures did not show significant long-term deformation, even when soaked. Using TDA with the soil improved the angle of internal friction, regardless of TDA content.

Tatlisoz et al. (1998) investigated the use of soil–TDA mixtures in geosynthetic-reinforced earthworks. The three soils used were one coarse grained and two fine grain (two sands and one clay). The clay was eliminated as early testing that showed clay–TDA combinations did not provide improved soil properties. One geotextile and two geogrids were used for the reinforcement. The TDA ranged in size from 30 to 110 mm.

Testing used direct shear rather than triaxial cell methods because of the large size of the TDA compared with the conventional triaxial cell. Pullout testing was conducted using a large steel pullout box to determine the interaction coefficient, which compares the effective strength of the soil–geosynthetic interface to the shear strength of the soil.

TABLE 48
SHEAR STRENGTH PARAMETERS OF SANDY SILT AND SANDY SILT–TDA MIXTURES

Sample	Unit Weight, lb/ft^3	c, psi	ϕ
Sandy Silt	116.5	230	30
Silt + 10% TDA	112.0	167	55
Silt + 20% TDA	108.2	793	54
Silt + 30% TDA	103.8	815	53

After Tatlisoz et al. (1997).

Results of the laboratory testing showed that soil–TDA mixtures have significantly higher shear strength than soil mixtures alone (Table 49). These mixes did not exhibit peak shear strength and the shear strength continues to increase with increasing displacement. The pull-out forces increase with increasing displacement. The interaction coefficients were generally around 0.5; however, the pullout capacity of the soil–TDA backfill was often equal to or greater than the pullout capacity of the soil-only backfill. Theoretically, the soil–TDA system would require fewer layers to reinforce walls constructed with soil–TDA, which was a function of the higher strength and lower unit weight. The soil–TDA system provided greater resistance against lateral sliding of embankments on geosynthetic layers because of the low active earth pressure and higher interface resistance. There was a greater resistance to bearing failure because of the lighter weight. It is important that these conclusions be validated through large-scale testing.

Abichou et al. (2004) evaluated a mechanically stabilized earth (MSE) wall reinforced with geotextiles and geogrids, then backfilled with a sand–TDA mixture (25% TDA by volume). Once constructed, a range of surcharges were applied to the backfill (42, 95, 148, and 200 kPa). Horizontal and vertical pressures and displacements were measured with sensors embedded behind the wall.

Materials used in the study were a fine, uniformly graded sand and TDA with sizes from 50 to 550 mm. Laboratory results from the earlier study were used to design the MSE. Construction was completed per recommendations by the block wall supplier. The wall was reinforced with two layers of geotextile and two layers of geogrids. Compaction was achieved using a vibratory plate compactor. The wall was allowed to stabilize for three months after construction before the surcharge was placed.

TABLE 49
SUMMARY OF PULL-OUT TEST RESULTS

Backfill	Geosynthetic	Normal Stress, psi	Shear Strength, psi	Pull-out Force	Interaction Coefficient
Tire Chips	Geotextile	1.16	0.67	3,147	1.51
		4.21	2.42	10,116	1.67
		7.25	4.19	14,837	1.27
	Miragrid 5T	1.16	0.67	3,822	1.95
		4.21	2.86	6,969	0.99
		7.25	4.18	8,992	0.72
	Miragrid 12XT	4.21	2.42	7,868	1.05
Sand	Geotextile	1.45	0.97	2,248	0.65
		4.35	2.93	10,566	0.93
		7.40	4.99	11,690	0.78
	Miragrid 5T	1.45	0.97	1,798	0.73
		4.35	4.38	6,295	0.63
		7.40	4.99	6,969	0.47
	Miragrid 12XT	4.35	2.93	5,620	0.61
Sand–Tire Chips	Geotextile	1.45	1.86	4,047	0.73
		4.35	5.57	9,442	0.54
		7.40	5.12	14,837	0.52
	Miragrid 5T	1.45	1.86	3,597	0.65
		4.35	5.57	8,093	0.47
		7.40	9.47	8,992	0.3
	Miragrid 12T	4.35	5.57	9,892	0.57
Sandy Silt	Geotextile	1.45	2.44	4,946	0.79
		4.35	4.10	9,892	0.86
		7.40	5.86	19,334	1.15
	Miragrid 5T	1.45	2.44	4,047	0.57
		7.40	5.86	9,892	0.57
	Miragrid 12XT	4.35	4.10	8,992	0.71
Sandy Silt–Tire Chips	Geotextile	1.45	7.59	4,496	0.2
		4.35	11.43	10,791	0.31
		7.40	15.48	17,535	0.38
	Miragrid 5T	1.45	7.59	5,395	0.24
		7.40	15.48	10,116	0.22
	Miragrid 12XT	4.35	11.43	11,016	0.31

After Tatlisoz et al. (1998).

Results showed that conventional geotechnical methods had horizontal and vertical stresses behind the wall that increased with the addition of the surcharge, as expected. Displacements of the wall decreased with increasing depth and were considered small compared with the size of the surcharge. Strains were highest near the wall face. A finite element analysis model reasonably predicted the measured stresses. The frictional characteristics of the soil–TDA mixture along the wall were not known. The final conclusion was that conventional design methods could be used for MSE walls with soil–TDA backfill.

Cetin et al. (2006) are Turkish researchers who evaluated the use of coarse and fine TDA mixed with a cohesive soil [CL by USCS (unified soil classification system)] at 10%, 20%, 30%, 40%, and 50%. Laboratory testing indicated that the permeability of the mix was dependent on the characteristics of the soil used in the mix. The cohesion increased with increasing TDA content up to 40% of either coarse or fine TDA.

Conclusions were that the clay–TDA mixture was an acceptable fill material when using a maximum of 20% coarse graded TDA or 30% of the fine graded TDA when used above the ground water table. Neither mix should be used where drainage is needed to prevent the development of pore water pressures during loading under saturated conditions.

Huat et al. (2007) evaluated the use of whole tires linked together to form a soil-filled earth wall in Malaysia. Testing evaluated the tensile strength (ASTM D4595) of scrap tires. Whole tires with the sidewall removed were loaded in tension at a rate of 2 in./min until failure. The study showed there was an 88% probability that the tensile strength of the available tires would be greater than 4,500 lb-force. Polypropylene rope was evaluated as a quick, economical, and locally available means of connecting the tires. Tensile testing was also conducted for various methods of wrapping and tying the rope (Table 50).

A full-scale field test section was constructed to evaluate the use of the proposed earth wall (Figure 4). Reinforcement mats were constructed and backfilled with native cohesive soil. Each layer was compacted with a 1-ton steel wheel roller. A total of 25 layers were used to construct the earth wall. Two vibrating wire earth pressure cells were used to

TABLE 50
TENSILE STRENGTH OF POLYPROPYLENE ROPE ATTACHMENT

Sample No.	Diameter of Rope, in.	No. of Wraps	No. of Knots	Maximum Load, lb
1	0.5	1	1	2,898
2	0.5	1	2	5,171
3	0.5	2	2	11,690

After Huat et al. (2007).

compare the theoretical with the field-measured lateral earth pressures. Instrumentation of the wall showed an initial settlement of about 15 mm after 10 days. The long-term settlement stabilized after this time at 14 mm. The conclusion was that the tire wall was in the Rankine's active state.

Tandon et al. (2007) instrumented and monitored three types of embankment backfill for the Texas DOT. The first section, a soil–TDA (50:50) mixture, was used to construct an embankment with a width of fill of approximately 20 ft, with a layer thickness of 6.6 ft using a sandy lean clay (CL by USCS). Density testing and optimum moisture contents were evaluated during placement. The second section was TDA with a geotextile section of embankment about 41 ft wide with a layer thickness of approximately 5.4 ft, which was constructed in six 1-foot lifts. The third section used a conventional soil to construct an embankment with a width of 88 ft and a height of 12.6 ft, and was constructed in 1-foot-deep lifts.

FIGURE 4 Construction of MSE wall (after Huat et al. 2007).

Testing included monitoring of vertical settlement, temperature change, and air and water changes. Sensor instruments placed during construction included inclinometers, thermal couples with data logger, moisture detection devices, air sampling ducts, and lysimeters. Little settlement was seen because of the attention to compaction during construction. Water did not drain downward through the pavement surface, mostly because of the low rainfall in the El Paso area.

After 2 years of monitoring, the temperature in the TDA fill was only slightly higher than in the soil–TDA fill (58°F to 84°F and 67°F to 88°F, respectively). Temperatures in the TDA section had less fluctuation than the ambient temperatures, which is a function of the insulation properties of the TDA. Air samples were used to identify potentially flammable concentrations per National Fire Protection Association (NFPA) specifications (Table 51). All of the results from the 100% TDA section were well below the specification limits. The conclusion was that there was little potential for environmental impacts for TDA fill used in the El Paso, Texas, climate region.

Wartman et al. (2007) conducted a laboratory study of soil–TDA combinations using both one-dimensional confined compression (shredded tires) and isotropic compression with a triaxial cell (tire chips). TDA dimensions were an average of 1.14 cm thick, 7.53 cm in width, and 17.84 cm in length. Using the USCS, the TDA can be described as poorly graded gravel (GP) with a maximum particle size of 3 cm. The TDA had a specific gravity of 1.07 owing to some metal content still in the TDA. The soil was medium sub angular sand classified as SP. The sand required a moisture content of about 2% to keep it from segregating when mixed with the TDA.

The density of the TDA materials was conducted during construction of a field project so that a companion compaction method for laboratory-prepared samples could be developed. Compaction energy of 600 kN/m^3 per ASTM D698 was found to provide relatively dense samples for testing (Table 52).

Testing determined that the secant modulus at 50 kPa was used to represent the immediate compression modulus. Volume changes in TDA tire chips under saturated, drained, isotropic compression showed that most of the volume strain was the result of the void reduction between rubber particles. The volume change from the compression of the rubber particles themselves was small and does not contribute to the immediate volume changes (Figure 5). The volume change had a decreasing

TABLE 51
VOLATILE ORGANIC SCAN OF AIR SAMPLE COLLECTED FROM SITE 2

Organic Compound	Results ppm·10^{-3}	Regulatory Limits		
		Immediately dangerous to life or health concentrations, ppm	Lower explosive Limit, ppm	Upper explosive Limit, ppm
1,4 Dichlorobenzene	1.1	Not noted	62,000	160,000
Ichlorodifluoromethane	3.1	15,000	—	—
Ethylbenzene	1.9	800	10,000	67,000
Styrene	1	700	11,000	—
Tetrachloroethylene	10.3	150	—	—
Toluene	43.3	500	12,000	71,000
Trichloroethylene	4	1,000	120,000	400,000
Trichlorofluoromethane	1.1	N/A	—	—
1,2,4-trimethylbenzene	3.4	N/A	—	—
1,3,5-trimethylbenzene	2.4	N/A	—	—
m,p-Xylene	6.7	900	11,000	70,000
o-Xylene	2	900	10,000	76,000

After Tandon et al. (2007).
— = not applicable.

TABLE 52
PHYSICAL PROPERTIES OF THE MATERIALS USED IN WARTMAN et al. STUDY (2007)

Material	kN/m^3	Porosity[b], n	Void Ratio[b], e	Specific Gravity	D_{max}, cm
Tire Chips	6.46[a]	0.38	0.62	1.07	3
Tire Shreds	4.74[a]	0.63	1.71	1.31	Varied
Sand	16.04	0.37	0.58	2.59	0.2

[a] Based on a selected compaction energy of 600 kNm/m^3
[b] As-compacted porosity and void ratio values.

linear relationship with the log of the time and the rate of volume change with time (i.e., slope of regression line) and is dependent on the percentage of TDA in the mixture (Figure 6). The rate of change became steady after 10 to 20 h of testing.

Results showed that subbase placement could be used to remove the immediate volume change in the TDA soil mixtures. The initial compaction requirement that resulted in an increase in the TDA mixture until the compaction was about 10% over that found in the laboratory-achieved densities. Volume changes are to be accounted for in any design.

The layer modulus increased with the decreasing volume of the mixtures. Based on consolidation data, a period of 8 weeks

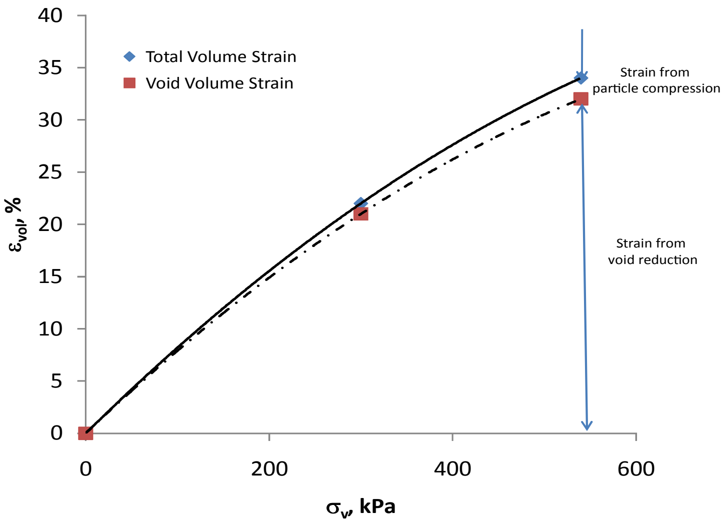


FIGURE 5 Proportion of strain owing to change in void space compared with compression of tire particles (after Wartman 2007).

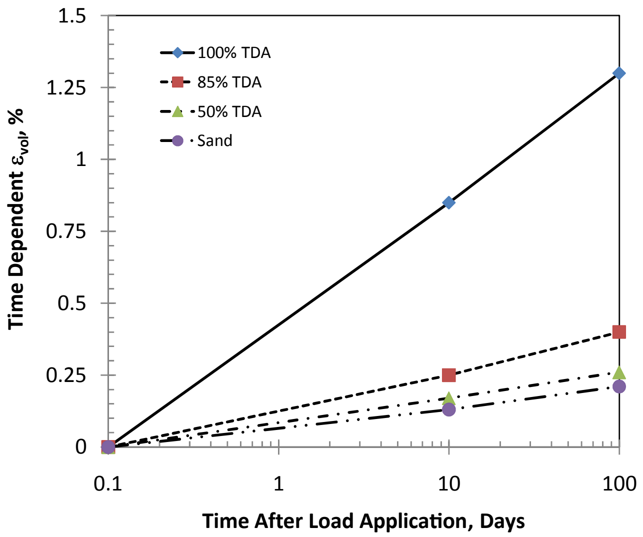


FIGURE 6 Influence of percentage TDA in soil–TDA combination on strain with time (after Wartman 2007).

was considered to be sufficient to allow for compression of the TDA soil mixture after the subbase surcharge has been added. Long-term field data are needed.

Choi et al. (2007) reported using TDA as an insulation layer to minimize frost penetration in Virginia, and allowed for the free draining of water to prevent frost heave in frozen winter conditions.

Mills and McGinn (2008) evaluated four options for a lightweight fill (Table 53). Ultimately, the TDA was selected that resulted in the use of 1.6 million scrap tires (about 2 years of discarded tires in New Brunswick). The TDA lightweight fill was placed in two separated 9.6-ft-thick layers within the soil fill. Key factors that made the use of TDA possible were the location of the recycling center and costs subsidized by discarded tire fees. The tire recycling plant was within 160 km of the embankment site. The transportation costs were offset by the use of fees collected for discarding tires, which paid about 97% of these costs. This made the transportation costs of the TDA significantly lower than any of the other options.

OTHER APPLICATIONS

The California Integrated Waste Management Board (2010) identified sound barriers as a use for crumb rubber PCC. The load bearing structural composite tongue and groove building planks (nonrecycled) filled with shredded post-consumer tires can be used to produce a 12-ft-high sound wall with about 250,000 lb of TDA used per mile of installation. The wall components can be constructed to meet ASTM E884 with a class A rating. A fire retardant can also be incorporated into the cell.

TABLE 53
COMPARISON OF OPTIONS CONSIDERED BY MILLS AND MCGINN (2008)

Repair Option	Benefits	Disadvantages
1. Removal of Soft Soils and Replacement with Imported Granular Fill	– Conventional construction techniques – Very low risk of future embankment failure – Minimizes secondary settlement – Eliminates the importance of soil profile and soil parameter assumptions	– Very deep excavation would be a challenge in the soft clays and a large excavation footprint would require gaining access to private land to the south, which was unfavorable. – Very large quantity of soft clay soils to dispose of off-site would be a challenge.
	– No instrumentation required	– Risk of undermining adjacent highway embankment – Estimated cost is three times the estimated cost of the TDA option.
2. Stone Columns (installed by a specialty contractor)	– Will allow embankment to be constructed relatively quickly after treatment using conventional soils. – Will allow for the original designed geometry of the embankment	– Large quantity of soft clay to be disposed of off-site. – Specialty contractor had some concerns that the clay soils may be too soft in areas and would not provide the necessary confining pressure for stone columns. – Estimated cost is 1.4 times the estimated cost of the TDA option.
3. Geofoam + TDA	– Can leave soft foundation soils in place – Very light weight and easy to construct – No wick drains required	– Geofoam on its own was considerably more expensive than Geofoam+TDA. – Estimated cost is 1.7 times the estimated cost of the TDA option.
4. TDA	– Can leave soft foundation soils in place – Limits extent of excavation required – Most economical option – Good track record and many successful cases reported in the literature – ASTM standards available for TDA use in civil engineering applications. – TDA locally available in NB	– Wick drains required in combination with TDA – Staged construction necessary – Instrumentation required to monitor foundation soil's response to loading.

NB = New Brunswick.

CHAPTER THREE

AGENCY SURVEY

The use of ground tires, crumb rubber (dry and wet) in HMA applications was the most often used (Table 54). Shredded tires were most commonly used in embankments. Asphalt rubber crack sealant products are also used by a number of agencies.

Table 55 summarizes which scrap tire byproducts are used by each state agency. Only Vermont used slit tires as drainage material. Only Texas used whole tires in embankments. Three states reported using scrap tire byproducts; however, the type of byproduct used was not known (see Figure 7).

The agency responses to the open-ended question with regard to performance experience are shown in Table 56. Four states commented on their experiences with using scrap tire byproducts in embankments and/or fills. Two states have had successful experiences, whereas one state indicated both poor performance and a tendency for spontaneous combustion. The literature search indicated the embankment design is key to preventing this type of problem, which would indicate that further examination of the design used by Washington State may provide information on further design guidance. The majority of the comments were received for the use of ground or crumb rubber in HMA applications. The comments about poor performance are mostly associated with the use of crumb rubber with the dry process. The two comments about using crumb rubber (wet process) for chip seals indicated favorable performance.

Written responses were also provided for barriers to increased use (Table 57). The responses can be summarized as follows:

- Cost (11 states)
- Poor performance (7 states)
- Construction issues (5 states)
- Unsuccessful experiences (3 states)

Individual responses on performance were received for lack of agency experience, lack of experienced contractors, unfavorable material properties, safety concerns, lack of data, proprietary product/process, and limited byproduct supply.

SUMMARY OF SCRAP TIRE BYPRODUCT INFORMATION

List of Candidate Byproducts

A number of terms for scrap tire byproducts were found in the literature and agency survey results. The types of byproducts along with the size of particles associated with each type are shown in Table 58. The lack of consistent terms and definitions made it difficult to compare different research projects.

CRM asphalt and terminal blend asphalt binders were both considered a wet process for adding the byproduct. CRM binders typically had higher percentages of byproduct, were produced on site at the HMA plant, and included agitation. This process was referred to as a *continuous blending* of CRM binder. *Terminal blends* tended to have a lower concentration of rubber that was added to the tanker truck at the refinery or blending terminal with the asphalt with no agitation during hauling to the plant. The crumb rubber for the terminal blends was finer than that used for continuous blending.

Test Procedures

The test procedures used to evaluate scrap tire byproducts or hybrid highway application products are shown in Table 59.

Material Preparation and Byproduct Quality Control

The following post-processing and QC points are to be considered:

- Density testing is recommended when using TDA in fills and embankments.
- Standard highway application testing is used for PCC and HMA applications.
- There was very little information found for quality control practices for scrap tire byproducts.

Materials Handling Issues

The following materials handling points need to be considered:

- The use of crumb rubber in HMA production may produce eye, nose, and throat irritations for paving crews that is related to the TPs measured.
- NIOSH noted that emissions for CRM HMA were higher than for conventional HMA and the temperature must to be kept as low as possible.

Transformation of Marginal Materials

- Combining TDA with soil can result in significantly improved properties.

TABLE 54
NUMBER OF STATES USING SCRAP TIRE BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Tire Rubber: Is your state using, or has ever used, these byproducts in highway applications? If you do not know what type of tire byproduct your state uses, check the Tire type, unknown type box at the end of the list.

*Ground tires: typically a no. 80 mesh (finely ground rubber)
*Shredded or chipped tires: primary processing produces shredded tires (12 to 18 in. long by 4 to 9 in. wide) A secondary process produces chips (0.5 to 3 in.)
*Slit tires: tires slit in half
*Whole tires: used as-is
*Crumb rubber aggregate (dry process): small size chips used as aggregate replacements
*Crumb rubber modifier (wet process): small size chips used as a binder modifier (e.g., substitute for polymer modification of asphalt)

	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embankments	Flowable Fill	HMA	Pavement Surface Treatments (non-structural)	PCC	Soil Stabilization
Ground Tires	6	9	0	2	0	13	2	0	0
Shredded or Chipped Tires	1	1	1	14	0	3	1	0	0
Slit Tires	0	0	1	0	0	0	0	0	0
Whole Tires	0	0	0	1	0	0	0	0	1
Crumb Rubber Aggregate (dry process)	3	1	0	0	0	15	3	0	0
Crumb Rubber Modifier (wet process)	8	4	0	0	0	22	8	0	0
Tires, Unknown Type or Size	2	2	1	2	1	1	1	1	2

- Combining crumb rubber with fly ash in PCC applications somewhat improves the compressive strength compared with crumb rubber without fly ash in PCC applications.

Design Adaptations

The following points are to be considered during the application design processes:

- Most common agency use for scrap tire byproducts are:
  - Embankments (14 states)
  - HMA applications using ground tires (12 states), dry process crumb rubber (15 states), and wet process crumb rubber (22 states).
  - Surface treatments with primarily crumb rubber wet process (8 states), crumb rubber dry process (3 states).
- Embankments, fills, and base applications:
  - Compacted TDA has a significantly lower thermal conductivity than conventional soils, which can provide good insulation.

TABLE 55
STATES USING SCRAP TIRE BYPRODUCTS IN HIGHWAY APPLICATIONS

Number of Highway Applications	States						
	Ground Tires	Shredded or Chipped Tires	Silt Tires	Whole Tires	Crumb Rubber (dry)	Crumb Rubber (wet)	Unknown Type
9	—	—	—	—	—	—	ID
4	AZ, TX, VA	—	—	—	—	PA, VA	—
3	—	—	—	—	—	AK, AZ, TX	MA
2	CT, IL, IA, MN, NE	CT, IA	—	TX	AK, CT, NE, PA	MO, NE, NY, OR	—
1	AL, CO, FL, ME, NC, OK, WI	CO, DE, IN, LA, ME, MN, NC, NH, NJ, NY, OK, PA, TX, VA, VT, WA	VT	—	IL, IA, KY, ME, MO, MS, NH, NJ, NV, NY, OK, OR, WI, WV	AL, DE, GA, IL, IA, KY, LA, ME, MN, MS, NJ, NV, OK, SC, VT, WA, WI	NJ

— = none


2009 Ground Tires

2009 Shredded or Chipped Tires

2009 Crumb Rubber Aggregate (Dry Process)

2009 Crumb Rubber Modifier (Wet Process)

FIGURE 7 State agencies reporting usage of scrap tire byproducts (numbers indicate number of highway applications using byproduct).

- TDA as a base can be evaluated using standard Boussinesq's solution for embankment design.
- Laboratory study of soil–TDA combinations of embankment fill show:
  - Higher strength and lower unit weight
  - Greater resistance to lateral sliding of embankments on geotextile layers
  - Low active earth pressure and higher interface resistance
  - Greater resistance to bearing failure because of lighter weight.
- Field studies of soil–TDA combinations for an MSE wall showed conventional design methods for the MSE wall can be used with soil–TDA backfill.
- TDA as a base can be evaluated using standard Boussinesq's solution for embankment design.
- Drinking water standards are not exceeded when the scrap tire byproduct is kept above the water table.
- Drinking water standards are likely to be exceeded when scrap tire byproducts are used when submerged in water; however, the concentrations are not usually detectable a short distance away.

- PCC applications:
  - Crumb rubber can be used in precast applications to produce lightweight, low-strength panels with good insulation and noise damping properties.
  - Crumb rubber in PCC reduces the thermal conductivity by more than half compared with conventional concrete. The magnitude of reduction is dependent on the amount and size of the crumb rubber.
  - Crumb rubber provides a hybrid PCC with a high resistance to chloride penetration and would be good when strength is not required of the concrete.
  - Crumb rubber decreases the PCC unit weight and porosity.
  - Crumb rubber decreases compressive and tensile strengths, but significantly improves the toughness of the concrete (large deformations before tensile failures).
  - Crumb rubber in PCC changes the damping characteristics used in seismic designs of structural concrete.
- Laboratory study of soil–TDA combinations of embankment fill show:
  - Higher strength and lower unit weight.

TABLE 56
COMMENTS FROM AGENCIES ON PERFORMANCE OF HIGHWAY APPLICATIONS USING SCRAP TIRE BYPRODUCTS

Use	State	Performance
Crack Sealant	CO	The ground tires did not perform well as a crack sealant at some locations in Colorado.
Geotech	IN	We are beginning to use large quantities of shredded tires in embankments.
	ME	Shredded tires have performed satisfactorily in lightweight fill applications.
	NC	No problems with shredded tires in embankments. One small retaining wall using whole tires bound together and filled with flowable fill worked well but was not aesthetically pleasing.
	WA	Poor performance as lightweight fill material; prone to spontaneous combustion.
HMA	AL	Crumb rubber has recently been specified on one project as an alternate for SBS or SBR polymer but has not been used.
	AZ	Crumb rubber asphalt has been used by ADOT since the late 1980s with much success. Both gap graded and open graded mixes have been used extensively.
	FL	Generally the use of GTR has improved the cracking resistance of HMA by allowing more binder to be placed in the mixture. Polymers are proving to be better in terms of performance than GTR, but recycling tires is also good for the environment.
	GA	Still evaluating the crumb rubber performance in HMA
	IA	High cost in HMA no improvement in performance noted.
	KY	The performance of the one HMA pavement in Kentucky containing tire rubber has been satisfactory. The mat is currently exhibiting significant distress, but the pavement is more than 15 years old.
	ME	Crumb rubber modifier HMA had satisfactory performance. Crumb rubber aggregate had performance issues.
	MO	Crumb rubber aggregate was used on one project, but failed after the first winter. The wet process resulted in the same failures because of wet freeze cycles of saturated pavements.
	MO	Failure of asphalt-rubber projects within months or a few years. Trying new process of rubber-modified asphalt that is performing well at this point.
	MS	Crumb rubber (dry process) has been used on trial projects with marginal success. Increased cracking of the pavement sections were observed creating durability issues with the pavement. Crumb rubber (wet process) is allowed by specifications as an asphalt modifier.
	NH	Surface treatment: Rubber chip seals using shredded tires have been used and have performed satisfactorily.
	NJ	We had mixed performance with dry process—some good jobs and some disasters. Wet process has been more consistent. Have not seen an improvement in performance for dense graded mixes, but we have been happy with the use of CRM (wet process) in OGFC (open-graded friction course). We are currently constructing our first SMAR (stone matrix asphalt rubber).
	NV	NDOT experienced very poor performance with crumb rubber (dry method) and a gap graded dense grade mix. Crumb rubber (wet process) has performed well as an Asphalt Rubber Friction Course over 10 year-old PCCP. NDOT has placed one research project (2008) using terminal blend rubber at 10% of the asphalt project.
	NY	Performance has been inconsistent in HMA.
	OH	General: Do not use crumb rubber replacement (small chips) in asphalt because of control and performance issues.
	OR	We did some research projects a number of years ago using tires in HMAC. The performance was not that good and ODOT has not done any further projects using this material.
	PA	Crumb rubber and chemically treated crumb rubber has been experimentally used on various projects mainly involving dense graded HMA pavement courses. Coarser crumb rubber aggregate (dry) has experienced raveling. Some recent experience with crumb rubber aggregate (dry) in two SMA mixtures as the stabilizing agent has gone well.
	TX	Tire rubber in HMA is mainly a benefit for high binder/high film thickness mixes to prevent draindown of the binder and provide more crack resistance.
	WA	Poor performance on a life-cycle cost basis.
Surface Treatment	NM	Surface treatments: No experience. We tried on one of the chip seal projects and because it has some very high temperatures; field crews didn't like to use for safety reasons.
	TX	Surface treatments: Tire rubber-modified chip seals have been observed to provide good chip retention.

  - Greater resistance to lateral sliding of embankments on geotextile layers.
  - Low active earth pressure and higher interface resistance.
  - Greater resistance to bearing failure because of lighter weight.
- Field studies of soil–TDA combinations for an MSE wall showed that conventional design methods for the MSE wall can be used with soil–TDA backfill.
- HMA applications:
  - The PG binder specification designation may or may not change with the addition of crumb rubber and is a function of the original binder actual temperature grading. When crumb rubber (continuous process) is added, the maximum summer temperature increased by about 1.2°C to 1.5°C per each 1% of CRM. The low winter temperature was decreased by about 0.2°C per each 1% of CRM.
  - CRM HMA open and gap graded mixes can significantly lower the noise level of the tire–pavement

TABLE 57
AGENCY COMMENTS ON BARRIER TO INCREASED USE

State	Barriers
AK	Initial cost. Lack of contractor's experience.
AL	In liquid asphalt cement one barrier would be the time restrictions and handling requirements for proper incorporation into HMA.
CO	Cost. Not familiar with the use.
DE	Education of designers
FL	Gradation and specific gravity issues and variability. More difficult to work with than neat binders, but overall is manageable. Performance not as good as polymer mixtures in terms of cracking and rutting.
IA	Cost
KY	The tire rubber technology utilized in the early 1990s in Kentucky was too costly for use on a larger scale.
MO	Previous failure of asphalt-rubber projects. Other uses never tried before.
MO	Cost of processing makes most uses not economical.
MS	Questions regarding durability of dry process crumb rubber HMA. Because crumb rubber is currently allowed by specifications, assume that the market for crumb rubber-modified asphalt is being driven by cost and/or successful use of other materials.
NC	Past experience with crumb rubber in pavements
NE	Was more costly to do the modification (wet), but recently more contractor interest and more competition have resulted in lower costs.
NJ	Worker exposure to fumes has been raised as an issue. Cost is higher for CRM mixes, so needs to be justified.
NV	Number of appropriate projects
NY	Previous HMA failures still concern us; no HMA performance advantage, generally increased cost.
OH	Typical barriers are cost, control of product, and overselling of what it can do with no real technical data.
PA	Additional cost added to HMA to incorporate crumb rubber either by the dry process or especially by the wet process. Tire shreds for embankments are also very difficult to process and place (and costly), with equal difficulty in assessing performance for acceptance. Rubber has more btus per pound than coal with less ash and sulfur. Rubber may be more valuable as a fuel.
TX	Common barriers as with implementing any new product include cost, lack of engineering design procedures, mixture design procedures standard specifications, project selection criteria, experienced contractors, and agency experience. At times, a proprietary specification or a limited number of suppliers or contractors appears to have inflated prices.
UT	UDOT typically has a performance-based spec and does not specify what materials go into the mix. However, crumb rubber use probably does not generally produce a material that will meet our spec.
VA	It takes a lot of heat to meld crumb rubber with asphalt binder. Also, it takes an extra step or two to mix chipped rubber with soil.
WA	Performance issues as noted above. Note that all the used tires in the state are being consumed, mostly in cement kiln combustion.
WV	The use of these materials is not cost-effective owing to the limited supply of consistent materials.

TABLE 58
TYPES AND ASSOCIATED SIZES OF SCRAP TIRE BYPRODUCTS

Term	Size of Scrap Tire Byproduct	
	Minimum, mm	Maximum, mm
Whole Tires	NA	NA
Slit Tires	NA	NA
Shredded or Chipped Tires	100 x 100	220 x 460
Ground Rubber	0.15 x 0.15	19 x 19
Crumb Rubber	0.075 x 0.075	4.75 x 4.75
Tire Derived Rubber	12	305
Tire Buffings	Not specified	
Coarse Rubber	4.75	25
Ground Rubber	0.18	2.0
Fine Ground Rubber	0.04	0.18
Shredded Tire Fibers (Rectangle)	25 x 50	25 x 125

NA = not available.

TABLE 59
TEST METHODS USED TO EVALUATE MATERIALS AND APPLICATION PRODUCTS WITH SCRAP TIRE BYPRODUCTS

Test Method		Title
ASTM Methods	AASHTO Methods	
ASTM C177	—	Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
ASTM C469	—	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
ASTM C642	—	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
ASTM D36	AASHTO T53	Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)
ASTM D217	—	Standard Test Methods for Cone Penetration of Lubricating Grease
ASTM D297	—	Standard Test Methods for Rubber Products—Chemical Analysis
ASTM D689	—	Standard Test Method for Internal Tearing Resistance of Paper (withdrawn 2009)
ASTM D2669	—	Standard Test Method for Apparent Viscosity of Petroleum Waxes Compounded with Additives (Hot Melts)
ASTM D3407	—	Standard Test Methods for Joint Sealants, Hot-Poured, for Concrete and Asphalt Pavements (withdrawn 1996) Replaced by D5329
ASTM D5084	—	Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
ASTM D6114	—	Standard Specification for Asphalt-Rubber Binder
EPA Method 8260	—	Volatile organic compounds
EPA Method 8270	—	Semi-volatile organic compounds
ISO 10534-1	—	Determination of sound absorption coefficient and impedance in impedance tubes—Part 1: Method using standing wave ratio

— Not applicable.

interaction when compared with conventional dense graded HMA. However, it is unclear if the reduction is a function of the crumb rubber or the gradation. It can be noted that the high film thickness and low draindown of the CRM binders facilitate the use of more open graded HMA than an unmodified binder.

  - CRM asphalt binders and RAP can be used in the same mixes, but care is needed in the design phase to make sure that the combined binder properties have acceptable high temperature rheology and are suitably crack resistant at cold temperatures.
  - Some evidence that standard pavement design equations can be used for crumb rubber PCC materials.
- Crack sealants:
  - Rubberized crack sealants have an expected life of between 5 to 8 years when placed in a standard or shallow-recessed "band-aid" configuration.

Construction Issues

The following points need be considered in construction of projects using scrap tire byproducts:

- Larger size scrap tire byproducts tend to separate during construction of PCC slurries. There is a maximum size that can be used without segregation.
- PCC slurries with larger scrap tire byproducts can be difficult to finish and are best in applications that will be covered (e.g., soil cap).
- WMA technologies have the potential to lower the workable temperatures of CRM binders and CRM HMA.
- Applying a hot CRM binder over paving fabric can result in wrinkling of the fabric and a tendency for the fabric to stick to the pneumatic tire rollers.

Failures, Causes, and Lessons Learned

- HMA applications with crumb rubber dry process produced the majority of the poor performance comments from agencies.
- HMA applications using crumb rubber wet process produced the majority of the acceptable, good, or excellent performance comments.

BARRIERS

The following barriers were found in the literature and the survey responses:

- Cost (11 states)
- Poor performance (7 states)
- Construction issues (5 states)
- Unsuccessful experiences (3 states).

Costs

The following information regarding costs associated with using scrap tire byproducts in highway applications included:

- No cost information was found for using scrap tire byproducts in PCC applications.
- CRM asphalts cost more than conventional asphalt cements. Some agencies reported that CRM binder cost more than polymer-modified binders; however, this comparison is dependent on the cost of the polymer, which has increased substantially in recent years.
- REAS costs more initially than conventional slurry seals, but is expected to last 50% longer.

Gaps

The main current use of scrap tire byproducts in highway applications is in HMA applications. The following gaps were found in the HMA portions of the literature and survey responses:

- Terms for scrap tire byproducts need to be standardized.
- Quality control testing programs for both the scrap tire byproducts and hybrid application products are essential.
- More performance experience with the hybrid application products is necessary (e.g., surface treatments, terminal versus a continuous blending of asphalt binders, etc.).
- Technology transfer is required to share successful state experiences.

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Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation